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FACULTY of  
TEXTILE  
TECHNOLOGIES  
and DESIGN

INTERNATIONAL  
**ITFC**  
2026  
CONGRESS

TEXTILE & FASHION

INTERNATIONAL

# TEXTILE & FASHION CONGRESS

“  
Innovate, Integrate, Inspire:  
The Future of Textiles  
”



PROCEEDING BOOK

**April 28-29, 2026**

ITU Gümüşsuyu Campus Taksim

**Istanbul**



Dalya

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## **2<sup>nd</sup> INTERNATIONAL TEXTILE & FASHION CONGRESS**

**28–29 April 2026 / Istanbul, Türkiye**

**Editor, Meltem TEKÇİN**

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Kongre ve Öğrenci Sosyal Merkezi

34469 Maslak

İSTANBUL

0212 285 75 05

[www.ituyayinevi.itu.edu.tr](http://www.ituyayinevi.itu.edu.tr) / [ituyayinevi@itu.edu.tr](mailto:ituyayinevi@itu.edu.tr)



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## INVITATION LETTER

Dear Colleagues,

It is with great pleasure that I invite you to participate in the **2nd International Textile and Fashion Congress (ITFC 2026)**, which will be hosted by **Istanbul Technical University** on **April 28–29, 2026**, in the vibrant city of Istanbul.

This prestigious event will take place at the Faculty of Textile Technologies and Design, located in Beyoğlu, the cultural heart of Istanbul. ITFC 2026 welcomes all researchers, academics, and professionals in the fields of textile and fashion to share their insights and latest developments.

With a central focus on innovation, sustainability, and digital transformation in textile and fashion, ITFC 2026 will provide a dynamic platform for networking and collaboration with globally recognized researchers, designers, and industry leaders.

We look forward to welcoming you to Istanbul on April 28–29, 2026.

**Prof. Dr. Nevin Çiğdem Gürsoy**

*Congress Chair*



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This list is arranged by academic rank and, within each rank, in alphabetical order by surname.

## SCIENTIFIC PROGRAMME

**2ND INTERNATIONAL TEXTILE AND FASHION CONGRESS (ITFC 2026)**  
**ISTANBUL TECHNICAL UNIVERSITY**  
**APRIL 28–29, 2026**

**28 APRIL 2026, TUESDAY**

|                  |                                                                                                                                                                                                                      |                                                                                                                                                        |                                                                                                                                                                                                                                     |
|------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 08:30-09:30      | REGISTRATION & WELCOME COFFEE                                                                                                                                                                                        |                                                                                                                                                        |                                                                                                                                                                                                                                     |
| 09:30-10:00      | TURKISH MUSIC RECITAL                                                                                                                                                                                                |                                                                                                                                                        |                                                                                                                                                                                                                                     |
| 10:00-11:00      | OPENING SPEECHES (HALL A)<br>PRESENTATION OF PLAQUES TO SPONSORS                                                                                                                                                     |                                                                                                                                                        |                                                                                                                                                                                                                                     |
| KEYNOTE SPEAKERS |                                                                                                                                                                                                                      |                                                                                                                                                        |                                                                                                                                                                                                                                     |
| 11:00-11:30      | KEYNOTE 1 - PROF. DR. VINCENT NIERSTRASZ<br>NOVEL SUSTAINABLE ROUTES TO FUNCTIONAL AND SMART TEXTILES                                                                                                                |                                                                                                                                                        |                                                                                                                                                                                                                                     |
| 11:30-12:00      | KEYNOTE 2 - PROF. DR. GEORGIOS PRINIOTAKIS<br>SYSTEMIC BIOMIMICRY AND HUMAN-CENTRIC RESILIENCE: ORCHESTRATING INDUSTRY 5.0 THROUGH SMART WEARABLES AND DYNAMIC ERGONOMICS                                            |                                                                                                                                                        |                                                                                                                                                                                                                                     |
| 12:00-13:15      | LUNCH<br>Art Exhibition*                                                                                                                                                                                             |                                                                                                                                                        |                                                                                                                                                                                                                                     |
|                  | HALL A                                                                                                                                                                                                               | HALL B                                                                                                                                                 | HALL C                                                                                                                                                                                                                              |
|                  | SESSION 1<br>FASHION TECHNOLOGIES & DIGITALIZATION<br>Chair: Lecturer Dr. Belgin Görgün                                                                                                                              | SESSION 2<br>ADVANCED MATERIALS & STRUCTURES<br>Chair: Prof. Dr. Emel Karaoğlu                                                                         | SESSION 3<br>ADVANCED MATERIALS & STRUCTURES<br>Chair: Prof. Dr. Hale Karakaş                                                                                                                                                       |
| 13:15-13:30      | FUTURETEX ISTANBUL FABRIC DESIGN COMPETITION<br>ÖZLEM KAYA<br>İTHİB<br>FASHION DESIGNER / MENTOR AT FUTURETEX ISTANBUL FABRIC DESIGN                                                                                 | SHAPING THE FUTURE OF DENİM: INNOVATION, RESPONSIBILITY AND PERFORMANCE<br>ERAY KARADUMAN<br>ÇALIK DENİM<br>GENERAL MANAGER                            | BRINGING SUSTAINABLE MATERIALS TO MARKET: SCALABLE INTEGRATION INTO TEXTILE COLLECTIONS<br>SÜLEYMAN İPEK<br>PALMIYE TEKSTİL<br>REGIONAL SALES&MARKETING MANAGER, RESEARCH&DEVELOPMENT MANAGER, SUSTAINABLE APPLICATIONS COORDINATOR |
| 13:30-13:45      | 5875<br>INNOVATIVE APPROACHES TO CONCEPTUAL COSTUME DESIGN IN CONTEMPORARY FESTIVALS: INTEGRATION OF LIGHTING TECHNOLOGIES, 3D PRINTING, AND DIGITAL ORNAMENTATION<br>PARINAZ MEHRI KAHNAMOUEI,<br>AYBEN PAKOLPAKÇIL | 7741<br>IMPROVİNG THE COMFORT PROPERTIES OF DENİM GARMENTS WITH SİLİCONE-BASED SOFTENERS<br>ONUR BALCI, EBRU ÇALIŞKAN, AYRİN İBİŞ, ESRA TABAŞ AŞİLTÜRK | 5314<br>MORPHOLOGICAL AND CHEMICAL CHARACTERIZATION OF PACLITAXEL-LOADED ELECTROSPUN PCL SCAFFOLDS<br>SUZAN ÖZDEMİR, JANSET ÖZTEMUR-SEZGİN , HANDE SEZGİN , İPEK YALÇIN-ENİŞ                                                        |





28-29 April 2026, Istanbul, Turkey

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| 16:00-16:15                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            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<p>3177</p> <p>THE EFFECT OF GRAPHENE COATING ON THE THERMAL BEHAVIOR OF WOOL-BASED WOVEN FABRICS</p> <p>NAZLI TATAR, <b>ELİF ALTÜRK</b></p>                                                                               |
| 16:15-16:30                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            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<p>9644</p> <p>DESIGNING STRENGTH AT THE SEAM: JOINING STRATEGIES FOR WOOL-CORDURA HYBRID TEXTILES</p> <p><b>NUR SEÇGİN</b>, ÖZGE ÇOLAK YILDIRIM, MELİKE ÇAVDAR, NURSEMA PALA AVCI, ÖZGÜR ATALAY, EMİNE DİLARA KOÇAK</p>   |
| 16:30-16:45                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            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<p>2572</p> <p>EVALUATION OF HIGH-TENACITY POLYESTER YARNS ON THE ABRASION RESISTANCE OF AUTOMOTIVE SEAT FABRICS</p> <p><b>EMİR BALTACIOĞLU</b>, BENAMİR FIDANCI, NUR CEYDA UYANIKTIR, SELENAY ELİF İSLER, SEMİH OYLAR</p> |
| 16:45-17:00                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            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<p>9786</p> <p>ENHANCED MOISTURE MANAGEMENT: DEVELOPMENT OF BIOFUNCTIONAL KNITTED FABRIC FOR SENSITIVE SKIN</p> <p><b>BİLGE KOYUNCU</b>, CEVZA CANDAN , F. BANU NERGİS , M. MURAT PEKSEN</p>                               |
| 18:00                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  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| <p>29 APRIL 2026, WEDNESDAY</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        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| 10:00-11:00                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            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| 10:00-10:30                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            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DR. MIRELA BLAGA</p> <p>TEXTILE MATERIALS FOR HUMAN BODY PROTECTION AGAINST MECHANICAL VIBRATIONS</p>                                                                                           |                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                            |
| 10:30-11:00                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            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DR.SAVVAS VASSILIADIS</p> <p>NEGATIVE TEMPERATURE COEFFICIENT OF RESISTANCE IN TEXTILE-BASED TEMPERATURE SENSORS</p>                                                                             |                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                            |
| 11:00-11:15                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            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28-29 April 2026, Istanbul, Turkey

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| 11:15-11:30 | <b>2694</b><br>DIGITAL CRAFTSMANSHIP IN FASHION DESIGN: HYBRIDIZING TRADITIONAL TECHNIQUES AND EMERGING TECHNOLOGIES<br><b>ARZU VURUSKAN, ENDER BULGUN,</b> AHMET BELEN, MELIS OZEN                                                               | <b>2324</b><br>SUSTAINABLE DYEING OF DIFFERENT SYNTHETIC FABRICS WITH ALGAE-BASED DYE STUFFS<br><b>AYŞE CEREN SEN,</b> HÜLYA KICIK                                                                                                          | <b>9573</b><br>AN INVESTIGATION OF FASHION DESIGN STUDENTS' PERCEPTIONS OF SUSTAINABILITY WITH RESPECT TO REBOUND EFFECT AWARENESS<br>MERAL İŞLER, <b>SELMA DOLANBAY DOĞAN</b>                                             |
| 11:30-11:45 | <b>9336</b><br>CONSUMER BEHAVIOR TOWARDS AUGMENTED REALITY APPLICATIONS IN PRODUCT TRIALS AND SHOPPING<br><b>CANAN SARICAM,</b> ENES TATLI, NAZAN OKUR, SINEM BIRSEN                                                                              | <b>4739</b><br>INVESTIGATION OF THE POTENTIAL FOR DYEING LUXURY FIBRES OBTAINED FROM CAMELIDS INTO COLOURS OTHER THAN THEIR NATURAL SHADES<br><b>DURUL BÜŞRA DEBRELİ,</b> MUHAMMET EMİN ŞENSOY, ÖZGE ÇOLAKOĞLU SEVER, ELİF AYDIN, RIZA ATAV | <b>5425</b><br>DESIGNING A UNISEX FUNCTIONAL CAPSULE WARDROBE USING SUSTAINABLE DENIM PROCESSES<br>HÜMEYRA ÇAKIR, <b>ZEHRA DOĞAN SÖZÜER</b>                                                                                |
| 11:45-12:00 | <b>3612</b><br>FROM ALGORITHMS TO APPAREL: ANALYZING AI INTEGRATION IN FASHION DESIGN<br><b>MELİS KÜÇÜKYILMAZ,</b> SERNA UÇAR HATİPOĞLU                                                                                                           | <b>3972</b><br>INVESTIGATION OF THE USE OF LAHOR TREE ROOT, WHICH GIVES COLOUR TO MARDIN BLUE ALMOND CANDY, IN TEXTILE DYEING<br>SİRAÇ BAKAY, <b>ÖNER GÜNDÜZ,</b> DURUL BÜŞRA DİLDEN, RIZA ATAV                                             | <b>7540</b><br>RECYCLING OF PRE-VULCANIZED RUBBER WASTE FOR SUSTAINABLE HEEL COUNTER APPLICATIONS IN FOOTWEAR PRODUCTION<br><b>BARIS BEKİROĞLU,</b> SEZEN UZUNOĞLU, MUSTAFA YENER                                          |
| 12:00-12:15 | <b>2355</b><br>BEYOND COMPLIANCE: UNLOCKING INVESTMENT-FREE FINANCIAL AND ENVIRONMENTAL SAVINGS THROUGH TRACEABILITY AND DIGITAL PRODUCT PASSPORTS IN THE TEXTILE VALUE CHAIN<br><b>SEREL BAŞAK KÖK,</b> SELİN HANİFE ERYÜRÜK, ZÜMBÜL ATAN        |                                                                                                                                                                                                                                             |                                                                                                                                                                                                                            |
| 12:15-12:30 | <b>3227</b><br>A STUDY ON THE ADOPTION OF DIGITAL TECHNOLOGIES IN APPAREL RETAILING<br><b>NAZAN OKUR,</b> FIDAN CENAL, CANAN SARICAM                                                                                                              |                                                                                                                                                                                                                                             | <b>1547</b><br>STUDENT ATTITUDES TOWARDS SUSTAINABILITY IN TEXTILES DURING THE TEXUNITE PROJECT<br><b>MIRELA BLAGA,</b> MIHAELA PERDEVARĂ, IOANA-OTILIA RUSU, DIANA-ANDREEA PLĂCINTĂ, ZLATIN ZLATEV, ANNE-MARIE GRUNDMEIER |
| 12:30-13:30 | <b>LUNCH</b>                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                             |                                                                                                                                                                                                                            |
| 13:30-14:30 | <b>POSTER SESSION</b>                                                                                                                                                                                                                             |                                                                                                                                                                                                                                             |                                                                                                                                                                                                                            |
|             | <b>HALL A</b>                                                                                                                                                                                                                                     | <b>HALL B</b>                                                                                                                                                                                                                               | <b>HALL C</b>                                                                                                                                                                                                              |
|             | <b>SESSION 13</b><br><b>SUSTAINABLE DYEING AND PRINTING SOLUTIONS</b><br>Chair: Prof. Dr. Rıza Atav                                                                                                                                               | <b>SESSION 14</b><br><b>FUNCTIONAL TEXTILES</b><br>Chair: Prof. Dr. Ali Demir                                                                                                                                                               | <b>SESSION 15</b><br><b>ENVIRONMENTAL SUSTAINABILITY</b><br>Chair: Prof. Dr. Nazan Okur                                                                                                                                    |
| 14:30-14:45 | <b>6388</b><br>INVESTIGATION OF VARIOUS PERFORMANCE AND DYEABILITY PROPERTIES OF COTTON BLEND YARNS PRODUCED USING NEXT-GENERATION REGENERATED FIBRES AND SILVER<br><b>SEDA KESKİN ATAĞ,</b> YASEMİN BALSEVEN, SÜMEYRA DEMİRTAŞ ÖZKAYA, RIZA ATAV | <b>6224</b><br>MULTI-CRITERIA ANALYSIS APPLICATION FOR EVALUATION OF THE SPECIALIZED TEXTILE PRODUCTS COMMERCIALIZATION POTENTIAL<br><b>MARCIN STRUSZCZYK,</b> DOMINIKA KAMIŃSKA, AGNIESZKA GUTOWSKA, MARZENA FEJDYŚ                        | <b>9793</b><br>DEVELOPMENT AND ENVIRONMENTAL EVALUATION OF REUSABLE WOVEN FILTERS FOR MICROFIBER EMISSION REDUCTION<br><b>GOKCE SAKMAR,</b> HANDE SEZGİN, İPEK YALÇIN-ENİŞ                                                 |
| 14:30-14:45 | <b>9672</b><br>SUSTAINABLE CIRCULAR YARN DYEING: AN INNOVATIVE SINGLE-STAGE DYEING APPROACH TO REACTIVE DYEABLE COTTON/ACRYLIC BLEND YARNS<br><b>NESLİHAN OKYAY,</b> FATİH İŞİK, MÜCAHİD YAHYA ŞEKER                                              | <b>8975</b><br>THE RELATIONSHIP BETWEEN REGIONAL PRESSURE AND THERMOPHYSIOLOGICAL COMFORT IN TROUSERS<br><b>SERAP PİRANOĞLU</b>                                                                                                             | <b>9983</b><br>TECHNOLOGY TREND FORECASTING IN SUSTAINABLE TEXTILE INNOVATION THROUGH IPC-BASED PATENT ANALYSIS (2010–2025)<br><b>BÜŞRA BOZYER</b>                                                                         |
| 14:45-15:00 | <b>4824</b><br>DEVELOPMENT OF A DISPERSE DYEING PROCESS FOR CELLULOSE ACETATE SOCKS AND INVESTIGATION OF FASTNESS PROPERTIES<br><b>SEYMA NUR KÖSEOĞLU,</b> HAVVA KARA ŞENSOY, İSMET EGE KALKAN, UMUT KIVANÇ ŞAHİN                                 | <b>9322</b><br>DESIGN OF A LEGGING WITH THERAPEUTIC EFFECT<br><b>SINEM BIRSEN,</b> NAZAN OKUR, CANAN SARIÇAM, FATMA SUDE GÜLLÜOĞLU, ELİF İŞİK, SİLA ÇELİK                                                                                   | <b>4520</b><br>FAST FASHION AND MICROPLASTIC POLLUTION: THE HIDDEN ENVIRONMENTAL COST<br><b>SEMİH ÖZKÜR,</b> HANDE SEZGİN, İPEK YALÇIN ENİŞ                                                                                |

28-29 April 2026, Istanbul, Turkey

|             |                                                                                                                                                                                                                                                                               |                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                            |
|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 15:00-15:15 | 3855<br>SUSTAINABLE APPROACHES WITH<br>ODORLESS AMMONIA AND<br>BENTONITE SUBSTITUTION IN<br>PIGMENT PRINTING RECIPES<br><u>AYÇA TEMREN</u> , OZLEM YARAR                                                                                                                      |                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                            |
| 15:15-15:30 | COFFEE BREAK                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                            |
|             | HALL A                                                                                                                                                                                                                                                                        | HALL B                                                                                                                                                                                                               | HALL C                                                                                                                                                                                                                                                     |
|             | <b>SESSION 16</b><br><b>INNOVATIONS IN COTTON</b><br><b>PROCESSING</b><br>Chair: Prof. Dr. Banu U. Nergis                                                                                                                                                                     | <b>SESSION 17</b><br><b>TEXTILE WASTE MANAGEMENT</b><br>Chair: Prof. Dr. Canan Sarıçam                                                                                                                               | <b>SESSION 18</b><br><b>COMPOSITES</b><br>Chair: Prof. Dr. İsmail Usta                                                                                                                                                                                     |
| 15:30-15:45 |                                                                                                                                                                                                                                                                               | 5248<br>EVALUATION OF THE UV-PROTECTION<br>PERFORMANCE OF FABRICS FINISHED<br>WITH POMEGRANATE PEEL POWDER<br><u>SİNEM ÖZTÜRK</u>                                                                                    | 1916<br>SINGLE-STEP DEVELOPMENT OF MULTIFUNCTIONAL<br>COTTON FABRICS USING BORON-BASED<br>NANOCOMPOSITE FOR ENHANCED FLAME<br>RETARDANCY AND ANTIBACTERIAL PERFORMANCE<br><u>DİLARA SEVİNDİK</u> , ESRA ÖRÜM, NECİP ATAR                                   |
| 15:45-16:00 | 6482<br>INVESTIGATION OF RING<br>SPINNING PERFORMANCE OF<br>KAPOK/COTTON BLENDED<br>WEAVING YARNS<br><u>BEYZAGÜL PAYAM</u> , ERKAN<br>EVAN                                                                                                                                    | 4732<br>GREEN REDUCTION OF GRAPHENE OXIDE<br>USING TOMATO PEEL EXTRACT FOR<br>FUNCTIONAL NONWOVEN TEXTILES<br><u>NERGİS DEMİREL GÜLTEKİN</u> , EFE<br>KUZAY YILMAZ, GÜL TOPAL, BEKİR<br>CENKKUT GÜLTEKİN             | 9595<br>HYBRID COMPOSITE DESIGN FOR SUSTAINABLE<br>AUTOMOTIVE INTERIORS: EFFECTS OF NATURAL<br>FIBER FABRIC POSITIONING IN BIDIRECTIONAL<br>GLASS FIBER REINFORCED COMPOSITE STRUCTURES<br><u>ALHAYAT GETU TEMESGEN</u> , JÖRG KAUFMANN,<br>HOLGER CEBULLA |
| 16:00-16:15 | 9941<br>CHARACTERIZATION OF<br>RECYCLED COTTON FIBERS<br>OBTAINED FROM KNITTED AND<br>DENIM FABRICS BASED ON AFIS<br>ANALYSIS<br><u>KÜBRA BAYKAN ÖZDEN</u> , ERKAN<br>EVAN, BEYZAGÜL PAYAM                                                                                    | 8059<br>ULTRASOUND-ASSISTED CELLULOSE<br>ISOLATION FROM LIGNOCELLULOSIC<br>AGRICULTURAL WASTES: A<br>COMPARATIVE STUDY OF BLEACHING<br>METHODS<br><u>NURSEMA PALA AVCI</u> , NEBAHAT ARAL<br>YILMAZ, E. DİLARA KOÇAK | 7172<br>DEVELOPMENT OF GREEN COMPOSITES REINFORCED<br>WITH BAST FIBER FOR ACOUSTIC APPLICATIONS<br><u>AKANDE CELEBİ</u> , ABDULKADİR PARS, FATMA<br>ZEHRİ ENGİN SAĞIRLI, ALİ BEYİT                                                                         |
| 16:15-16:30 | 3547<br>DEVELOPMENT OF BEDROOM<br>TEXTILES FROM SUSTAINABLY<br>SOURCED YARNS WITH<br>DIFFERENT FUNCTIONAL<br>PROPERTIES AND INVESTIGATION<br>OF THEIR HAND (TACTILE)<br>CHARACTERISTICS<br>AYLİN KUŞEN, ONUR BALCI,<br><u>NESLİHAN OKYAY</u> , SEDA ÜNAL,<br>ECE ŞEVVAL ÖZCAN |                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                            |
| 16:30       | CLOSING CEREMONY                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                            |



## ORAL PRESENTATIONS

## A COLLECTION DEVELOPED FROM UPCYCLED WASTE FISH SCALES, DESIGNED TO PROVIDE SUPPORT DURING THE MENOPAUSAL PERIOD

Gizem Ezer<sup>1\*</sup>, Füsun Tayan Aras<sup>2</sup>

<sup>1</sup>Penti Giyim Tic Aş, Turkey

<sup>2</sup>Penti Giyim Tic Aş, Turkey

\*fusun.tayan@penti.com.tr

### ABSTRACT

According to the World Health Organization (WHO), menopause is defined as a natural biological process that typically occurs in women in their 40s and 50s and is characterized by the permanent cessation of menstruation for 12 consecutive months as a result of the loss of ovarian function. Globally, the age of menopause ranges between 45 and 55. Due to increasing life expectancy, the menopausal period now constitutes a significant portion of women's lives, increasing the demand for products focused on improving comfort, health, and quality of life during this stage. During menopause, women experience various physiological and psychological symptoms such as hot flashes, night sweats, sleep disturbances, anxiety, depression, musculoskeletal pain, and skin dryness. Among these, hot flashes are the most common symptom, affecting approximately 60–80% of women. Hot flashes and night sweats, in particular, reduce sleep quality and negatively impact daily life comfort. This study was conducted to develop a textile-based, long-lasting solution for hot flashes and night sweats experienced by menopausal women. Within the scope of the project, focus group studies carried out in collaboration with an international research company revealed that menopausal women have a strong need for breathable, comfortable garments with a cooling effect, particularly in loungewear products. As a result of literature and patent research, Umorefil® Bionic Fiber technology—developed in the Taiwanese textile industry and derived from upcycled fish scales—was incorporated into the project. Umorefil® Bionic Fiber is an innovative textile technology that achieves its functional properties not through a surface finishing application, but through collagen peptides integrated directly into the fiber structure. This enables high air and oxygen permeability, effective moisture management, a cooling sensation, and functional properties that support skin elasticity, which are permanently maintained throughout the product's lifespan. These embedded functional properties prevent performance loss after washing and use, thereby helping to alleviate menopausal symptoms. Furthermore, the production of Umorefil® technology through the upcycling of waste fish scales contributes to the reduction of environmental pollution by valorizing food waste and supports the principles of the circular economy. As a result of the study, an innovative, functional, and sustainable collection of menopausal-friendly loungewear products was developed.

**Keywords:** *Fish Scale Collagen, Functional Fabric, Menopause, Sustainable Textiles, Umorefil® Bionic Fiber*

### 1. INTRODUCTION

Menopause, defined by the World Health Organization as the permanent cessation of menstruation for 12 consecutive months due to the loss of ovarian activity, is a natural biological process that typically occurs in women in their 40s and 50s. The term menopause is derived from the Greek words *mens* (month) and *pause* (cessation). The onset age of menopause, which is not related to the age at menarche (the first menstrual period), is largely associated with genetic and environmental factors. The average age of menopause is between 45–55 worldwide and 46–48 in Türkiye. According to the classification by the World Health Organization, menopause is divided into three stages: perimenopause, menopause, and postmenopause.

Some of the symptoms experienced during menopause include hot flashes, night sweats, headaches (including migraines), dizziness, palpitations, nausea, paresthesia, anxiety, sleep disturbances, memory problems, and depression. The most commonly reported symptoms among women are hot flashes, irritability, and musculoskeletal

pain. Hot flashes most frequently begin during the perimenopausal period (Source: IGUSABDER, 23 (2024): 993–1003).

Hot flashes are observed in approximately 60–80% of women. They may occur in the facial region or spread throughout the body, with duration varying from person to person. Another common issue during menopause is night sweating. This condition, caused by hormonal changes, may lead to sleep interruptions due to excessive perspiration during the night. To cope with hot flashes, women often prefer breathable, cotton-based comfortable clothing. Patent research conducted worldwide has identified textiles designed for menopause-related hot flashes, including fabrics that facilitate heat transfer, provide heating and cooling effects, and absorb body fluids/sweat [1],[2].

An analysis of textile apparel products suitable for menopausal women in the industry reveals that there is a lack of products specifically designed to address hot flashes and night sweats, which are among the most common concerns. Therefore, it has been decided to develop a product group for homewear aimed at reducing hot flashes and night sweats. Fabric research has identified Umorfil® technology, which offers high oxygen permeability, breathability, and a cooling effect, while also being environmentally sustainable through upcycling. The main objective of this project is to transfer Umorfil® technology into homewear and underwear products in alignment with current fashion trends.

Research into highly breathable and oxygen-permeable fabrics has led to the discovery of “Upcycled Umorfil Technology,” developed in Taiwan using fish waste. The name Umorfil is derived from the Latin word *umor* meaning “moisture” and the French word *fil* meaning “fiber.” Umorfil is used in denim, activewear, underwear, home textiles, padding, and footwear uppers. It consists of peptide amino acids, specifically collagen, obtained from fish scales. Another important feature of Umorfil® is that it is produced from recycled food waste, thereby contributing to the reduction of environmental pollution and supporting the circular economy [3].

According to data from the Food and Agriculture Organization, the volume of fisheries production has been increasing annually, reaching a total of 180 million tons by 2020, of which 87 million tons come from capture fisheries. A significant amount of food waste is generated from fish products, and if buried in soil, it may lead to severe soil acidification, while incineration may contribute to air pollution. Through the use of Umorfil® bionic fibers, which possess numerous natural properties, fish scales and extracted amino acids can be upcycled, thereby reducing global food waste and environmental pollution.

## **2. EXPERIMENTAL STUDY**

Within the scope of the project, a focus group study was initially conducted in collaboration with an international research firm in order to accurately identify and address the needs of women during the menopausal period. The study involved a group of women aged 45–55, including both premenopausal and menopausal participants, accompanied by one psychologist and one gynecologist.



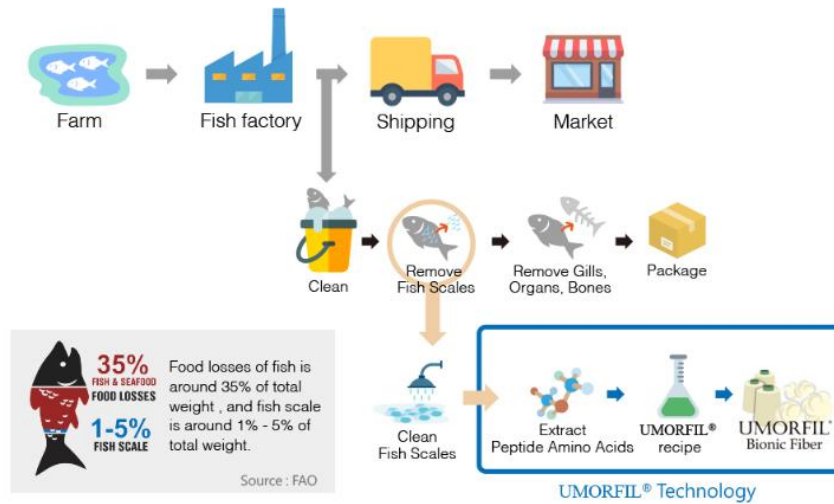


Figure 1. Umorfil Technology

During these sessions, the physical and emotional effects of menopause on women were examined, and the subjective experiences associated with this period were evaluated. The symptoms encountered during menopause and their impacts on daily life were analyzed in detail. In addition, participants were asked to express their expectations and needs in order to alleviate these symptoms and to manage this phase more comfortably.

The findings indicated that women most frequently complained of hot flashes and night sweats during this period. Based on the interviews and identified needs, it was revealed that women demand garments and underwear made from fabrics that prevent excessive sweating, provide a cooling effect, allow the skin to breathe, and enhance overall comfort [4].

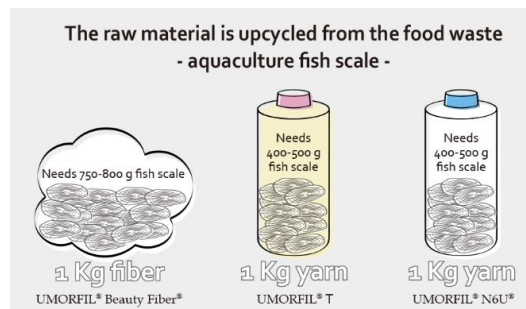


Figure 2. Aquaculture Fish Scale

An evaluation of existing products in the sector showed a lack of menopause-specific clothing that adequately meets these expectations and needs. In response, a menopause-oriented collection consisting of homewear and underwear was developed using Umorfil® technology to address these demands.

All products within the collection are manufactured using Umorfil® technology. Due to its collagen content, the material helps retain moisture, supports skin elasticity, and enables the skin to breathe comfortably [5]. The presence of collagen has been validated through tests conducted by Umorfil®. These cooling and comfort-enhancing fabrics are intended to reduce the effects experienced during premenopause and menopause. Furthermore, the fabric's ability to regulate skin moisture balance is expected to help prevent skin dryness [6].

**Table 1.** Symptom of Menopause on Women

| Symptom Category | Symptom      | Description                                                    |
|------------------|--------------|----------------------------------------------------------------|
| Vasomotor        | Hot flashes  | Sudden feelings of heat, especially in the face and upper body |
| Vasomotor        | Night sweats | Excessive sweating during sleep, often disrupting rest         |
| Psychological    | Mood swings  | Sudden changes in emotional state, irritability                |
| Psychological    | Depression   | Persistent sadness and loss of interest                        |
| Psychological    | Anxiety      | Feelings of worry, nervousness, or unease                      |

### 3. RESULTS

In conclusion, the menopause collection developed within this project successfully addresses the physiological and psychological needs of women during the menopausal period. The integration of innovative textile technologies, particularly Umorefil®-Modal fiber, has enabled the design of breathable, cooling, and moisture-managing garments that effectively respond to common symptoms such as hot flashes and night sweats. The collection, consisting of sleepwear and lingerie products, provides enhanced comfort, skin-friendly properties, and functional performance. Additionally, the use of upcycled materials contributes to environmental sustainability, aligning the project with contemporary ecological concerns. Beyond its functional benefits, the collection also reflects current fashion trends through carefully designed colors, patterns, and fits tailored to user expectations. As a result, this project not only offers a practical solution for menopausal women but also represents an innovative and pioneering approach within the textile industry, with the potential to inspire future research and product development in menopause-focused apparel.

### 4. CONCLUSION

This study was initiated to address the specific needs of women during the menopausal period. The collection developed within the scope of the project is planned to be commercialized under the brand name “Penti Aging.” In the initial phase, a focus group study was conducted to identify user expectations, followed by an extensive review of the literature and patent landscape to determine unmet needs and potential solution areas.

The findings revealed an innovative R&D approach in the Taiwanese textile industry involving a bionic fiber derived from the upcycling of fish waste. Through collaborative efforts, a menopause-oriented collection consisting of homewear and underwear products was developed by integrating Upcycled Umorefil® Bionic Fiber technology. The collection comprises bra models, panty options, undershirt designs, and homewear. The primary material utilized in the project is Umorefil®-Modal fiber. This fiber is characterized by high air permeability and a cooling effect, contributing to reduced perspiration. Accordingly, the developed products aim to alleviate common menopausal symptoms such as hot flashes and night sweats, which affect approximately 60–80% of women.

The project integrates technological innovation with fashion-oriented design principles. In addition to the functional properties of the fabric, design elements such as color, pattern, and garment construction have been carefully developed to align with the physiological and psychological needs of menopausal women.

In terms of its scope and application, this study represents a pioneering initiative within the Turkish textile industry. Furthermore, it holds significant potential for knowledge generation and transfer, thereby establishing a foundation for future research and product development efforts targeting menopause-related textile solutions.

## ACKNOWLEDGMENT

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## A FUNCTIONAL PILLOW DESIGN AND PRODUCT INNOVATION WITH A PROTECTIVE EFFECT AGAINST ELECTROMAGNETIC POLLUTION

Hacer ÇELEBİ<sup>1</sup>, Faruk MISIRLIOĞLU<sup>1</sup>, Hatice ALTUN<sup>1</sup>, Büşra AYYILDIZ SOYLAK<sup>1</sup>

<sup>1</sup>DOQU EV TEKSTİLİ SANAYİ ve TİCARET A.Ş.

### ABSTRACT

With the increasing use of electronic devices in daily life, electromagnetic pollution has become a significant environmental risk factor to which individuals are particularly exposed during sleep. The low-intensity yet continuous effects of electromagnetic fields may adversely affect physiological regeneration processes and sleep quality. This study addresses the design and product innovation process of a functional pillow developed to provide a protective solution to this problem. The proposed design is based on the integration of a Biocare® steel-fiber protective fabric, capable of reducing electromagnetic wave permeability by 98.5%, with Down-Proof finished (extra-soft hand feel effect) natural cotton fabric in a dual-layer structure. The gray–white contrast of the dual surface is not merely an aesthetic preference but a deliberate design strategy that enables users to intuitively perceive the functional layer differentiation. Ergonomic form optimization, material selection, user comfort, and protective performance requirements constituted the key components of the design process. During the prototype development phase, technical drawings, three-dimensional digital modeling, and performance tests in compliance with the TS 2994 standard were conducted. The findings demonstrate that the product meets the targeted criteria in terms of both electromagnetic protection and usage ergonomics. This study presents an innovative approach to integrating protective textile technologies into home textile products and contributes to design-oriented product innovation in the context of electromagnetic pollution.

**Keywords:** *Biocare Yarn, Electromagnetic Pollution, Functional Pillow Design, Protective Properties*

## A FUNCTIONAL MODERN WOMEN’S GARMENT DESIGN REFLECTING NATURE INSPIRED- TRADITIONAL ANATOLIAN MOTIFS

Nisa Yavaş<sup>1\*</sup>, Damla Erdem<sup>1</sup>, Müge Tuğru Yıldırım<sup>1</sup>, Emine Dilara Koçak<sup>2</sup>,

<sup>1</sup>Mudo ,Giyim A.Ş. Design Center, Istanbul / Türkiye

<sup>2</sup>Marmara University, Textile Engineering Department, Istanbul / Türkiye

\* [nisa.yavas@mudo.com.tr](mailto:nisa.yavas@mudo.com.tr)

### ABSTRACT

In this study, jacquard weft knitted fabrics with different pattern geometries inspired by biomimetic natural topographic forms were produced. Three different knitted surfaces—topography-inspired zigzag (A), horizontal striped (B), and chevron zigzag (C)—were manufactured using a 60% polyester / 40% cotton blended yarn (Ne 10/1), at a gauge of 20 gg and within a fabric weight range of 230–240 g/m<sup>2</sup>. The fabrics were evaluated in terms of dimensional stability, bursting strength, color fastness, heat transfer, and moisture absorption according to standard test methods. The chevron zigzag fabric (C) exhibited the highest mechanical performance, reaching approximately 480 kPa in bursting strength and showing dimensional changes of 2.0–1.5%. The horizontal striped fabric (B) showed lower strength (~360 kPa) and higher dimensional change (4.5–3.5%). The topography-inspired zigzag fabric (A) demonstrated a balanced performance with intermediate values (~420 kPa, 3.0–2.0%). In terms of thermal and moisture properties, structure B stood out with higher moisture absorption (~7.5%), while structure C provided better insulation with higher thermal resistance (~0.070 m<sup>2</sup>K/W). Color fastness results were good for all fabrics, with structure C achieving the highest values. As a result, it was determined that pattern geometry directly affects the mechanical strength, dimensional stability, and comfort properties of knitted fabrics; compact structures increase strength, while open structures improve comfort properties. This study quantitatively reveals the structure–performance relationship in jacquard knitted fabric design.

**Keywords:** *jacquard weft knitting, knitted fabric structure, comfort properties, biomimetic design*

### INTRODUCTION

Increasing competition in the textile and apparel industry has increased the importance of functional performance alongside aesthetic design. In knitted fabrics, comfort is directly related to heat transfer, air permeability, and moisture management, which are affected by structural parameters such as loop density, yarn type, and knit construction [1,2,10]. Polyester/cotton blended knitted fabrics are preferred in functional garment studies because they balance mechanical strength and moisture management [3,9]. Moisture absorption and transport support sweat removal and evaporation, directly affecting clothing comfort [5,7]. In addition, porosity and loop geometry influence heat transfer through their effect on air permeability [2,8]. Jacquard weft knitted structures allow patterns to be formed directly within the knit construction, making pattern design both an aesthetic and structural component. These structures affect dimensional stability, bursting strength, and surface durability [6,10]. Previous studies have shown that structural variations directly influence mechanical and comfort properties [4,8]. In textile surface design, biomimicry enables the abstraction of natural topographic forms such as mountains, river paths, and fractured surfaces into directional and repetitive patterns. These formations affect loop density, void distribution, and surface porosity, influencing heat transfer and moisture absorption [4,7].

In this study, jacquard weft knitted surfaces inspired by natural topographic forms were evaluated in terms of dimensional stability, bursting strength, color fastness, heat transfer, and moisture absorption.



## 1. EXPERIMENTAL STUDY

### 2.1. Material

The properties of the yarns used in the production of the knitted fabrics in this study are given in Table 1.

**Table 1.** Properties of Yarns

| Properties                      | Values           |
|---------------------------------|------------------|
| Fiber Composition (Ring eğirme) | %60 PES / %40 CO |
| Yarn number                     | Ne 10/1          |
| Twist (TPI)                     | 15               |
| Twist Direction                 | Z                |
| Tensile Stenght (cN)            | 388              |
| Elongation at Break (%)         | 13,5             |

### 2.2. Formation and Design of Knitted Surfaces

Figure 1 shows the three developed jacquard knitted surfaces with different patern geometries. In this study, the knitted surfaces were produced on a Mayer & Cie. OVJA 1.6 EE model weft knitting machine equipped with an electronic jacquard system. The machine used has a fineness of 20 gauge (gg), a cylinder diameter of 30 inches, and a 48-feeder system. The machine speed was set between 18–22 rpm, yarn feeding tension was adjusted to 8–12 cN, and take-down speed ranged from 4.5 to 6.0 m/min. The stitch length (stitch cam) was varied between 0.28–0.34 mm depending on the fabric weight to obtain different structural characteristics.



**Structure A** – Topographic Zigzag Jacquard fabric



**Structure B** – Horizontally Stripped Jacquard Fabric



**Structure C** – Chevron (Classic) Zigzag Jacquard Fabric

**Figure 1.** Knitted surfaces with three different pattern geometries

The structural parameters related to different pattern geometries (zigzag, horizontal, and vertical) and loop density variations used in the study are given in Table 2.

**Table 2.** Loop and Structural Parameters by Pattern

| Parameters                  | A- Topographic Zigzag Jacquard | B- Horizontally Stripped Jacquard | C- Chevron Zigzag Jacquard |
|-----------------------------|--------------------------------|-----------------------------------|----------------------------|
| GSM (g/m <sup>2</sup> )     | 230 ± 5                        | 210 ± 5                           | 240 ± 5                    |
| Loop length (mm)            | 2.8                            | 3.0                               | 2.5                        |
| Course/cm                   | 12                             | 11                                | 14                         |
| Wale/cm                     | 11                             | 10                                | 12                         |
| Pattern density (repeat/cm) | 3.5                            | 3.0                               | 4.5                        |
| Machine speed (rpm)         | 21                             | 20                                | 22                         |
| Yarn tension (cN)           | 11                             | 10                                | 12                         |
| Take-down speed (m/dk)      | 5.5                            | 5.0                               | 6.0                        |
| Stitch cam (mm)             | 0.32                           | 0.34                              | 0.30                       |

The patterns were created using CAD-based jacquard design programs and integrated into the knitting structure through electronic needle selection. As shown in Figure 1, three jacquard knitted surfaces were developed: topography-inspired zigzag (Structure A), horizontal linear pattern (Structure B), and horizontally striped jacquard pattern (Structure C). These patterns were designed through a biomimetic approach to obtain different structural densities and surface characteristics. The fabrics were tested according to standard methods: bursting strength (ISO 13938-2), dimensional stability (ISO 5077), washing fastness (ISO 105-C06), rubbing fastness (ISO 105-X12), thermal properties (ISO 11092), and moisture management (AATCC 195).

### 3. RESULTS

#### 3.1. Dimensional Change Results of Knitted Surfaces

**Table 3.** Dimensional Stability Results by Pattern (Post-Wash % Change)

| Parameters           | A – Topographic Zigzag | B – Horizontally Stripped | C – Chevron Zigzag |
|----------------------|------------------------|---------------------------|--------------------|
| Course direction (%) | -3.0 ± 0.5             | -4.5 ± 0.7                | -2.0 ± 0.4         |
| Wale direction(%)    | -2.0 ± 0.4             | -3.5 ± 0.6                | -1.5 ± 0.3         |
| Change of Area (%)   | -5.0 ± 0.8             | -7.5 ± 1.0                | -3.5 ± 0.6         |

As shown in Table 3, dimensional stability depended on stitch length and structural density. Structure B showed the highest shrinkage due to its longer stitch length and lower density, while compact Structure C provided the highest stability. Structure a showed moderate stability. These results agree with the literature, which states that longer stitch length reduces stability and compact structures show lower dimensional change [11].



### 3.2. Bursting Strength Results of Knitted Surface

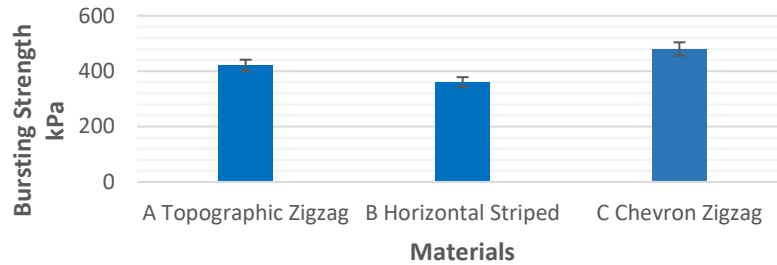


**Figure 2.** Bursting Strength of Knitted Surfaces

Figure 2 shows that the chevron zigzag structure (C) had the highest bursting strength due to its shorter stitch length, higher course/wale density, and compact loop organization. In contrast, the more open horizontal striped structure (B) showed lower bursting strength, while the topography-inspired zigzag structure (A) exhibited balanced mechanical behavior. These results are consistent with studies reporting that fabric structure and fiber type significantly affect bursting strength, and that compact structures provide higher bursting resistance [12].

### 3.3. Thermal Conductivity Results of Knitted Surfaces

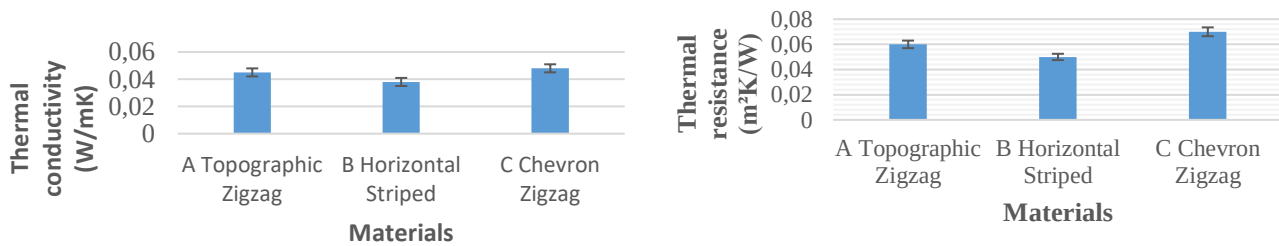


**Figure 3.** Thermal Conductivity of Knitted Surfaces

Figure 3 shows that thermal behavior differed according to pattern geometry and structural density. Heat transfer in knitted fabrics was mainly affected by structural porosity and loop density. The more open horizontal striped fabric (B) showed higher heat transfer and lower thermal resistance, while the compact chevron zigzag fabric (C) provided better heat retention. The topography-inspired zigzag structure (A) exhibited balanced thermal behavior. These results are consistent with studies reporting that higher porosity decreases thermal resistance, whereas denser structures improve thermal insulation [13,14].

### 3.4. Moisture Absorption Results of Knitted Surfaces

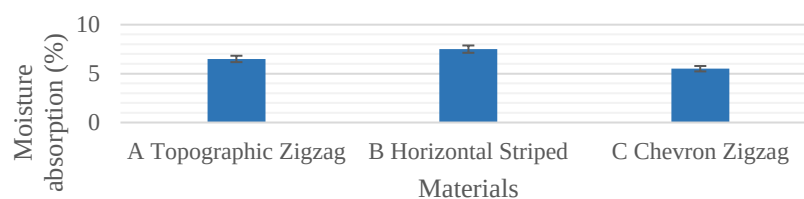


**Figure 4.** Moisture Absorption of Knitted Surfaces

Figure 4 shows that moisture absorption depended on surface openness, loop density, and compactness. Structure B showed the highest moisture absorption due to its open structure, while compact Structure C had lower absorption. Structure A showed balanced behavior. Overall, higher porosity and stitch length increased moisture absorption, confirming that pattern geometry affects comfort performance [15,16,17].

### 3.5. Fastness Results of Knitted Surfaces

**Table 4.** Fastness of Knitted Surfaces

| Parameters             | A Topographic Zigzag | B Horizontal Striped | C Chevron Zigzag |
|------------------------|----------------------|----------------------|------------------|
| Washing fastness       | 4–5                  | 4                    | 4–5              |
| Rubbing fastness (dry) | 4–5                  | 4                    | 4–5              |
| Rubbing fastness (wet) | 3–4                  | 3                    | 4                |
| Light fastness         | 5                    | 4–5                  | 5                |

As shown in Table 4, fastness properties varied depending on structural density and surface compactness. All fabrics showed good washing and light fastness. Wet rubbing fastness was lower in the more open Structure B, while compact Structure C showed higher fastness performance. Overall, compact structures provided better fastness than open structures.

## 4. CONCLUSIONS

The results of the study show that the performance of knitted fabrics is mainly determined by pattern geometry, stitch length, and structural density. From a mechanical perspective, the chevron zigzag fabric (C), with its compact structure, provided the highest bursting strength and dimensional stability, while the more open horizontal striped fabric (B) exhibited the lowest mechanical performance. In terms of thermal and moisture properties, structure B, due to its high porosity, enabled better air and moisture transfer, whereas structure C showed better insulation with higher thermal resistance. The topography-inspired zigzag structure (A) demonstrated a balanced performance across all properties. When fastness properties were examined, it was determined that dye fixation improved with increasing structural density, and compact structures provided higher fastness values.

As a result, open structures offer advantages in terms of comfort (air and moisture transfer), while compact structures provide advantages in strength and stability; the topography-inspired zigzag structure offers an optimal balance between these two characteristics.

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## **A STUDY ON THE ADOPTION OF DIGITAL TECHNOLOGIES IN APPAREL RETAILING**

**Nazan Okur<sup>1,\*</sup>, Fidan Cenal<sup>1</sup>, Canan Saricam<sup>1</sup>**

<sup>1</sup> Istanbul Technical University, Department of Textile Engineering, Turkey

\* okurn@itu.edu.tr

### **ABSTRACT**

The role of technology in apparel retailing has expanded rapidly, especially after the COVID-19 pandemic accelerated the adoption of digital solutions such as online ordering, click-and-collect, and automated operations. Advances in e-commerce, data analytics, virtual and augmented reality, and blockchain have transformed the shopping experience, optimized supply chains, enhanced transparency, and supported sustainability initiatives. Additionally, social media and mobile platforms have reshaped consumer behavior and contributed to the unprecedented growth of fast fashion.

This study explored consumers' acceptance, adoption, active use, recommendation intentions, and future usage intentions regarding emerging technologies in apparel retailing. Survey findings indicated that participants showed strong interest in these technologies and generally perceived them as useful and beneficial. Although they expressed confidence in ease of use and security, concerns related to privacy persist to some extent. Participants also supported the continued development of retail technologies and report intentions to maintain their usage in the future. Consequently, the results suggested that technological innovations in apparel retailing are positively received and broadly accepted by consumers.

**Keywords:** *Apparel retailing, digital technologies, fashion, consumer adoption*

### **1. INTRODUCTION**

Emerging technologies and digital tools have fundamentally reshaped the fashion retail sector, transforming how consumers interact with, purchase, and experience fashion. Technological innovations play a central role in optimizing operations, increasing efficiency, and improving sustainability, as well as enhancing service quality by delivering the right product to the consumer at the right time through real-time sales data and consumer behavior analytics. On the consumer side, these technologies are highly effective in enhancing customer engagement and providing a pleasant and exceptional shopping experience. An increasing number of fashion retailers are progressively integrating digital technologies such as smart shelves, interactive displays, smart fitting rooms, shopping assistance systems, touchless payment solutions, smart shopping carts, and self-checkout systems into physical stores, marking a shift toward technologically enabled and data-driven retail environments commonly conceptualized as “smart stores” [1].

Smart stores are physical retail environments deeply integrated with interconnected technologies designed to automate, personalize, and elevate the shopping experience. A smart store is characterized by the use of interactive devices, radio frequency identification (RFID) systems, augmented reality (AR) applications, and IoT-enabled tools that enhance both operational effectiveness and consumer engagement throughout the shopping journey [2].

According to the State of Fashion Technology Report of McKinsey & Company, in 2021 fashion companies invested between 1.6% and 1.8% of their revenues in technology, and this figure is expected to rise to between 3.0% and 3.5% by 2030, indicating a growing commitment to digital adoption. More than 60% of fashion executives believe that creating integrated digital processes across their organizations will be among their top five areas for

digitization by 2025, highlighting the strong internal prioritization of digital transformation [3]. These indicators show that digital technologies are not only discussed conceptually but are also increasingly funded and prioritized in the fashion retail industry.

In smart retail environments, integrated technological systems enable personalized communication with consumers, creating unified omnichannel experiences that connect physical and digital touchpoints [4]. Technologies such as smart mirrors, interactive displays, and IoT- and AR-enabled fitting rooms significantly enhance service quality and customer experience by personalizing recommendations and improving overall consumer satisfaction and engagement [5]. Interactive digital technologies enhance customer and user engagement by enabling co-creation, interactivity, sensory appeal, and participation in both online and physical retail environments. Integrating a wide range of digital technologies across brick-and-mortar and online channels strengthens customer engagement and improves retailers' competitive positioning [6].

Digital atmosphere in retail stores plays a crucial role in capturing consumer attention, which in turn drives interest, desire, and behavioral responses such as searching, purchasing, and sharing. Oversized digital displays and touch screens positively influence product evaluations and stimulate electronic word-of-mouth while also encouraging consumers to search and shop across channels in an omnichannel context [7].

In luxury fashion retailing, Burberry demonstrates how immersive digital installations and RFID-enabled “magic mirrors” transform the flagship store into an experiential extension of the brand's online presence. In the fast-fashion segment, Topshop uses mobile applications, live streaming, and social media integration to engage consumers beyond the store and generate data that informs buying and merchandising decisions. From a department store perspective, Harrods employs a mobile application and proximity technologies to support in-store navigation, enrich the luxury service experience, and attract international and younger customers [8].

In their study, Kim et al. [9] highlighted that usefulness enhanced by enjoyment is a key factor in consumers' adoption of smart in-store technologies. Similarly, a recent study conducted in the United States on apparel-related digital retail technologies found that consumers' intention to adopt these technologies is significantly influenced by effort expectancy (ease of use), facilitating conditions (technical infrastructure), perceived physical risk, and time or convenience loss risk [10]. Consumers associate emerging fashion technologies with convenience, efficiency, and innovation, aligning them with hedonic and self-directed values. Conversely, adoption barriers are largely driven by intangible concerns such as psychological, cultural, societal, and privacy issues, which activate values related to security, conformity, tradition, benevolence, and universalism [11].

Despite the increasing adoption of digital technologies in fashion retailing, there is still limited empirical research examining how consumers perceive and evaluate these technologies within physical store environments. While previous studies have often focused on online retail technologies or general digital adoption, fewer studies have specifically investigated the determinants of consumer acceptance of smart in-store technologies in fashion retail contexts.

Addressing this gap is particularly important for fashion retailers seeking to invest effectively in retail technologies and design technology-enhanced shopping environments that align with consumer expectations. The purpose of this study is to examine consumers' perceptions, attitudes, and behavioral intentions toward the use of retail technologies in fashion retail environments. Specifically, the study aims to investigate how key factors derived from the Technology Acceptance Model (TAM), including perceived usefulness, perceived ease of use, perceived risk, as well as personal innovativeness affect consumers' intentions to adopt and continue using retail technologies. By doing so, this study contributes to the literature by providing insights into consumer acceptance of smart retail technologies in fashion retail settings and offers practical implications for retailers aiming to enhance technology-driven shopping experiences.

## **2. METHODOLOGY**

### **2.1 Data Collection**

Data were collected through an online survey administered to consumers with experience or familiarity with retail technologies. The online questionnaire approach was selected to ensure broad accessibility and efficient data

gathering. Participation was voluntary, and respondents were informed about the purpose of the study prior to completing the survey.

## 2.2 Measures and Data Analysis

The survey instrument consisted of items adapted from technology acceptance and consumer behavior literature and was structured to measure key constructs related to retail technology adoption. All items were measured using a five-point Likert scale, where 1 = Strongly disagree and 5 = Strongly agree.

“Personal innovativeness” was measured using four items, capturing respondents’ knowledge of retail technologies, willingness to try new technologies, relative innovativeness within their social circles, and perceptions of retail technologies as fashionable and trendy. “Perceived risk” was assessed with three items evaluating perceived safety of using retail technologies, concerns regarding personal privacy, and skepticism toward the development of retail technologies. “Perceived ease of use” was measured using two items, reflecting the extent to which respondents perceived retail technologies as easy to learn and easy to use. “Perceived usefulness” was captured through four items assessing the perceived contribution of retail technologies to facilitating the shopping process, saving time, and overall evaluations of retail technologies as a good and smart idea. “Behavioral intention” to use was measured with three items, examining respondents’ intentions to use retail technologies as much as possible, continue using them in the future, and recommend their use to others.

Descriptive statistics, including mean values (M), were calculated to examine participants’ overall adoption of retail technologies.

## 3. RESULTS

Table 1 presents the demographic characteristics of the participants. The survey was conducted to 108 participants.

**Table 1.** Demographic properties of the participants.

|                        |                       | Frequency | %    |
|------------------------|-----------------------|-----------|------|
| <b>Gender</b>          | Female                | 61        | 56.5 |
|                        | Male                  | 46        | 42.6 |
|                        | Prefer not to specify | 1         | 0.9  |
| <b>Age</b>             | 18-28                 | 14        | 13.0 |
|                        | 29-47                 | 84        | 77.8 |
|                        | 48-59                 | 10        | 9.3  |
| <b>Education</b>       | High School           | 4         | 3.7  |
|                        | Associate Degree      | 10        | 9.3  |
|                        | Bachelor’s Degree     | 64        | 59.3 |
|                        | Master’s Degree       | 26        | 24.1 |
|                        | Doctoral Degree       | 4         | 3.7  |
| <b>Personal income</b> | 20.000 TL and below   | 5         | 4.6  |
|                        | 20.000-50.000         | 33        | 30.6 |
|                        | 50.000-100.000        | 43        | 39.8 |
|                        | 100.000 TL and above  | 27        | 25.0 |

The sample consists of 56.5% female participants, and 42.6% male participants. In terms of age distribution, the majority of respondents fall within the 29–47 age group (77.8%), indicating a largely middle-aged sample, whereas younger participants aged 18–28 constitute 13.0% and those aged 48–59 account for 9.3% of the sample.

Regarding educational background, most participants hold a bachelor’s degree (59.3%), followed by those with a master’s degree (24.1%). Smaller proportions of respondents reported having an associate degree (9.3%), a doctoral degree (3.7%), or a high school education (3.7%). With respect to personal income, the largest share of participants reported a monthly income between 50,000 and 100,000 TL (39.8%), followed by those earning between 20,000



and 50,000 TL (30.6%). Participants with an income of 100,000 TL and above represent 25.0% of the sample, while a smaller proportion (4.6%) reported an income of 20,000 TL or below.

Table 2 presents the average scores of the factors and their related items measured on a five-point Likert scale. Overall, the findings indicate generally positive attitudes toward the use of retail technologies across most dimensions. With respect to personal innovativeness, the mean scores suggest a moderate to high level of openness to retail technologies. Respondents reported a relatively strong tendency to try new technologies when they are of interest ( $M = 3.78$ ) and perceived retail technologies as fashionable and trendy ( $M = 4.31$ ). The reverse-coded item indicates that respondents do not strongly perceive themselves as late adopters within their social circles ( $M = 3.90$ ).

**Table 2.** Average scores of factors and related items.

| Factors and related items                                                                                                          | Mean score (M) |
|------------------------------------------------------------------------------------------------------------------------------------|----------------|
| <b>Personal innovativeness</b>                                                                                                     |                |
| I have more knowledge about the use of retail technologies than most other people.                                                 | 3.57           |
| When a new technology that interests me is introduced, I want to try it immediately.                                               | 3.78           |
| In general, I am among the last people in my social circle to be knowledgeable about retail technologies. ( <i>reverse-coded</i> ) | 3.90           |
| I think using retail technologies is fashionable and trendy.                                                                       | 4.31           |
| <b>Perceived risk</b>                                                                                                              |                |
| Shopping using retail technologies is safe.                                                                                        | 3.68           |
| Using retail technologies may lead to violations of personal privacy.                                                              | 3.22           |
| The development of retail technologies is a waste of resources. ( <i>reverse-coded</i> )                                           | 4.18           |
| <b>Perceived ease of use</b>                                                                                                       |                |
| I think learning how to use retail technologies is easy.                                                                           | 4.00           |
| I think acquiring the skills to use retail technologies is easy.                                                                   | 4.06           |
| <b>Perceived usefulness</b>                                                                                                        |                |
| Retail technologies contribute to improving and facilitating the shopping process.                                                 | 4.05           |
| I think I can shop in less time by using retail technologies.                                                                      | 4.06           |
| Overall, using retail technologies is a good idea.                                                                                 | 4.03           |
| Using retail technologies is smart.                                                                                                | 4.00           |
| <b>Behavioral intention</b>                                                                                                        |                |
| I intend to use retail technologies as much as possible.                                                                           | 3.95           |
| I will probably continue to use retail technologies in the future.                                                                 | 3.89           |
| I would recommend the use of retail technologies to others.                                                                        | 3.96           |

Regarding perceived risk, participants expressed moderately positive perceptions of safety when shopping using retail technologies ( $M = 3.68$ ). Concerns related to personal privacy were present but not dominant ( $M = 3.22$ ), while the reverse-coded item suggests that respondents generally do not view the development of retail technologies as a waste of resources ( $M = 4.18$ ). The results for perceived ease of use show high mean scores, indicating that participants find retail technologies easy to learn ( $M = 4.00$ ) and easy to use ( $M = 4.06$ ). Similarly, perceived usefulness yielded consistently high scores, with respondents agreeing that retail technologies facilitate the shopping process ( $M = 4.05$ ), save time ( $M = 4.06$ ), and represent a good ( $M = 4.03$ ) and smart idea ( $M = 4.00$ ).

Finally, the behavioral intention dimension also demonstrated strong positive tendencies. Participants reported intentions to use retail technologies as much as possible ( $M = 3.95$ ), to continue using them in the future ( $M = 3.89$ ), and to recommend them to others ( $M = 3.96$ ).

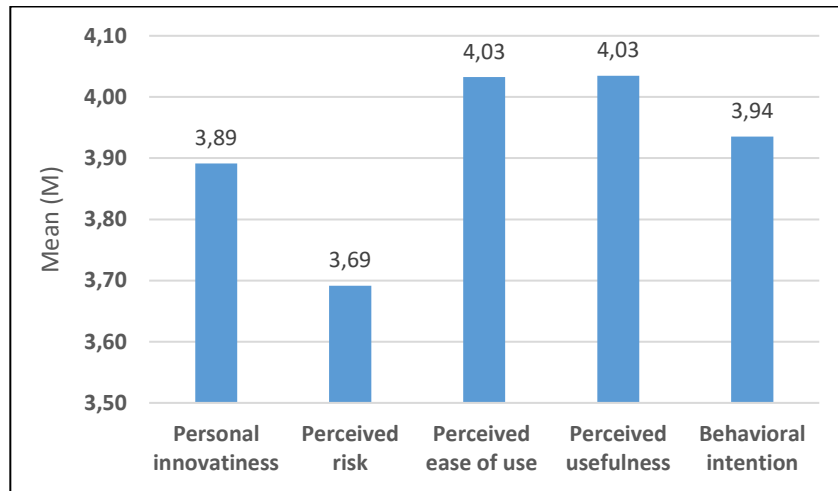


**Figure 1.** Mean values of the answers given on a 5-point Likert scale

As shown in the Figure 1, the results indicate generally positive perceptions toward the technology, with all constructs scoring above the midpoint. Perceived ease of use and perceived usefulness have the highest mean values (both 4.03), suggesting that respondents find the technology both easy to use and beneficial, which are key drivers of adoption. Behavioral intention is also relatively high (3.94), indicating a strong willingness to use the technology, while personal innovativeness shows a moderately positive level (3.89). In contrast, perceived risk has the lowest mean score (3.69), implying that although concerns exist, they are less dominant compared to usability and usefulness considerations in shaping consumer responses.

#### 4. CONCLUSION

The rapid digital transformation of the retail sector has significantly altered how consumers interact with fashion brands and physical store environments. As technological innovations continue to reshape the apparel retail landscape, understanding consumers' perceptions and behavioural responses toward these technologies becomes increasingly important.

This study examined consumers' personal innovativeness, perceptions, and behavioural intentions regarding the use of retail technologies in apparel retail environments. The findings indicated that consumers generally hold positive attitudes toward digital technologies in fashion retailing and perceive them as useful tools that enhance convenience, efficiency, and overall shopping experience. These results are consistent with previous research emphasizing the central role of perceived usefulness and ease of use in shaping technology adoption behavior [12]. At the same time, although participants expressed confidence in the usability and functional benefits of retail technologies, concerns related to privacy and data security were not entirely eliminated. This finding aligns with earlier studies suggesting that perceived risks, particularly privacy-related concerns, can influence consumers' attitudes toward digital retail technologies [13]. Therefore, while consumers appear willing to engage with technology-enhanced retail environments, their trust in data management and privacy protection remains a critical factor influencing long-term adoption.

Another important implication of the findings is the role of consumer innovativeness in technology adoption. Individuals who are more open to new technologies are more likely to adopt and recommend smart retail technologies. This observation is consistent with prior studies highlighting the influence of personal innovativeness on technology acceptance and diffusion [12]. For fashion retailers, this suggests that encouraging trial experiences and demonstrating the benefits of new technologies may facilitate greater adoption.

From a managerial perspective, the results suggest that retailers should focus not only on implementing advanced technologies but also on designing user-friendly and engaging retail experiences that clearly communicate functional benefits to consumers. Technologies that combine practical usefulness with enjoyable and interactive experiences are more likely to enhance consumer engagement and increase adoption rates. Furthermore, retailers

should address consumer concerns regarding privacy and data protection by ensuring transparency and building trust in their technological systems.

Future research could extend the present study by employing inferential statistical techniques to examine the relationships between these variables in greater depth and to provide a more comprehensive understanding of consumer adoption behavior. As fashion retailers continue to integrate smart technologies into physical stores, understanding the factors that shape consumer adoption will remain essential for designing effective and engaging technology-driven retail environments.

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## ADVANCEMENTS IN TEXTILE SURFACE PILLING TESTING: IMPROVED EVALUATION METHOD USING UNIFORM DIGITAL IMAGING

Juro Živičnjak <sup>1,\*</sup>, Antoneta Tomljenović <sup>1</sup>, Igor Zjakić <sup>2</sup>

<sup>1</sup> University of Zagreb Faculty of Textile Technology, Department of Materials, Fibres and Textile Testing, Zagreb, Croatia

<sup>2</sup> University of Zagreb Faculty of Graphic Arts, Department of Printing Processes, Faculty of Graphic Arts, Zagreb, Croatia

\* juro.zivcnjak@ttf.unizg.hr

### ABSTRACT

During use, textile materials are susceptible to abrasion, which can cause surface pilling that impairs their aesthetic and functional properties. Pilling in textile testing is often evaluated by the visual method (EN ISO 12945-4:2020). Currently, the occurrence of pilling can also be quantitatively assessed by advanced instrumental methods involving digital imaging, image analysis, and a pilling grading process. In published research, the conditions for digital imaging are often non-uniform and usually deviate from standard visual methods in terms of distance, angle, and light source, which affects the appearance of pilling captured in digital images. Therefore, an improved instrumental evaluation method was introduced using innovative apparatus designed and built to provide uniform digital imaging under the conditions of the visual method. The applicability of the apparatus was tested on cotton and viscose standard woven fabric specimens, which were pretreated by the modified Martindale method (EN ISO 12945-2:2020) with two different abrasive fabrics. Grading was performed by both the visual and the improved instrumental evaluation method, which is based on nine grading classes defined by the selected numerical pilling parameter determined through image analysis. The results demonstrate high correlation values between the grades assigned by the two pilling evaluation methods, as the digital imaging conditions for the tested fabric specimens were consistent with the standard conditions.

**Keywords:** *Pilling occurrence, Digital imaging, Improved evaluation method, Innovative apparatus, Woven fabric*

### 1. INTRODUCTION

Pilling is a readily noticeable surface change, characterized by the entanglement of protruding fibres into clusters (pills) that are slightly raised above the fabric surface and dense enough to block light and cast a shadow [1]. A textile fabric's abrasion resistance significantly influences its pilling occurrence [2]. Cotton fabrics usually have a moderate pilling tendency, while viscose fabrics typically exhibit more intense pilling [3]. The pilling tendency of textile fabrics is often evaluated by the visual method according to EN ISO 12945-4:2020. In this method, observers evaluate pretreated specimens (usually prepared by the modified Martindale method EN ISO 12945-2:2020) by comparing their surfaces with an untreated specimen and, if applicable, with standard photographs. The visual method is subjective and depends on the observers' experience and the availability of standard photographs for the specific fabric [4]. Alternatively, in research, the evaluation process is often conducted using advanced, that is, instrumental methods, which are unstandardized and therefore not uniform. The instrumental evaluation method consists of a digital imaging process, in which digital images of the fabric specimen surfaces are acquired, followed by a software analysis process, by which the numerical values of pilling parameters are obtained and the grading of pilling intensity is performed [5]. Therefore, the need for improvement of the instrumental evaluation method was identified to enable uniform digital imaging of the tested fabric specimen surface area in a way that resembles the visual impact detected by the visual evaluation method.

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## 2. EXPERIMENTAL STUDY

### 2.1 Materials and Pilling Induction Method

Standard plain weave fabrics made from cotton and staple viscose fibres, as specified in ISO 105-F02:2009 and purchased from SDC Enterprises Limited, UK, were used in this research. Pilling was induced by pretreating the fabric specimens using a modified Martindale method (EN ISO 12945-2:2020), in which the specimens were abraded with two different abrasive fabrics: the same fabric as the one being tested (F1) and standard wool abrasive fabric (F2, EN ISO 12947-1:1998+AC:2006). The pretreatment process was conducted for six predefined numbers of pilling rubs (125, 500, 1000, 2000, 5000, and 7000) under a constant weight of 415 g at standard atmospheric conditions for textile testing. For each fabric, one specimen was prepared for both abrasive fabrics and each predefined number of pilling rubs.

### 2.2 Visual and Improved Evaluation Pilling Methods

Induced pilling was evaluated using both a visual method and an improved instrumental evaluation method. Three observers performed the visual evaluation by comparing the surface appearance of pretreated specimens with untreated specimens, following the standard conditions defined in EN ISO 12945-4:2020 (Figure 1a), and using a viewing unit (Figure 1b) under artificial daylight (D65) illumination. The visual evaluation result is a numerical grade from 5.0 (no change) to 1.0 (severe pilling), including half grades (4.5, 3.5, etc.), calculated as the arithmetic mean of the three grades assigned by the observers to each tested specimen.

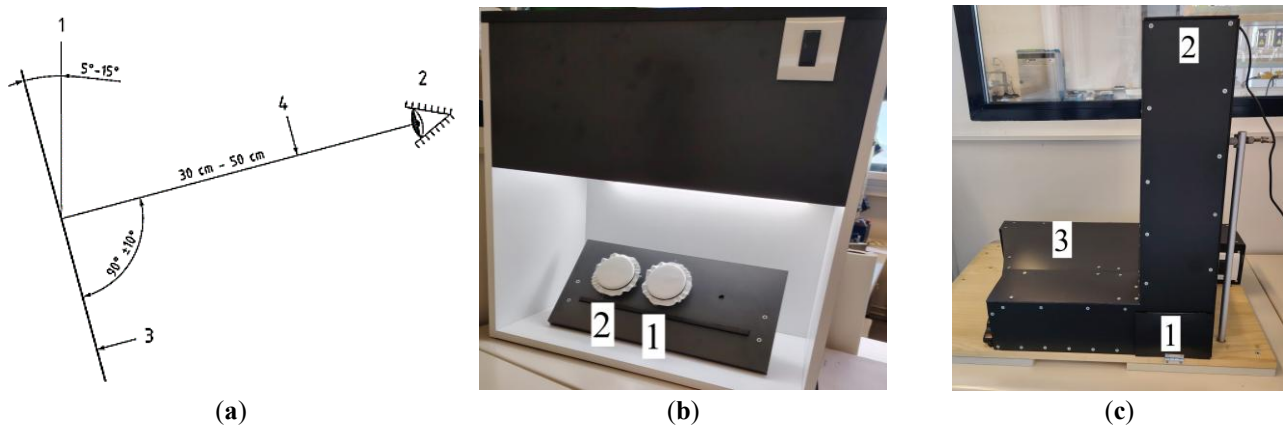


**Figure 1.** Evaluation conditions for the visual method: (a) illumination angle (1), observer position (2), tested fabric specimen surface (3), viewing distance from the tested fabric specimen surface (4); (b) viewing unit: pretreated specimen (1), untreated specimen (2); (c) innovative apparatus with closed housing for the improved instrumental evaluation method: observed specimen position (1), imaging camera position (2), illumination source position (3).

The improved instrumental evaluation method was conducted using an innovative apparatus (Figure 1c) and the image analysis software Fiji (version 2.17.0 [9]). The apparatus was developed to enhance the instrumental evaluation method, specifically the digital imaging process, as it is designed and constructed to capture the entire area of the tested fabric specimen according to the standard visual evaluation method conditions, including viewing distance and angle, as well as illumination source (artificial daylight - D65). The device used to capture grayscale digital images at a resolution of  $1280 \times 1024$  pixels (Figure 2a) was a Dino-Lite digital microscope.



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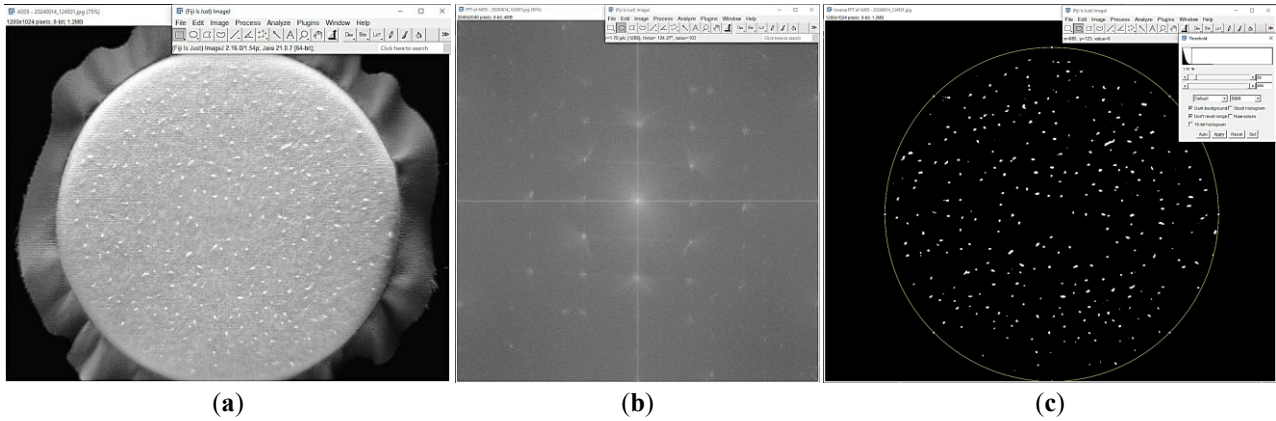


**Figure 2.** Image analysis process of the improved instrumental evaluation method: (a) viscose fabric specimen abraded by wool abrasive fabric for 5,000 rubs; (b) fast Fourier transform of the captured image; (c) isolated occurrence of pilling on the inverse fast Fourier transform image using a modified threshold value.

The image analysis software Fiji was used to numerically characterize pilling occurrence, employing Fast Fourier Transform (Figure 2b) and threshold adjustment (Figure 2c). This image analysis enabled extraction of numerical parameters describing pilling, with the selected reference parameter being the percentage of the specimen surface area occupied by pills ( $A_{op}$  [%]). The improved instrumental evaluation method was graded using numerical grades (from 5.0 to 1.0), assigned based on the  $A_{op}$  value, with nine grading classes (1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0). The grading classes are defined as intervals of  $A_{op}$  values, determined by linear interpolation between the  $A_{op}$  values of the best (5.0) and worst (1.0) graded fabric specimens during the visual evaluation method (Equation 1) [10].

$$x = x_1 + \frac{(y_x - y_1) \times (x_2 - x_1)}{(y_2 - y_1)} \quad \text{Eq. 1}$$

Where:

$x$  –  $A_{op}$  value of the half grade;  $x_1$  –  $A_{op}$  value of the tested fabric specimen with the worst visual evaluation grade;  $x_2$  –  $A_{op}$  value of the tested fabric specimen with the best visual evaluation grade;  $y_x$  – intermediate grade;  $y_1$  – worst visual evaluation grade;  $y_2$  – best visual evaluation grade.

### 3. RESULTS

The results of the visual evaluation method for cotton and viscose fabric specimens, abraded with either the same fabric as the one being tested (F1) or the standard wool abrasive fabric (F2), and subjected to six predefined numbers of rubs, are shown in Table 1. The arithmetic means of the pilling grades assigned by the three observers during the visual evaluation indicate that both cotton and viscose fabrics are prone to pilling, but the intensity of pilling is higher in viscose fabric specimens. This is attributed to the lower abrasion resistance of viscose fibres and their greater tendency toward fibrillation [2]. A noticeable difference between the specimens abraded with F1 and F2 fabrics was also observed in both fabric types. Cotton fabric specimens abraded with F1 fabric exhibited an earlier and more pronounced occurrence of pilling, reaching grade 3.0 after only 125 rubs, compared to those abraded with F2 fabric, which reached the same grade after 1000 rubs. In both cases, the most severe pilling intensity for cotton fabric specimens was observed after 7000 rubs. For viscose fabric specimens, a similar difference in pilling tendency between those abraded with F1 and F2 fabrics was observed as with cotton fabric specimens, but after fewer abrasion rubs (F1: after 125 rubs, grade 1.0; F2: after 500 rubs, grade 2.0).



**Table 1.** Arithmetic means of the pilling grades assigned by the three observers during the visual evaluation method, along with the variability of these grades, for cotton and viscose fabric specimens abraded by each abrasive fabric after six predefined numbers of pilling rubs.

| Number of rubs | Arithmetic mean of the pilling grades |           |         |           |
|----------------|---------------------------------------|-----------|---------|-----------|
|                | Cotton                                |           | Viscose |           |
|                | F1                                    | F2        | F1      | F2        |
| 0              | 5.0                                   | 5.0       | 5.0     | 5.0       |
| 125            | 3.0                                   | 5.0       | 1.0     | 4.5 ± 0.5 |
| 500            | 3.0                                   | 4.0       | 1.0     | 2.0       |
| 1000           | 3.0                                   | 3.0       | 1.0     | 2.0       |
| 2000           | 3.0                                   | 3.0       | 1.0     | 1.5 ± 0.5 |
| 5000           | 3.0                                   | 1.5 ± 0.5 | 2.0     | 1.0       |
| 7000           | 1.0                                   | 1.5 ± 0.5 | 2.0     | 1.0       |

F1 - Abrasive fabric: same as the fabric being tested; F2 - Abrasive fabric: standard wool abrasive fabric.

The results of the improved instrumental evaluation method – the interval values for each of the nine pilling grades (from 1.0 to 5.0), determined by the percentage of the specimen surface area occupied by pills ( $A_{op}$ )—for cotton and viscose fabric specimens abraded with the same fabric (F1) and the standard wool abrasive fabric (F2) are shown in Table 2. The pilling grades assigned by the improved instrumental evaluation method and these interval values are presented in Table 3.

**Table 2.** Interval values for nine grading classes, based on the percentage of the specimen surface area occupied by pills ( $A_{op}$  [%]).

| Pilling grade | Grading classes interval values |             |             |             |
|---------------|---------------------------------|-------------|-------------|-------------|
|               | Cotton                          |             | Viscose     |             |
|               | F1                              | F2          | F1          | F2          |
| 1.0           | ≥1.409                          | ≥0.648      | ≥1.662      | ≥1.624      |
| 1.5           | 1.234–1.408                     | 0.568–0.647 | 1.456–1.661 | 1.423–1.623 |
| 2.0           | 1.059–1.233                     | 0.488–0.567 | 1.251–1.455 | 1.222–1.422 |
| 2.5           | 0.884–1.058                     | 0.408–0.487 | 1.045–1.250 | 1.021–1.221 |
| 3.0           | 0.709–0.883                     | 0.329–0.407 | 0.840–1.044 | 0.821–1.020 |
| 3.5           | 0.534–0.708                     | 0.249–0.328 | 0.634–0.839 | 0.620–0.820 |
| 4.0           | 0.359–0.533                     | 0.169–0.248 | 0.428–0.633 | 0.419–0.619 |
| 4.5           | 0.184–0.358                     | 0.089–0.168 | 0.223–0.427 | 0.218–0.418 |
| 5.0           | ≤0.183                          | ≤0.088      | ≤0.222      | ≤0.217      |

F1 - Abrasive fabric: same as the fabric being tested; F2 - Abrasive fabric: standard wool abrasive fabric.

The percentage of the specimen surface area occupied by pills ( $A_{op}$  [%]) represents the proportion of the surface affected by pilling, taking into account both the number of pills and their individual areas (sizes). This provides a comprehensive measure that more accurately reflects the visual impact of pilling under standard illumination, as the variability of pill area (size) on the observed specimen surface is high. Therefore,  $A_{op}$  is used to define nine grading classes in this improved instrumental pilling evaluation method [4, 6]. The grading classes consist of interval values of equal length, as shown in Table 2. However, the length of  $A_{op}$  interval values differs between cotton and viscose fabrics, as well as between specimens abraded with the same fabric (F1) and those abraded with standard wool abrasive fabric (F2). Cotton fabric specimens have a longer  $A_{op}$  interval value when rubbed against F1 fabric (Table 2), indicating a higher pill formation to detachment rate for those specimens. Viscose fabric specimens have similar  $A_{op}$  interval values between specimens abraded with F1 and F2 fabrics, but as shown in Table 3, the difference in pill formation to detachment rate for specimens rubbed with F1 and F2 fabrics is also present.

**Table 3.** Pilling grades assigned by the improved instrumental evaluation method.

| Number of rubs | Improved instrumental method pilling grades |     |         |     |
|----------------|---------------------------------------------|-----|---------|-----|
|                | Cotton                                      |     | Viscose |     |
|                | F1                                          | F2  | F1      | F2  |
| 0              | 5.0                                         | 5.0 | 5.0     | 5.0 |
| 125            | 3.0                                         | 4.5 | 1.0     | 4.5 |
| 500            | 2.5                                         | 3.0 | 1.0     | 3.0 |
| 1000           | 2.5                                         | 3.0 | 1.0     | 3.0 |
| 2000           | 3.0                                         | 2.0 | 1.0     | 3.0 |
| 5000           | 2.5                                         | 1.5 | 1.0     | 1.0 |
| 7000           | 1.0                                         | 1.5 | 1.0     | 2.0 |

F1 - Abrasive fabric: same as the fabric being tested; F2 - Abrasive fabric: standard wool abrasive fabric.

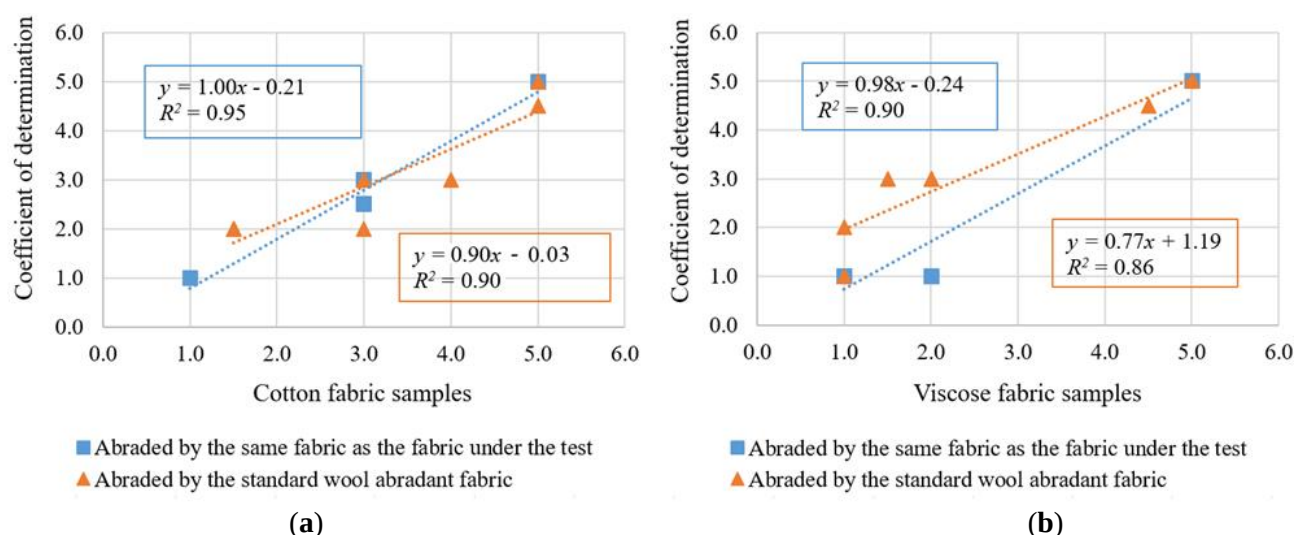


**Figure 3.** Correlation diagram of the pilling grades assigned by the visual evaluation method and the improved instrumental evaluation method for cotton and viscose fabric specimens abraded with either the same fabric or the standard wool abrasive fabric.

The comparability of the pilling grades assigned by the visual method and the improved instrumental evaluation method was confirmed by the very high coefficients of determination (0.76–1.00) (Figures 3a, 3b), calculated with a 95% confidence interval.

#### 4. CONCLUSION

The aim of this research was to improve the pilling evaluation method by enabling uniform digital imaging of the fabric specimen surface while complying with the conditions of the standard visual method (EN ISO 12945-4:2020). This was accomplished through the use of innovative apparatus.

#### ACKNOWLEDGMENT

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## AN ALTERNATIVE TEST METHOD FOR EVALUATING BACK POCKET TEAR STRENGTH IN WOVEN BOTTOM GARMENTS

İsmail İvedi<sup>1,\*</sup>, Bahadır Güneşoğlu<sup>2</sup>

<sup>1,2</sup> Roteks Tekstil İhr. San. Ve Tic. A.Ş., R&D Department, İzmir, Türkiye

ismailivedi@roteks.com.tr

### ABSTRACT

Back pocket failures constitute a critical quality problem in denim garments, where tear weakness typically occurs at the bar tack region under stresses generated predominantly in the weft direction during use. The current standard method, ASTM D7506/D7506M, measures tear strength only in the warp direction and simultaneously clamps both the pocket fabric and the body fabric, which leads to inaccurate results since the measured force is influenced by the body fabric's strength. Additionally, the standard clamping geometry is not suitable for all pocket types, limiting its applicability across woven bottom garments. This study aimed to develop a new test method and sample preparation system capable of accurately measuring the tear strength of back pocket regions under conditions that more realistically simulate wearer-induced stresses.

A standardized 10 × 10 cm test template was designed to ensure rapid, reproducible sample preparation and precise alignment of the bar tack relative to the point of force application. Using the template, three fabric compositions (100% CO, 90/6/4% CO/T400/EL and 99/1% CO/EL) were subjected to light and heavy washing treatments. Tear strength measurements were performed using a modified clamping configuration based on ISO 13935-2 principles, but with the jaws positioned 50 mm apart and oriented to apply force in the weft direction. Three clamping methods were compared which are pocket-only clamping, body-only clamping, and dual clamping.

Results demonstrated that the use of the template significantly reduced data variability. Among the three methods, the pocket-only clamping configuration produced the most realistic and repeatable results, as it isolates the force required to separate the pocket fabric from the body fabric at the bar tack mirroring actual wear conditions. Across all fabric types, samples with back pocket tear values below 100 N were found to be easily broken off by hand after heavy wash processes, suggesting that 100 N should be considered a critical performance threshold for product acceptance.

The developed template and test method provide a standardized, reliable, and applicable procedure for evaluating back pocket tear strength in denim and other woven bottom garments.

**Keywords:** Denim, Tear strength, Back pocket, Test method, Woven garments

### 1. INTRODUCTION

Mechanical durability is a critical performance parameter in denim garments, which are subjected to repeated deformation, abrasion and localized stresses during wear. Among common failure modes, back pocket tearing is frequently reported and represents a significant source of quality loss in mass production [1]. These failures typically occur at the bartack seam, where stress concentration develops and loading is predominantly applied in the weft direction during daily activities such as sitting and bending.

Tear strength in woven fabrics is influenced by fiber composition, yarn structure, fabric density and finishing processes. Fabrics with higher yarn mobility generally exhibit greater resistance to tear propagation, while intensive finishing processes such as bleaching and stone washing treatments reduce strength by damaging fiber structure and increasing yarn slippage [2]. In denim garments, washing processes play a dominant role in determining final mechanical performance.

The commonly used ASTM D7506/D7506M standard evaluates pocket reinforcement strength under warp-direction loading and clamps both pocket and body layers simultaneously [3]. This approach does not reflect the actual failure mechanism observed in use, where tearing occurs at the pocket body interface in the weft direction. Moreover, variations in pocket geometry limit the applicability of standard testing fixtures.

Although several studies have investigated seam strength and general tear behavior in textiles, limited attention has been given to localized failure mechanisms in denim back pockets [4]. Therefore, there is a need for a test method that accurately represents real usage conditions and provides reliable, repeatable results.

The aim of this study is to develop a new tear strength test method that simulates weft direction loading, isolates the pocket body interface, ensures standardized specimen preparation and defines a practical performance threshold for denim back pocket durability.

## **2. EXPERIMENTAL STUDY**

This study was designed to develop a weft direction tear strength method capable of accurately replicating the failure mechanisms observed in denim back pockets during real use. Experimental work was conducted through a systematic sequence of fabric selection, washing treatments, specimen conditioning, standardized template sample preparation, and tensile testing under controlled clamping configurations. The methodology was structured to ensure strict repeatability, eliminate geometric inconsistencies common in current industrial practices, and isolate the mechanical behavior of the pocket and body interface.

### **2.1. Fabric selection and garment preparation**

Three commercially relevant denim qualities were selected to represent a range of fiber compositions, elasticities, and weave structures commonly found in mass-produced denim garments. These fabric samples included: FN (90% CO, 6% T400, 4% EL), FS (99% CO, 1% EL), and F1 (100% CO). Each fabric was cut and sewn into standardized trouser constructions using identical five pocket dimensions and bar tack reinforcement patterns to eliminate sewing related variability. All garments were produced on the same production line to ensure consistent stitching density, needle type, thread characteristics, and bar tack settings.

### **2.2. Washing treatments**

Because mechanical degradation in denim predominantly arises from wet processes rather than wear alone, controlled washing treatments were applied to capture realistic performance. Three finishing routes were selected, reflecting typical industrial practice: (i) rinse wash; (ii) heavy wash, consisting of rinse, stonewash, bleach, neutralization, bisulfite, and tinting stages; and (iii) Enzyme wash consisting of rinse wash with additional cellulase enzyme and softener treatments [5]. These processes were chosen to represent increasing levels of fiber surface damage, yarn slippage, chemical oxidation, and yarn frictional changes known to alter tear and tensile behavior in denim fabrics. All washes were carried out in a controlled wet processing laboratory using consistent liquor ratios, mechanical loadings, and chemical dosages.

Following laundering, all trousers were conditioned in a standardized climate room at  $20 \pm 2^\circ\text{C}$  and  $65 \pm 2\%$  relative humidity for 24 hours, in accordance with general textile testing requirements. Conditioning was essential to ensure moisture equilibrium in both pocket and body fabrics, as humidity variations can significantly affect tear and tensile responses. Conditioned specimens were used for mechanical testing.

### **2.3. Development and use of the standardized cutting template**

A key methodological advancement of this study was the creation of a standardized  $10 \times 10$  cm cutting template designed to eliminate geometric inconsistencies commonly encountered in existing tear testing procedures (Figure 1). The template incorporated a central 0.8 cm circular alignment hole, positioned to coincide precisely with the bartack reinforcement in the garment, and a series of peripheral reference slots that allowed fine rotational and translational alignment with the pocket boundary. This configuration ensured that the bar tack was placed exactly at the center of the loading axis of the tensile tester.

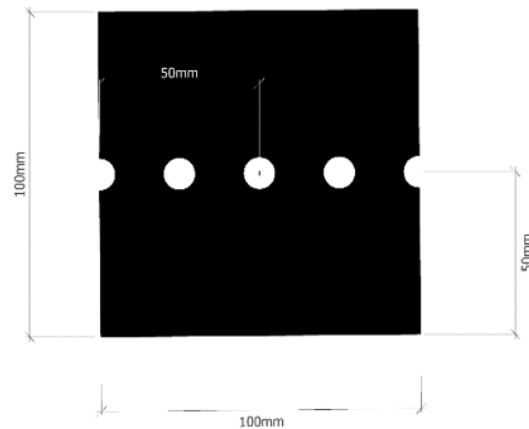


**Figure 1.** Cutting template

During specimen preparation, the template was placed onto the back pocket region, visually aligned through the reference apertures, and fixed in position before cutting (Figure 2). This ensured that each extracted specimen possessed identical geometry, bar tack position, and load path orientation. The adoption of this template directly addressed challenges in denim testing, where small deviations in cutting angle, bar tack offset, or pocket curvature can introduce significant measurement variability.

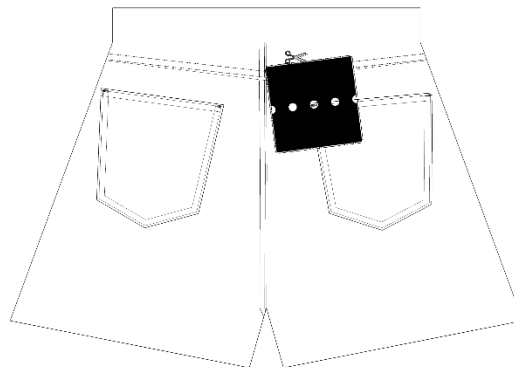


**Figure 2.** Specimen preparation

#### **2.4. Mechanical testing configuration**

Mechanical testing was performed using Titan 10 from James Heal, UK a constant rate tensile tester adapted from the ISO 13935-2 seam rupture framework but modified to suit the unique geometry and failure mode of back pocket separation [6]. The jaw separation was set to 50 mm, enabling controlled propagation of tear along the weft direction. The test direction was intentionally restricted to the weft because real world failures consistently arise from lateral loading rather than longitudinal stretching.

To evaluate the influence of clamping configuration on measured tear strength, three distinct setups were examined. The pocket-only configuration (Figure 3a) placed the pocket fabric in the lower jaw and the body fabric in the upper jaw, isolating the pocket and body interface and reproducing the actual separation behavior observed in wear. The body-only configuration (Figure 3b), gripping only the garment body fabric in both jaws, served as a structural reference representing the underlying fabric strength. The dual-clamping configuration (Figure 3c), which clamped both layers in the upper jaw while gripping only the body layer in the lower jaw, approximated current industrial testing but did not fully reflect the localized tear mechanism. All jaws were lined with high-friction elastomeric material to prevent specimen slippage, and all tests were conducted at a controlled extension rate of 50 mm/min, consistent with standardized tensile test practices.



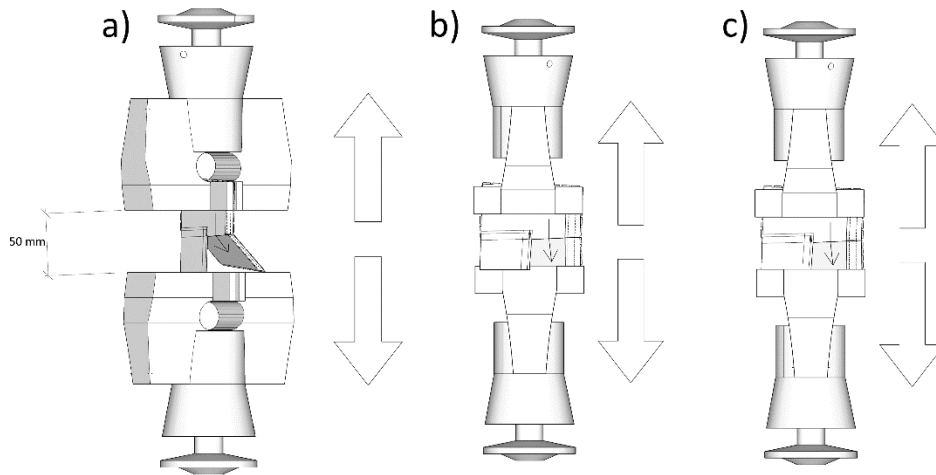


**Figure 3.** Clamping configuration (a. pocket-only configuration, b. body-only configuration, c. dual-clamping configuration)

For each fabric, wash and clamping combination, multiple replicates were tested to ensure statistical robustness. Peak tear force was automatically recorded as the maximum load at which the pocket and body fabrics separated at the bar tack region. In addition to mechanical measurements, a qualitative hand-tear assessment was performed after washing treatments to verify correspondence between laboratory values and real world failure potential. All data were analyzed to determine variability, sensitivity to washing intensity, and the discriminative power of each clamping method. The relationship between mechanical force and hand tearability was further examined to identify a practical performance threshold.

### 3. RESULTS

The results obtained from the standardized cutting template and the three clamping configurations demonstrate clear distinctions in tear strength behavior across fabrics, washing treatments and loading conditions. Overall, the findings confirm that the weft-direction tear mechanism of denim back pockets is highly sensitive to garment finishing processes and specimen geometry, and that conventional testing methodologies do not adequately capture this localized failure mode.

#### 3.1. Effect of template assisted specimen preparation

Analysis of back pocket tear strength in the unwashed state revealed clear and consistent differences among the three clamping configurations (Table 1). For all three fabrics, the pocket-only configuration produced distinct and internally coherent datasets, with relatively low scatter between replicates. For the FN series (90% CO, 6% T400, 4% EL), pocket-only tear strength values ranged between approximately 255–262 N; for the FS series (99% CO, 1% EL) between 229–240 N; and for the F1 series (100% CO) between 182–189 N. These trends are consistent with the expected influence of fiber composition and elastomeric content on tear resistance, with the dual-core and elastane-containing FN fabric exhibiting the highest initial performance.

Introducing the 10 × 10 cm cutting template substantially reduced data dispersion compared with preliminary trials conducted without geometric standardization. Variance decreased across all fabric types, indicating that misalignment of the bartack region and inconsistencies in specimen contour had previously contributed to artificially inflated scatter in tear force measurements. This observation is in line with previous reports that tear testing is highly sensitive to notch positioning and fabric orientation [7]. By aligning each specimen precisely along the weft direction and ensuring a reproducible load path through the bartack, the template improved the discriminatory power of the method and strengthened the reliability of the subsequent analyses. The reduction in variability is particularly important for denim fabrics, which often exhibit heterogeneous deformation due to elastomeric yarns and non-uniform finishing treatments.

**Table 1.** Back pocket tear strength results prior to washing treatments for three clamping configurations

| Fabric Code | Fabric Composition     | Pocket-only Tear Strength (N) | Body-only Tear Strength (N) | Dual Clamping Tear Strength (N) |
|-------------|------------------------|-------------------------------|-----------------------------|---------------------------------|
| FN-1        | 90% CO, 6% T400, 4% EL | 258.3                         | 247.7                       | 290.3                           |
| FN-2        | 90% CO, 6% T400, 4% EL | 261.4                         | 266.1                       | 268.6                           |
| FN-3        | 90% CO, 6% T400, 4% EL | 261.6                         | 273.9                       | 296                             |
| FN-4        | 90% CO, 6% T400, 4% EL | 259.2                         | 258.2                       | 228                             |
| FN-5        | 90% CO, 6% T400, 4% EL | 255                           | 279.3                       | 302.7                           |
| FS-1        | 99% CO, 1% EL          | 237.2                         | 230.5                       | 271.3                           |
| FS-2        | 99% CO, 1% EL          | 239.8                         | 256.9                       | 242.9                           |
| FS-3        | 99% CO, 1% EL          | 230.3                         | 236.8                       | 283.6                           |
| FS-4        | 99% CO, 1% EL          | 234.2                         | 260.4                       | 251.4                           |
| FS-5        | 99% CO, 1% EL          | 229.3                         | 277.9                       | 288.6                           |
| F1-1        | 100% CO                | 189.3                         | 216.8                       | 248                             |
| F1-2        | 100% CO                | 188.1                         | 231.4                       | 226                             |
| F1-3        | 100% CO                | 181.7                         | 225.5                       | 191.2                           |
| F1-4        | 100% CO                | 186.6                         | 242.1                       | 250.2                           |
| F1-5        | 100% CO                | 188.2                         | 203.9                       | 239.6                           |

### 3.2. Influence of washing treatments on tear strength

The influence of washing treatments on back pocket tear strength is summarized in Table 2. Across all three denim qualities, tear strength decreased systematically with increasing washing severity. Rinse-washed specimens exhibited the highest resistance, enzyme-washed specimens showed intermediate values, and heavy-washed specimens consistently produced the lowest tear strengths.

For the pocket-only configuration, mean tear strength for FN decreased from approximately 259 N in the unwashed state to around 211 N after rinse washing, 162 N after enzyme washing and 118 N after heavy washing. Similar trends were observed for FS (from 234 N unwashed to 200 N, 149 N and 104 N for rinse, enzyme and heavy washes, respectively) and for F1 (from 187 N unwashed to 166 N, 128 N and 99 N). These reductions represent the cumulative effect of mechanical abrasion, chemical oxidation and enzymatic action on the yarn network. In particular, enzyme treatments disrupt the amorphous regions of cellulose, promote fibrillation and increase inter-yarn mobility, thereby facilitating tear propagation once a crack has initiated at the bartack [8].

As washing intensity increased, the differences among fabric types became less pronounced, especially after heavy washing, where all three fabrics converged toward a relatively narrow range between approximately 99–118 N in pocket-only mode. This convergence suggests that aggressive finishing can dominate the mechanical response of the back pocket region, partially overriding the inherent structural advantages of specific constructions. This implies that while initial fabric choice is important, the washing recipe can critically determine end-use performance and may, in severe processes, negate the benefits of higher-performance yarn or weave designs.

**Table 2.** Back pocket tear strength results after washing treatments for three clamping configurations

| Fabric Code | Washing Process (R:rinse, H: Heavy wash, E: Enzyme) | Pocket-only Tear Strength (N) | Body-only Tear Strength (N) | Dual Tear Strength (N) | Clamping Strength |
|-------------|-----------------------------------------------------|-------------------------------|-----------------------------|------------------------|-------------------|
| FN-1-R      | R                                                   | 210.8                         | 216.1                       | 252.2                  |                   |
| FN-2-R      | R                                                   | 211.7                         | 244.1                       | 258.4                  |                   |
| FN-3-R      | R                                                   | 201.5                         | 229                         | 216.1                  |                   |
| FN-4-R      | R                                                   | 214.4                         | 205.2                       | 208.7                  |                   |
| FN-5-R      | R                                                   | 216.1                         | 209.3                       | 212.2                  |                   |
| FS-1-R      | R                                                   | 201.4                         | 222.6                       | 232.4                  |                   |
| FS-2-R      | R                                                   | 201.5                         | 200.9                       | 222.3                  |                   |
| FS-3-R      | R                                                   | 199.3                         | 191.4                       | 269.5                  |                   |
| FS-4-R      | R                                                   | 200.5                         | 216.5                       | 231.9                  |                   |
| FS-5-R      | R                                                   | 198.6                         | 193.5                       | 216.4                  |                   |
| F1-1-R      | R                                                   | 168.2                         | 171.2                       | 203.7                  |                   |
| F1-2-R      | R                                                   | 168.5                         | 153.2                       | 201.6                  |                   |
| F1-3-R      | R                                                   | 161.7                         | 153.5                       | 233.4                  |                   |
| F1-4-R      | R                                                   | 166.1                         | 168.7                       | 189.1                  |                   |
| F1-5-R      | R                                                   | 167.2                         | 201.2                       | 210.6                  |                   |
| FN-1-E      | E                                                   | 164                           | 150.8                       | 190.8                  |                   |
| FN-2-E      | E                                                   | 161.5                         | 169.1                       | 216                    |                   |
| FN-3-E      | E                                                   | 161.6                         | 151.3                       | 219.9                  |                   |
| FN-4-E      | E                                                   | 159.9                         | 176.9                       | 159.1                  |                   |
| FN-5-E      | E                                                   | 163.5                         | 145.9                       | 141.3                  |                   |
| FS-1-E      | E                                                   | 147.8                         | 131.3                       | 120.1                  |                   |
| FS-2-E      | E                                                   | 149.2                         | 117.8                       | 119.8                  |                   |
| FS-3-E      | E                                                   | 149.3                         | 152.7                       | 167.5                  |                   |
| FS-4-E      | E                                                   | 148.1                         | 134.9                       | 110.2                  |                   |
| FS-5-E      | E                                                   | 148.4                         | 143.5                       | 132.3                  |                   |
| F1-1-E      | E                                                   | 129.5                         | 110.8                       | 141                    |                   |
| F1-2-E      | E                                                   | 128.7                         | 142.1                       | 119.3                  |                   |
| F1-3-E      | E                                                   | 128.3                         | 133.7                       | 123.6                  |                   |
| F1-4-E      | E                                                   | 129.6                         | 125.9                       | 100.4                  |                   |
| F1-5-E      | E                                                   | 125.1                         | 109.1                       | 133.8                  |                   |
| FN-1-H      | H                                                   | 117.3                         | 129                         | 98.3                   |                   |
| FN-2-H      | H                                                   | 118.5                         | 103.8                       | 110.2                  |                   |
| FN-3-H      | H                                                   | 117.3                         | 99.6                        | 121.5                  |                   |
| FN-4-H      | H                                                   | 119.1                         | 119.5                       | 95.3                   |                   |
| FN-5-H      | H                                                   | 119.4                         | 123.4                       | 111.8                  |                   |
| FS-1-H      | H                                                   | 107.2                         | 105.3                       | 109.1                  |                   |
| FS-2-H      | H                                                   | 104.8                         | 91.4                        | 116.2                  |                   |
| FS-3-H      | H                                                   | 101.9                         | 120.4                       | 91.9                   |                   |
| FS-4-H      | H                                                   | 104.1                         | 117.2                       | 104.7                  |                   |
| FS-5-H      | H                                                   | 103.8                         | 108.9                       | 109.5                  |                   |
| F1-1-H      | H                                                   | 100.1                         | 97.3                        | 117.1                  |                   |
| F1-2-H      | H                                                   | 98.6                          | 91.9                        | 105.2                  |                   |
| F1-3-H      | H                                                   | 96.7                          | 115                         | 111.6                  |                   |
| F1-4-H      | H                                                   | 99.4                          | 104.3                       | 98.2                   |                   |
| F1-5-H      | H                                                   | 98.8                          | 111.5                       | 89.4                   |                   |

Across all fabrics and washing conditions, the pocket-only method generated the lowest and most stable tear strength values, with standard deviations typically below 5 N in raw and rinsed conditions. This high level of repeatability demonstrates the effectiveness of the standardized cutting template in eliminating geometric misalignment as a major source of variability and confirms that the pocket-only configuration is highly suitable for comparative assessments of durability.

### 3.3. Comparative performance of clamping configurations

The three clamping setups displayed distinct mechanical responses. The body-only configuration generally produced intermediate tear strength values, reflecting primarily the intrinsic tensile strength of the base fabric rather than the localized failure at the pocket–body interface. Because this configuration excludes the pocket piece from the critical load path, it does not replicate the actual stress distribution in use and therefore tends to overestimate durability.

The dual-clamping configuration, which partially constrained both layers in the upper jaw while gripping only the body fabric in the lower jaw, generated the highest tear strength values and the largest variability. This method resembles current industrial practice; however, it fails to isolate the interface where failure typically initiates. The measured forces represent a hybrid response influenced by fabric bending stiffness, friction between the pocket and body layers and complex load redistribution across the garment structure. As a result, dual-clamping data often span a wide range within the same fabric and washing condition, making it difficult to set meaningful acceptance criteria.

In contrast, the pocket-only configuration produced the lowest and most realistic tear values. This approach closely simulates the natural separation mechanism observed during consumer use, wherein the pocket layer detaches from the garment body under lateral, weft-direction loading. The dominance of pocket-only loading in reproducing actual failure behavior reinforces the inadequacy of warp-based conventional methods such as ASTM D7506, which overlook the critical role of weft-direction stresses in denim back pockets [3]. The consistency of pocket-only results across fabric and wash combinations further demonstrates that this configuration provides a robust and sensitive measure of back pocket durability, capturing meaningful differences that are largely masked under alternative clamping strategies.

Taken together, the results indicate that the combination of a standardized cutting template and a pocket-only, weft-direction loading configuration offers a technically sound and practically applicable framework for evaluating back pocket tear strength, while conventional methods systematically misrepresent true durability by blending unrelated structural responses.

#### **4. CONCLUSION**

This study introduced and validated a new tear strength test method specifically designed to capture the weft-direction failure mechanism of denim back pockets which is a mode of rupture that is not adequately represented in existing standards. By combining a standardized 10 × 10 cm cutting template with a pocket-only clamping configuration, the proposed method effectively isolated the localized stress path through the bar tack region and substantially reduced measurement variability relative to conventional dual-layer and body only approaches. The high repeatability observed across fabrics and finishing treatments demonstrates that controlling specimen geometry is essential for reliable tear evaluation in denim garments.

Washing treatments exerted a pronounced influence on tear strength, with rinse washing producing the highest resistance, enzyme washing yielding intermediate performance, and heavy washing resulting in severe mechanical deterioration. Across all fabrics, tear strengths converged toward a narrow range after heavy washing, indicating that aggressive finishing can dominate end-use performance and diminish inherent material advantages. Importantly, the pocket-only configuration consistently produced values that aligned with observed failure behavior, in contrast to the elevated and highly variable results obtained from the dual-clamping method, which measures a hybrid structural response unrelated to real wear conditions.

A critical durability threshold of approximately 100 N was identified for practical use. Fabrics falling at or below this limit after heavy washing demonstrated high susceptibility to tear initiation during manual inspection, suggesting that this threshold provides a meaningful acceptance criterion for back pocket performance evaluation. Because the proposed method accurately reflects functional stresses encountered during wearing, it enables more effective quality control, supports process optimization in denim finishing, and provides actionable data for the engineering of more durable pocket constructions.

Overall, the developed testing framework offers a reproducible, and industrially applicable alternative to existing standards. Its ability to directly characterize the true failure mechanism positions it as a valuable tool for

manufacturers seeking to enhance garment longevity, reduce claims and returns, and improve consumer satisfaction through evidence based durability assessment.

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## **A UNISEX FUNCTIONAL CAPSULE COLLECTION DESIGN: SUSTAINABLE DENIM PROCESSES**

**Hümeýra Çakır<sup>1,\*</sup>, Zehra Doğan Sözüer<sup>2</sup>**

<sup>1</sup>Istanbul Nişantaşı University, Textile and Fashion Design Department, İstanbul, Türkiye

<sup>2</sup>Istanbul Technical University, Textile Engineering Department, İstanbul, Türkiye

\*dogansozuer@itu.edu.tr

### **ABSTRACT**

This study aims to propose a denim collection—commonly present in wardrobes with numerous colors and model variations—through a multifunctional and modular clothing concept from a design-driven perspective, and to produce them by applying sustainable industrial processes. In this context, the first part of the study briefly discusses the dry and wet processes applied in denim production, their sustainability impacts, and characteristics. The second part examines modular and convertible clothing design, which is included in today's sustainable clothing trends and offers alternative looks by extending the life of the garment. The study's data were obtained from literature, and semi-structured interviews with Eroğlu Giyim Company's R&D, production, and design unit managers provided support for the industrial procedures used in denim manufacture. Based on this information, a unisex capsule denim collection called ‘CityExplorer’ was designed and produced, featuring 9 garments (as 6 looks) with 27 different usage options. In this study, sustainability was addressed in two separate contexts: design and production. The choices made during the production stages and the EIM (Environmental Impact Measuring) sustainability reports generated during production are presented along with the study results. In this context, the average carbon footprint per garment was determined to be 0.19 kg CO<sub>2</sub>/garment, resulting in a total carbon footprint of 2.49 kg CO<sub>2</sub>/garment. The total sustainability value per garment was determined to be an average of 32.18, and based on this ratio, it was concluded that the garment has a low environmental impact.

**Keywords:** *Sustainable, Denim, Functional, Design.*

### **INTRODUCTION**

Today's one of the most popular garment, denim's history dates back to the 15th century, but it shifted from industrial use (sails and covers) to apparel occurred in the 1850s. During the San Francisco Gold Rush, Levi Strauss and Jacob Davis repurposed durable denim into trousers to meet the practical needs of miners [1-2]. The global popularization of denim was driven by several key factors: its use by American soldiers in WWII, the influence of the hippie movement, and its adoption by Hollywood icons; Marilyn Monroe and Marlon Brando [2-3]. This cultural shift transitioned denim from workwear to a fashion staple, eventually entering the luxury market through designers like Yves Saint Laurent [4-5]. Today, the industry continues to evolve through diverse distressing techniques and styles that remain central to modern fashion [3].



## **Denimwear manufacturing processes**

Denim finishing involves a combination of wet and dry processes designed to enhance the fabric's durability and create distinctive aging effects.

Denim finishing techniques, divided into wet and dry processes, are applied post-weaving to create a vintage appearance. Wet processes modify fabric texture, strength, and color [6]. This phase begins with desizing to remove yarn-durability starches applied during weaving [7-8], thereby softening the fabric for subsequent treatments [8-9]. While stone washing utilizes pumice stones for mechanical abrasion to create a used look despite equipment wear and environmental waste [8-10-11], enzyme washing degrades cellulose to remove indigo [12]. Additionally, resin treatments provide durable, lustrous, or wrinkled finishes [3-13], and bleaching chemically lightens the fabric [14].

Conversely, dry processes physically scrape indigo to create localized wear [3-6]. Manual sanding on inflatable mannequins ensures an authentic aging effect that robotic alternatives cannot replicate [15-16], whereas sandblasting achieves similar results but poses severe health risks [17-18]. Finally, attrition is applied to edges to mimic organic wear, followed by a final wash to enhance these abrasions [9-17].

## **Sustainable approaches to denim production**

Traditional wet and dry denim finishing processes pose severe environmental and occupational health hazards, notably generating wastewater sludge from stone washing and inducing silicosis through sandblasting [18]. To mitigate these impacts, eco-friendly alternatives like laser technology, ozone bleaching, and enzyme washing have been developed [12, 18, 29]. Among these, laser technology utilizes concentrated light beams as an innovative, sustainable solution [19-20], primarily deployed in the denim sector for fading and fraying [21] to ecologically replicate traditional sanding or sandblasting effects [22]. By digitally transferring designs via varying beam intensities, this technology ensures consistent mass-production results [6, 22-24] while significantly reducing labor costs, processing time, and water consumption in a safer workspace [21, 25-28]. Complementing this, ozone bleaching lightens denim without hot water, saving up to 50% in electricity, water, and detergents [1, 29]. Concurrently, enzyme washing serves as a safe biochemical aging process that degrades cotton's cellulose molecules for surface abrasion [12], utilizing specific enzymes like amylase, cellulase, and laccase, while anti-pilling enzymes minimize sludge formation during purification [30]. Ultimately, modern R&D continues to advance these low-water and waterless technologies to further minimize the industry's environmental footprint [31].

## **Sustainability-focused design methods**

Textile waste management is fundamentally addressed in two stages: pre-consumer waste, generated during the production process from fiber to garment, and post-consumer waste, which refers to household textile products discarded by the consumer [32]. To minimize pre-consumer waste, the "Zero Waste Design" vision has emerged, focusing on three primary methods: zero-waste pattern preparation, patchwork, and fabric manipulation [33].

This method differentiates itself from traditional production by integrating the design and pattern-making stages simultaneously. While conventional patterns often result in significant fabric scrap due to their curved and angular forms, zero-waste patterns are typically designed in geometric shapes to utilize the entire plan [34-35-36-37]. This method ensures that no waste remains after the cutting process, requiring high technical expertise from the designer to maintain both efficiency and style.

Patchwork and fabric manipulation methods offer additional creative solutions for waste reduction. Patchwork involves modularly combining fabric scraps and repeating geometric motifs to create large surface areas, effectively transforming small waste pieces into new designs [38-39]. Similarly, fabric manipulation enriches the textile surface through techniques such as pleating, gathering, and applique [38]. These methods

allow designers to incorporate production scraps directly into the garment’s aesthetic, enhancing the fabric’s texture while promoting sustainability.

Unisex clothing contributes to sustainability by blurring gender boundaries and focusing on design elements like color, texture, and pattern that are suitable for both men and women [40-41]. This approach encourages a “shared wardrobe” concept, which saves significant time and energy during both the design and production phases [42]. Rather than being merely genderless, unisex design prioritizes gender-independent silhouettes, offering a versatile and sustainable alternative to traditional fast fashion.

Functional clothing represents an innovative sustainable approach by transforming garments into a multi-functional experience for the user [36]. These designs often feature modular components—such as zippers, snaps, and buttonholes—that allow a single garment to take on multiple appearances or functions [43-44]. By providing variety and adaptability, functional clothing extends the product’s lifecycle and reduces the need for excessive consumption. This study utilizes both functional and unisex design philosophies in its practical application phase.

## EXPERIMENTAL STUDY

### Design Process

In this study, a sustainable, denim capsule collection titled ‘City Explorer’ was designed to accommodate various body shapes, daily temperature shifts, and multiple styling alternatives for urban life. Preliminary interviews were conducted with R&D, design, and business development departments regarding sustainable approaches in the design, sewing, washing, and aging stages. The collection was manufactured at Eroğlu Giyim A. Ş., a facility holding various sustainability certifications (such as BCI, GRS, Sedex, Higg Index, and ZDHC). To objectively assess the environmental footprint of the finishing phase, Jeanologia’s Environmental Impact Measuring (EIM) software was utilized to calculate the carbon footprint and generate sustainability reports for each piece [45]. The EIM system categorizes industrial impact into three zones—Low (Green), Medium (Orange), and High (Red)—across four critical categories: water consumption, energy consumption, chemical usage, and worker health (Table 1). Additionally, the scoring system differentiates between dry processes (indicated by an orange panel and ‘D’) and wet processes (indicated by a blue panel and ‘W’), while also accounting for manual processes to measure impact on workers.

| Impact Category    | Low Impact<br>(Green) | Medium<br>Impact<br>(Orange) | High Impact<br>(Red) |
|--------------------|-----------------------|------------------------------|----------------------|
| Water Consumption  | 0 – 35                | 35 – 80                      | 35 – 80              |
| Energy Consumption | 0 – 2.1               | 2.1 – 4.1                    | 2.1 – 4.1            |
| Chemical Usage     | 0 – 25                | 25 – 50                      | 25 – 50              |
| Worker Health      | 0 – 20                | 20 – 35                      | 20 – 35              |

**Table 1.** EIM Score definitions and ranges



### Figure 1. Concept and Moodboard



### Figure 2.Moodboard

### Figure 3.Collection Line Up

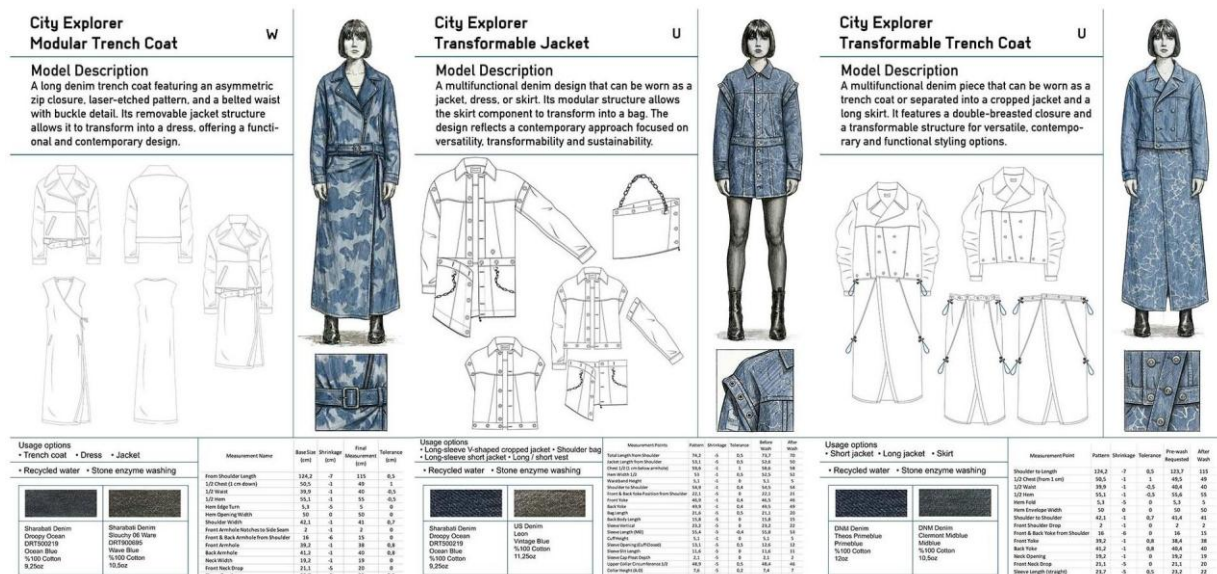


**Figure 4:** Modular Trench Coat Technical Package (T.P) **Figure 5.** Transformable Jacket T.P  
**Figure 6.** Transformable Trench Coat T.P



**Figure 7.** Transformable Skirt Jacket T.P **Figure 8.** Transformable Skirt&Jacket T.P.  
**Figure 9.** Transformable Jean&JacketT.P



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### Production Process

In the pre-production phase, digital patterns were developed using Gerber 12.0 software based on fabric shrinkage and elasticity tests, which then guided the preparation of Sample Request Forms and technical Model Files. The automated marker plan was printed via a Gerber Plotter, fused onto fabric layers using an industrial iron for precise cutting, and assembled in a specialized sewing machinery park. For finishing, Adobe Photoshop designs were transferred to the Jeanologia Lasersystem (e-mark software) as a sustainable, eco-friendly alternative to traditional distressing, within ten sites calibrated to fabric thickness. This was integrated with an eco-efficient enzyme stone wash to minimize stone consumption and sludge waste while preserving fabric integrity. The production cycle concluded with consecutive rinsing, bleaching, neutralization for effect stabilization, hydro-extraction, and drying, utilizing sustainable accessories such as recycled zippers and removable metal buttons.



**Figure 10.** Production processes: small-scale pattern, Control Panel-Laser System, Laser Distress.

### RESULTS

The design phase of the study culminated in a functional, gender-neutral denim collection initially developed as 23 original sketches, comprising 11 unisex (48%), 9 women's (39%), and 3 men's (13%) garments to optimize pattern efficiency and resource utilization. Following expert reviews with Eroğlu Giyim A.Ş., 9 specific pieces (4 women's and 5 unisex) were produced and configured into 6 distinct looks, achieving a threefold transformation rate that yielded 27 different usage alternatives. According to the Environmental Impact Measuring (EIM) benchmarks—which classify processes based on specific thresholds for water, energy, chemicals, and worker safety—the collection demonstrated high ecological efficiency, resulting in a sustainability rate of 0.19 kgCO<sub>2</sub>e/garment and a total carbon footprint of 2.49 kgCO<sub>2</sub>e/garment. The collection is presented through AI-generated conceptual editorial visuals, which place the functional denim designs within a high-speed urban narrative, bridging the digital innovation and street-wear aesthetics together, shown in Figure 13.



**Figure 11:** Collection break out.



**Figure 12:** AI-Generated Conceptual Editorial Visuals

## CONCLUSION

This study develops a sustainable capsule wardrobe solution featuring adaptable, multifunctional garments designed to counter overconsumption and maximize product lifecycles through a circular design strategy. By holistically integrating ecological production, traditional denim craftsmanship, digital design, and AI-driven visual conceptualization, the research offers an innovative roadmap for the industry. Future research directions include evaluating the long-term wear performance and user experience of these functional designs, as well as combining AI-supported work flows with diverse raw materials to advance zero-waste objectives in denim manufacturing.

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# BEYOND COMPLIANCE: UNLOCKING INVESTMENT-FREE FINANCIAL AND ENVIRONMENTAL SAVINGS THROUGH TRACEABILITY AND DIGITAL PRODUCT PASSPORTS IN THE TEXTILE VALUE CHAIN

Serel Başak KÖK<sup>1</sup>, Prof. Dr. Selin Hanife Eryürük<sup>1\*</sup>, Prof.Dr Zümbül ATAN<sup>2</sup>

<sup>1</sup> Istanbul Technical University, Faculty of Textile Technologies and Design, Textile Engineering Department, Istanbul, Türkiye

<sup>2</sup> Eindhoven University of Technology, Department. of Industrial Engineering and Innovation Sciences  
Eindhoven, The Netherlands

\* email address of corresponding author: eryluruk@itu.edu.tr

## ABSTRACT

The European Union’s Ecodesign for Sustainable Products Regulation (ESPR) and the Digital Product Passport (DPP) mandate are compelling textile manufacturers to transition from generic secondary data to facility-specific primary data [1]. Within the industry, this transition is often framed as a compliance cost requiring heavy administrative burdens and significant Capital Expenditure (CapEx). Current literature indicates that generic secondary data is fundamentally insufficient for accurate environmental assessment, as it merely provides approximate quantifications based on industry averages rather than reflecting the specific dynamics and hidden inefficiencies of a given value chain [2]. This paper argues that significant financial and environmental savings can be achieved solely through data awareness, parameter optimization, and behavioural changes without requiring new machinery investments. In light of sustainable business model archetypes and current case studies, this research posits that the cost of traceability is not merely a regulatory shield; it functions internally as a diagnostic tool that identifies hidden inefficiencies and externally as a strategic asset that neutralizes greenwashing risks.

**Keywords:** Digital Product Passport (DPP), Ecodesign for Sustainable Products Regulation (ESPR), Life Cycle Assessment (LCA)

## INTRODUCTION

The transition of the global textile and apparel sector toward a circular economy is not a sudden regulatory disruption, but rather the culmination of a systematic, decade-long legislative evolution. Building upon foundational frameworks such as the 2009 Ecodesign Directive, the Product Environmental Footprint (PEF) methodology introduced in 2013, and the 2020 Circular Economy Action Plan, the European Union has progressively laid the groundwork for comprehensive supply chain transparency [1]. The pinnacle of this regulatory progression is the Ecodesign for Sustainable Products Regulation (ESPR), which officially entered into force in July 2024 [3]. As a broad legal framework, the ESPR mandates the implementation of a Digital Product Passport (DPP) to digitally record a product’s entire life cycle, yet it relies on the adoption of targeted delegated acts to enforce specific operational measures [4]. For the textile sector, which is heavily prioritized in the first working plan, these specific delegated acts dictating the exact data requirements have not yet been published, providing a critical preparatory window for the industry [5]. Consequently, while absolute traceability has definitively become a fundamental prerequisite for entering the European market, the industry is currently utilizing this interim period to establish the necessary data infrastructure before the regulations take full effect [1].

While the traditional perspective often views these regulations as a costly “compliance tax,” particularly for Small and Medium-sized Enterprises (SMEs), recent research argues the exact opposite. Discussions in the literature that began over a decade ago, such as the EU COST Action 628, stated that life cycle assessments (LCA) should not be used exclusively for external reporting, but must be actively utilized to

identify inefficient "hotspots" in production [6]. Today, evidence shows that advanced traceability can significantly increase operational efficiency, potentially reduce material waste by 15–20%, and provide an increase in net profit margins ranging from 3 to 7 percent [7].

This study proposes that the DPP is not merely a bureaucratic burden, but rather a powerful internal diagnostic tool when evaluated within the framework of "Sustainable Business Model Archetypes" [8]. Empirical findings obtained from the Turkish textile sector demonstrate that the transition to primary data tracking uncovers hidden production inefficiencies and generates financial savings without requiring additional machinery investments. Ultimately, the Digital Product Passport transforms environmental responsibility from a passive regulatory obligation into an active, profit-oriented business strategy.

## **METHODOLOGY**

This study employs a qualitative research design to examine the operational and strategic impacts of Digital Product Passport (DPP) regulations and primary data mandates on the textile value chain. In accordance with the conference paper format, the research consists of two primary stages: the examination of empirical project outcomes within a theoretical framework, followed by a comprehensive sectoral strategy analysis.

In the first stage, the study utilized a dataset comprising field data and corporate reports from pioneering sustainability-driven firms in the Turkish textile sector. To uphold ethical standards and commercial confidentiality, the researchers coded these actors as: "Large-Scale Integrated Manufacturer," "Technology-Driven Leading Supplier," "Medium/Large Scale Garment Manufacturer," and "Global Fashion Brand." The research compiled projects where firms utilized facility-specific primary data (e.g., sensor, scale, real-time wastewater, and energy meter data) instead of generic secondary data to achieve multimillion-dollar savings without requiring major capital expenditure (CapEx). This list of empirical projects was classified using the "Sustainable Business Model Archetypes" theory introduced by Bocken [8], specifically focusing on the archetypes of "Maximizing Material and Energy Efficiency" and "Creating Value from Waste." This classification aims to theoretically demonstrate that digital traceability is not merely a legal requirement but a design tool for waste-preventing business models.

In the second stage, the project findings from the first phase were synthesized with the structural mandates of the regulation to construct a comprehensive SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis tailored to the textile sector. While the DPP is often treated in the literature as a costly compliance process, this study maps how it effectively remedies "operational blindness" in the light of empirical data. This SWOT analysis identifies the barriers facing the sector—such as ERP integration challenges and the risk of SME exclusion (Weaknesses and Threats)—while objectively synthesizing the "internal diagnostics and operational savings" capabilities (Strengths and Opportunities) observed in the analysed projects.

## **RESULTS**

The empirical findings from the examined textile manufacturers are systematically evaluated through the theoretical framework of the "Sustainable Business Model Archetypes" [8]. By categorizing the field data into specific archetypes, this section demonstrates how the transition from generic secondary data to facility-specific primary data—as mandated by the forthcoming Digital Product Passport (DPP)—functions as a powerful internal diagnostic tool. To maintain commercial confidentiality while ensuring academic integrity, the investigated entities are classified by their supply chain roles.

### **1. Archetype 1: Maximizing Material and Energy Efficiency**

According to "Sustainable Business Model Archetypes" framework [8], this archetype focuses on doing more with fewer resources, thereby generating less waste and emission. The empirical proxies reveal that tracking primary data at the batch level allows manufacturers to identify invisible inefficiencies that are typically masked by industry-average datasets. For instance, a *Large-Scale Integrated Manufacturer* abandoned generic recipe estimations in their indigo and sulfur dyeing processes, opting instead to measure machine-specific water consumption. This data-driven diagnosis broke the "traditional recipe blindness,"

leading to new formulations that reduced water usage by 80% and generated an annual saving of \$6,000,000. In a separate initiative by the same manufacturer, the operational speeds of existing spinning and weaving machines were measured and optimized without any additional machinery investments. This simple parameter adjustment yielded an annual electricity saving of 300,000 kWh [12]. Similarly, a *Technology-Driven Leading Supplier* replaced generic quality control statistics with real-time camera data on their knitting machines. By diagnosing production errors at the source rather than at the end of the line, the facility prevented 33 tons of fabric waste and 3.7 million liters of water waste, resulting in direct savings of \$199,979. Further downstream [13], a *Global Fashion Brand* utilized real-time meter data to track power consumption in its retail stores, moving beyond generic estimates to achieve operational energy savings of up to 3.9 million TL per month [14].

## 2. Archetype 2: Creating Value from Waste and Substituting with Natural Processes

This archetype aims to eliminate the concept of waste by turning existing waste streams into useful inputs and replacing finite or harmful resources with benign alternatives. The transition to granular data collection provides the mathematical foundation necessary to execute these complex circular strategies. A Medium/Large Scale Garment Manufacturer ceased using generic waste percentage calculations and began measuring fabric scrap directly on the factory floor using scales integrated with their ERP system. This precise primary data enabled the company to reclassify 225 tons of cotton scraps from general waste to valuable raw materials, successfully reintegrating them into a closed-loop production cycle [15].

In the realm of substituting harmful chemicals, a Large-Scale Integrated Manufacturer diagnosed its wastewater treatment processes by measuring chemical dosage per meter of fabric. The primary data revealed that 2.91 kg of sulfuric acid could be effectively replaced by just 0.060 kg of environmentally benign carbon dioxide, an intervention that generated \$750,000 in net savings over a six-year period [12]. Additionally, another Integrated Denim Manufacturer measured the exact heat values (150°C) of exhaust gas emitted from stenter machines. By quantifying this previously ignored thermal data, the facility installed a heat recovery system that saved 1.4 million kWh of natural gas annually, amortizing its initial installation cost in just 1.15 years [16]. Finally, a Global Fashion Brand adopted a stewardship role by collecting real-time water and chemical usage data from 176 of its sub-suppliers. This unprecedented level of supply chain visibility allowed the brand to precisely diagnose dyeing requirements, achieving up to a 30% reduction in water consumption [14].

**Table 1.** Empirical Outcomes of Primary Data Utilization within the Framework of Sustainable Business Model Archetypes

| Manufacturer<br>(Coded Name)               | Project / Initiative                                             | Sustainable<br>Business Model<br>Archetype           | Primary Data & Diagnostic<br>Application                                                                                                                                                          | Operational & Financial Gains<br>(Correction Effect)                                                                              | Impact<br>ratio |
|--------------------------------------------|------------------------------------------------------------------|------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|-----------------|
| <b>Large-Scale Integrated Manufacturer</b> | Water-Saving and Sulfur (Slasher)                                | Indigo Maximizing Dyeing Material Energy Efficiency  | Machine-based specific water 80% water reduction at the source; and consumption measurement instead of generating \$6,000,000 in annual net financial savings.                                    |                                                                                                                                   |                 |
| <b>Large-Scale Integrated Manufacturer</b> | CO <sub>2</sub> Usage Wastewater Neutralization                  | for Substituting with Measuring pH Natural Processes | chemical dosage per meter of fabric to diagnose environmental toxicity and cost inefficiencies.                                                                                                   | Replaced 2.91 kg of sulfuric acid with 0.060 kg of environmentally benign CO <sub>2</sub> ; \$750,000 net savings over 6 years.   |                 |
| <b>Large-Scale Integrated Manufacturer</b> | REEMAIN (Resource Maximizing and Energy Efficient Manufacturing) | Maximizing Material Energy Efficiency                | Real-time data optimization of existing and spinning and weaving machine speed achieved without any new machinery investments (Zero CapEx).                                                       | 300,000 kWh annual electricity savings                                                                                            |                 |
| <b>Large-Scale Integrated Manufacturer</b> | VAP Insulation and LED Conversion                                | and Maximizing Material Energy Efficiency            | Measuring specific heat losses of 2,600,000 kWh heat and 58,000 sm <sup>3</sup> and internal steam valves and drying natural gas savings via insulation; plus cylinders alongside lighting loads. | 2,200,000 kWh savings via LED conversion.                                                                                         |                 |
| <b>Technology-Driven Leading Supplier</b>  | Smartex AI-Supported Quality Control System                      | Maximizing Material Energy Efficiency                | Real-time camera and sensor data on and knitting machines for source-based quality control, replacing standard error percentages.                                                                 | Prevented 33 tons of fabric waste and 3.7 million liters of water waste; yielding \$199,979 in direct savings at the source.      |                 |
| <b>Technology-Driven Leading Supplier</b>  | Wastewater Plant Recovery                                        | Adopting Stewardship (Circularity)                   | a Real-time tracking of the hourly and daily water requirements of the dyehouse to design closed-loop processes.                                                                                  | and 65% of the daily dyehouse water requirement met by recovered water (48,366 m <sup>3</sup> recovered during the 45-day pilot). |                 |

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|                                                |                                           |                                             |                                                                                                                                                   |                                                                                                                                                |
|------------------------------------------------|-------------------------------------------|---------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Technology-Driven Leading Supplier</b>      | Raising Machine and Broken Needle Kaizens | Maximizing Material Energy Efficiency       | Analysis of specific machine stoppage and breakdown data integrated with employee feedback.                                                       | Prevented fabric waste and emissions; generated <b>773,914 TL</b> total financial gain in 2023.                                                |
| <b>Medium/Large Scale Garment Manufacturer</b> | Second Life Movement                      | Creating from Waste                         | Value Physical measurement of fabric scraps by color and fabric type via scales and ERP integration, rather than using generic waste assumptions. | <b>225 tons</b> of textile scraps removed from production and successfully reintegrated into closed-loop production as valuable raw materials. |
| <b>Integrated Denim Manufacturer</b>           | Electrostatic System (EFS) and Recovery   | Filter Creating Heat from Waste             | Value Facility-specific measurement of the thermal values of exhaust gas (150°C) emitted from stenter machines.                                   | <b>1.4 million kWh</b> annual natural gas savings; the system amortized its initial investment cost in just 1.15 years.                        |
| <b>Global Brand</b>                            | <b>Fashion</b> Lowscore Program           | Adopting Stewardship Role                   | a Collection of real-time water and chemical usage data from 176 sub-suppliers to overcome supply chain blindness.                                | Diagnosed specific dyeing requirements across the fragmented supply chain, achieving up to a <b>30%</b> reduction in water consumption.        |
| <b>Global Brand</b>                            | <b>Fashion</b> Naturally Cotton & Rpet    | Colored Substituting with Natural Processes | Tracking primary agricultural data for naturally colored (undyed) cotton produced from ancestral seeds.                                           | Eliminated the dyeing process for specific batches, resulting in a <b>30%</b> savings in water footprint.                                      |
| <b>Global Brand</b>                            | <b>Fashion</b> KNX Automation             | Maximizing Material Energy Efficiency       | Real-time energy meter data tracking and from retail stores instead of relying on generic consumption estimates.                                  | Exceeded generic estimates, achieving up to <b>3.9 million TL</b> in monthly operational energy savings.                                       |

### 3. Strategic Evaluation: SWOT Analysis of the Digital Product Passport (DPP)

When the empirical findings are synthesized with the broader regulatory framework of the Ecodesign for Sustainable Products Regulation (ESPR) and recent literature on supply chain traceability, a comprehensive strategic profile of the DPP emerges for the textile sector:

#### Strengths:

**Evidence-Based Transparency & Diagnostic Power:** The DPP effectively neutralizes greenwashing by replacing opaque generic claims with verifiable, batch-level primary data [9]. Beyond external reporting, it functions as a powerful internal diagnostic dashboard that pinpoints invisible resource leakages (e.g., water, energy, chemicals), possessing the empirical potential to increase industry net profit margins by 3 to 7 percent[7].

**Enabling the Circular Economy:** By providing precise, accessible information on fiber composition and chemical usage, the DPP significantly enhances the efficiency of downstream sorting and textile-to-textile recycling operations, acting as the "golden thread" for circularity.

#### Weaknesses:

**High Integration Costs & Low Digitalization:** The transition from secondary to primary data requires substantial initial investments in digital infrastructure, sensors, and complex ERP synchronization. This is particularly challenging in a sector historically characterized by a low level of digitalization and manual processes [10].

**Data Privacy and Confidentiality Concerns:** Manufacturers express severe and valid concerns regarding the mandatory sharing of proprietary dyeing recipes, chemical formulations, and complex subcontractor networks, fearing the loss of intellectual property and competitive advantage [1].

**Supply Chain Complexity:** The highly fragmented nature of the textile supply chain—spanning across multiple global tiers (Tier 1 to 4)—creates structural barriers, such as language differences, varying technological capacities, and a lack of harmonized data standards [11].

#### Opportunities:

**New Circular Business Models:** The standardized data architecture of the DPP will unlock and optimize novel business opportunities, such as "product as a service" models, second-hand marketplaces, repair services, and Extended Producer Responsibility (EPR) take-back schemes [9].



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**First-Mover Advantage:** Early adopters who proactively integrate traceability systems during the current preparatory window can secure a significant competitive edge, improved brand resilience, and premium market positioning among sustainability-conscious consumers and major global retailers [7].

#### Threats:

**Risk of Market Exclusion for SMEs:** The most critical threat is the potential exclusion of Small and Medium-Sized Enterprises (SMEs). SMEs, which constitute more than half of the textile supply chain, may lack the financial capital and technical expertise required to establish primary data collection mechanisms, risking complete exclusion from the European market [1].

**Regulatory Uncertainty:** Although the ESPR is in force, the specific *delegated acts* outlining the exact DPP data requirements for textiles have not yet been published. This regulatory ambiguity causes hesitation among companies regarding early technology investments [4].

**Unfair Competition:** There is a persistent risk of an uneven playing field if products manufactured outside the European Union are not subjected to the same rigorous primary data verification and customs enforcement mechanisms as domestic products [1].

## CONCLUSION

The Digital Product Passport (DPP) is not merely a bureaucratic compliance obligation for the textile industry; it is a strategic internal diagnostic tool that transforms environmental transparency into a proactive, measurable, and profit-oriented business strategy. Long before the DPP was established as a legal mandate by the European Union, pioneering manufacturers in the sector were already utilizing facility-specific primary data to conduct more accurate Life Cycle Assessments (LCA) and unlock significant operational cost savings. With the introduction of the Ecodesign for Sustainable Products Regulation (ESPR), this data-driven approach has captured the attention of the broader industry and evolved into a mainstream standard.

As the mandatory collection of granular, batch-level primary data expands across sub-contractors in the global supply chain, the industry's heightened data awareness will inevitably reveal a multitude of new financial and environmental savings opportunities. Crucially, these data-driven optimizations will no longer be confined to the manufacturing shop-floor. With access to precise and traceable data, the focus of optimization will shift upstream to the initial product design and production planning phases—a vital transition given that up to 80% of a product's entire lifecycle environmental impact is determined during its design phase. [17]

Ultimately, this enforced transparency will eliminate information asymmetry, empowering brands to fully diagnose hidden inefficiencies and risks within their highly fragmented production networks. The impending risk of market exclusion—stemming from reliance on suppliers in distant geographies whose data cannot be accurately measured, tracked, or verified—will force a structural reorganization of the sector. Consequently, it is highly foreseeable that the widespread implementation of the DPP will steer the industry away from opaque supply networks, catalyzing a strategic shift toward more localized (near-shoring), data-transparent, resilient, and sustainable business decisions.

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## CHARACTERIZATION OF RECYCLED COTTON FIBERS OBTAINED FROM KNITTED AND DENIM FABRICS BASED ON AFIS ANALYSIS

Kübra Baykan Özden<sup>1,\*</sup>, Erkan Evran<sup>2</sup>, Beyzagül Payam<sup>3</sup>

<sup>1</sup> Sanko Textile, R&D Center, Gaziantep, Türkiye

\* [kubra.baykan@sanko.com.tr](mailto:kubra.baykan@sanko.com.tr)

### ABSTRACT

Growing environmental sustainability concerns in the textile industry have accelerated the transition toward circular production systems, particularly through mechanical recycling of cotton-based textiles. Although recycled cotton offers significant sustainability advantages, mechanical recycling processes result in fiber degradation, including fiber shortening, increased short fiber content, and nep formation. These structural alterations directly affect spinning performance and final product quality.

This study aims to provide a comprehensive fiber-level characterization of recycled cotton fibers obtained from knitted and denim fabrics, considering both pre-consumer and post-consumer waste streams. Recycled cotton samples were evaluated using the Advanced Fiber Information System (AFIS). Key fiber parameters, including total nep count, number-weighted mean fiber length ( $L(n)$ ), and short fiber content ( $SFC(n)$ ), were statistically analyzed.

The results indicate that post-consumer recycled fibers exhibit significantly shorter mean fiber length and higher short fiber content compared to pre-consumer fibers. Denim-derived fibers exhibit more pronounced degradation characteristics than knit-derived fibers, reflecting the combined effects of fabric structure and end-use history.

The findings are consistent with existing literature on mechanical cotton recycling and confirm that feedstock identity is a critical determinant of recycled fiber quality. This study contributes to the establishment of realistic quality benchmarks for mechanically recycled cotton and facilitates improved industrial quality control strategies.

**Keywords:** *AFIS analysis, mechanical recycling, nep formation, recycled cotton, short fiber content*

### 1. INTRODUCTION

The textile and fashion industry is among the most resource-intensive industrial sectors, generating significant amounts of post-industrial and post-consumer waste [1]. Increasing environmental concerns, regulatory pressures, and sustainability commitments have accelerated the transition toward circular economy models, particularly textile-to-textile recycling systems [2]. In this context, cotton has become a key focus material due to its widespread use and suitability for recovery through mechanical recycling processes. Mechanical recycling is widely adopted because of its technical feasibility, cost-effectiveness, and relatively lower environmental impact compared to chemical recycling methods [3].

Despite these advantages, mechanical recycling introduces critical quality limitations. The repeated opening, tearing, and fiber separation processes lead to substantial fiber damage, including fiber shortening, increased short fiber content, and nep formation [4]. Previous studies have consistently reported that mechanically recycled cotton fibers exhibit inferior fiber characteristics compared to virgin cotton, which directly affects spinning performance, yarn irregularity, and mechanical properties [5,7]. These structural

changes are therefore considered the main limiting factors for the effective utilization of recycled cotton in textile production [8,12].

A major challenge in recycled cotton systems is the variability of feedstock materials. Recycled textiles are generally categorized as pre-consumer (industrial waste generated during production) and post-consumer (used garments collected after consumer use). Pre-consumer wastes are typically more homogeneous and less degraded, whereas post-consumer wastes exhibit higher variability due to wear, laundering cycles, contamination, and finishing treatments [6,9]. As a result, fibers obtained from post-consumer sources tend to exhibit more severe degradation and reduced processability.

In addition to waste origin, fabric structure plays a crucial role in determining recycling behavior. Knitted fabrics, characterized by looped structures and relatively lower yarn twist, may respond differently to mechanical recycling compared to denim fabrics, which have dense woven structures, higher yarn twist, and compact construction [10]. These structural differences influence fiber fragmentation mechanisms and result in distinct fiber degradation patterns. In particular, denim-based wastes have been reported to exhibit more severe fiber breakage due to their structural rigidity and resistance during mechanical processing [16,17].

To evaluate recycled fiber quality, fiber-level characterization techniques are essential. The Advanced Fiber Information System (AFIS) provides detailed measurements of fiber length distribution, short fiber content, and nep count, making it a widely used tool in cotton research and industrial quality control [11]. Recent studies and technical reports emphasize that AFIS parameters, particularly fiber length, short fiber content, and neps, are critical indicators for assessing the processability of mechanically recycled cotton fibers [13,15].

Although numerous studies have investigated recycled cotton performance at yarn and fabric levels, comprehensive fiber-level evaluations that simultaneously consider fabric type and waste origin remain limited. In particular, comparative analysis of recycled fibers derived from knitted and denim fabrics, considering both pre-consumer and post-consumer streams, has not been sufficiently addressed in the literature.

Therefore, this study aims to characterize recycled cotton fibers derived from knitted and denim fabrics using AFIS analysis, to compare pre-consumer and post-consumer waste streams, and to evaluate the obtained results within the framework of existing mechanical recycling literature.

## **2. EXPERIMENTAL STUDY**

Recycled cotton fibers used in this study were obtained from mechanically processed textile wastes. The materials consisted exclusively of 100% cotton fabrics and were categorized into four groups: pre-consumer knitted fabrics, post-consumer knitted fabrics, pre-consumer denim fabrics, and post-consumer denim fabrics. Mechanical recycling was carried out under industrial conditions involving opening and fiber separation stages. No chemical treatment was applied during the recycling process in order to preserve the physical characteristics of the fibers.

Fiber characterization was performed using USTER AFIS Pro 2. The analysis focused on key fiber parameters used to evaluate recycled cotton quality, including total nep count, number-based mean fiber length ( $L(n)$ ), and number-based short fiber content ( $SFC(n)$ ). Each sample was measured five times under controlled laboratory conditions, and the average values obtained from these repeated measurements were used for further evaluation. These parameters provide critical insights into fiber damage, fragmentation behavior, and processability.

For clarity and ease of interpretation, abbreviations were used to represent different recycled fiber groups, as presented in Table 1.

**Table 1.** Abbreviations and descriptions of recycled cotton fiber sample groups

| ABBREVIATION  | DESCRIPTION                  |
|---------------|------------------------------|
| <b>PRE-K</b>  | Pre-consumer knitted fabric  |
| <b>POST-K</b> | Post-consumer knitted fabric |
| <b>PRE-D</b>  | Pre-consumer denim fabric    |
| <b>POST-D</b> | Post-consumer denim fabric   |

### 3. RESULTS

#### 3.1 Descriptive Statistics

Descriptive statistics of AFIS parameters are presented in Table 2. The range-based evaluation reveals clear differences among recycled fiber groups in terms of nep count, fiber length, and short fiber content.

**Table 2.** Range distribution of AFIS parameters for recycled cotton fibers

| GROUP         | NEP RANGE  | L(N) RANGE (MM) | SFC(N) RANGE (%) |
|---------------|------------|-----------------|------------------|
| <b>PRE-K</b>  | 800 – 1385 | 10.0 – 14.0     | 42.5 – 63.0      |
| <b>POST-K</b> | 860 – 1130 | 7.5 – 8.5       | 73.0 – 80.0      |
| <b>PRE-D</b>  | 500 – 685  | 9.5 – 12.5      | 54.0 – 70.5      |
| <b>POST-D</b> | 400 – 465  | 7.0 – 9.0       | 72.0 – 84.5      |

Pre-consumer knitted samples exhibited the widest nep range, indicating higher variability in fiber entanglement. In contrast, post-consumer denim samples showed the lowest nep values, suggesting that different degradation mechanisms dominate depending on fabric structure and recycling conditions.

Fiber length differences between pre-consumer and post-consumer groups were pronounced. Pre-consumer samples exhibited L(n) values approximately 2–4 mm higher than post-consumer samples, indicating lower structural damage prior to recycling. Conversely, post-consumer fibers showed consistently reduced L(n) values due to cumulative effects of wear, laundering, and mechanical processing [6].

Short fiber content increased significantly in post-consumer groups. In particular, post-consumer denim fibers exhibited SFC(n) values exceeding 70%, indicating severe fiber fragmentation. These findings are consistent with previous studies reporting increased short fiber fractions in mechanically recycled cotton materials [4,7].

#### 3.2 Fiber Length and Short Fiber Content

Fiber length reduction is one of the most critical consequences of mechanical recycling. The combined effect of use-phase fatigue and repeated mechanical processing leads to progressive fiber breakage, which is more pronounced in post-consumer materials.

Post-consumer fibers exhibited a narrower and lower L(n) distribution compared to pre-consumer samples, indicating a more uniform but degraded fiber structure. In contrast, pre-consumer fibers retained a wider distribution, reflecting less severe mechanical damage. Figure 1 presents the comparison of mean fiber length values across recycled fiber groups.

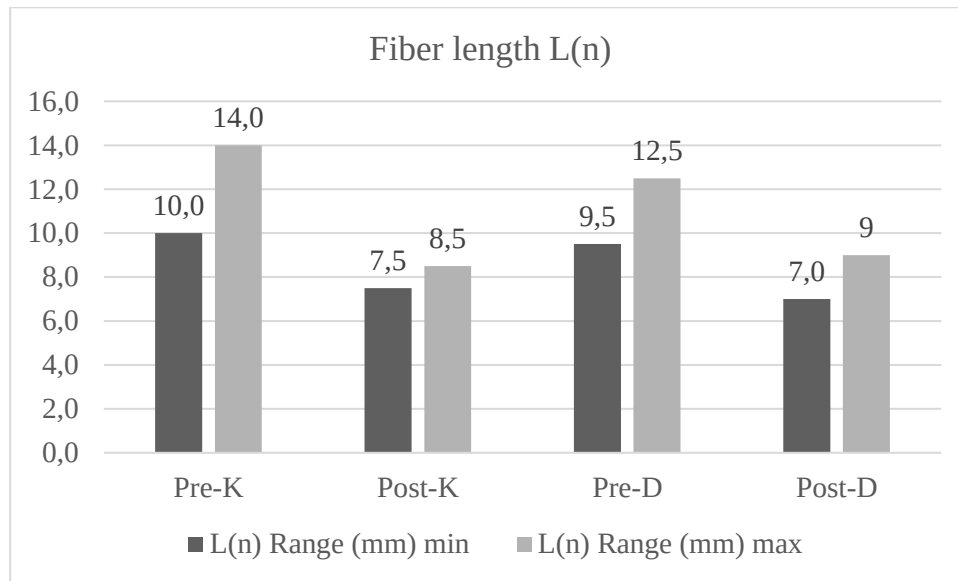


**Figure 1.** Comparison of mean fiber length (L(n)) for recycled cotton fibers

As shown in Figure 1, both post-consumer groups exhibited significantly reduced fiber length values compared to their pre-consumer counterparts.

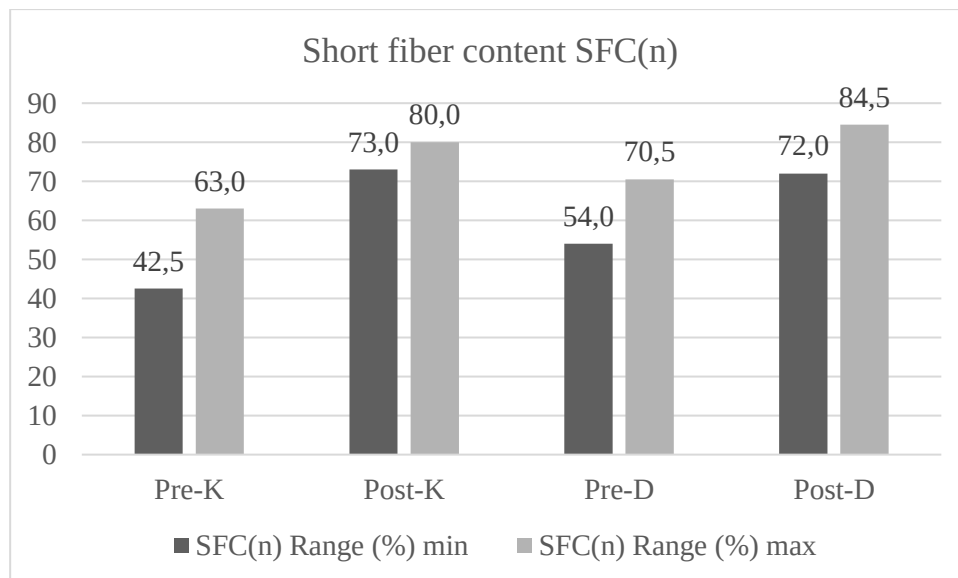


**Figure 2.** Comparison of short fiber content (SFC(n)) for recycled cotton fibers

As illustrated in Figure 2, post-consumer fibers showed an increase in short fiber content of approximately 20–30%.

Post-consumer fibers exhibited a narrow and consistently lower L(n) range compared to pre-consumer samples, indicating a more uniform but degraded fiber structure. In contrast, pre-consumer fibers showed a wider distribution, suggesting less severe and more variable mechanical impact.

Short fiber content results further support this observation. Post-consumer samples, particularly denim-derived fibers, exhibited significantly higher SFC(n) ranges. This can be attributed to the dense fabric structure and higher yarn twist of denim fabrics, which increase resistance during mechanical opening and result in more intensive fiber fragmentation.

The elevated short fiber content observed in these groups is critically important, as SFC(n) is widely recognized as a primary factor limiting the spinnability and processing performance of recycled cotton

fibers [7,8]. These changes are expected to negatively influence spinning performance by reducing drafting stability, increasing yarn unevenness, and decreasing tensile strength.

### 3.3 Nep Formation and Overall Evaluation

Nep formation exhibited a strong dependency on both fabric structure and waste origin. Mechanical recycling processes promote fiber entanglement and cluster formation, particularly under repeated mechanical stress conditions [5].

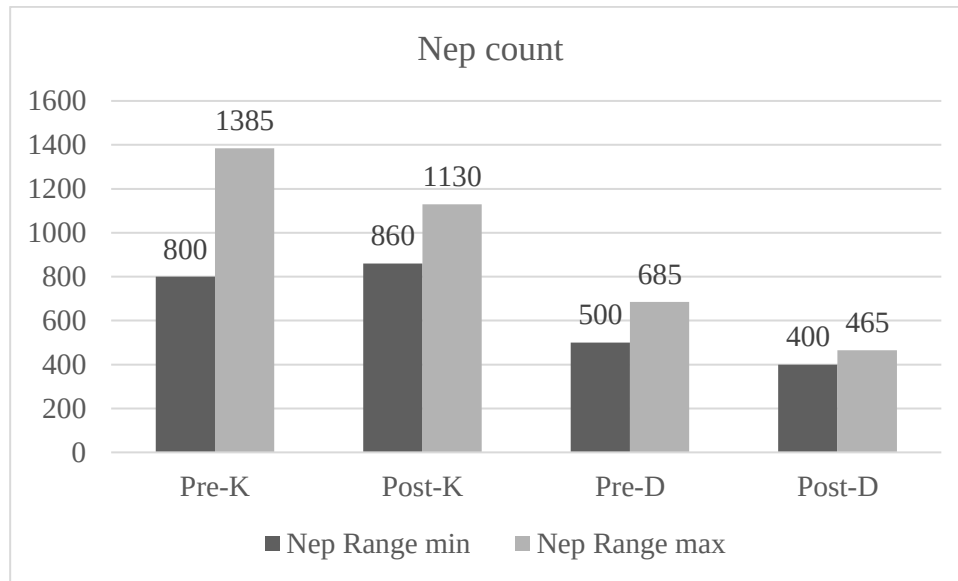


**Figure 3.** Distribution of nep count across recycled fiber groups

Interestingly, although denim-derived samples exhibited relatively lower nep values compared to knitted samples, they demonstrated more severe fiber shortening and higher short fiber content. This indicates that different degradation mechanisms are dominant depending on fabric structure. While knitted fabrics tend to generate higher nep levels due to their looped structure and fiber mobility, denim fabrics exhibit more intensive fiber breakage due to their compact woven structure [10].

Overall, the results clearly demonstrate that recycled cotton fibers cannot be treated as a uniform raw material. Instead, their properties are strongly influenced by both waste origin and fabric type. Post-consumer streams exhibited more severe degradation, supporting previous findings that highlight reduced processability and spinnability of post-consumer cotton recyclates [6,9].

Short fiber content emerges as the most critical parameter governing recycled fiber performance. The high SFC(n) ranges observed in this study suggest that blending strategies, process optimization, or controlled recycling conditions may be required to ensure stable spinning performance.

The combined evaluation of nep count, fiber length, and short fiber content provides a comprehensive understanding of fiber degradation mechanisms. Therefore, AFIS-based multi-parameter analysis is recommended as a reliable and practical approach for industrial monitoring and quality control of recycled cotton fibers [11].

To provide a clearer comparison of degradation behavior, a qualitative classification of fiber properties is presented in Table 3.



**Table 3.** Relative degradation severity of recycled cotton fibers

| GROUP  | FIBER LENGTH | SFC(N)      | NEP LEVEL | OVERALL DEGRADATION |
|--------|--------------|-------------|-----------|---------------------|
| PRE-K  | High         | Medium      | High      | Medium              |
| POST-K | Low          | High        | Medium    | High                |
| PRE-D  | Medium       | Medium–High | Low       | Medium              |
| POST-D | Low          | Very High   | Low       | Very High           |

#### 4. CONCLUSION

This study presented a detailed characterization of recycled cotton fibers obtained from knitted and denim fabrics using AFIS analysis, considering both pre-consumer and post-consumer waste streams. The results demonstrate that fiber properties are strongly influenced by both fabric structure and usage history. Pre-consumer fibers exhibited higher fiber length and lower short fiber content compared to post-consumer fibers, indicating lower structural damage prior to recycling. In contrast, post-consumer fibers showed reduced L(n) values and elevated SFC(n) levels, reflecting cumulative degradation caused by wear, laundering, and repeated mechanical processing.

Clear differences were also observed between knitted and denim-derived fibers. Knitted fabrics showed higher nep variability, whereas denim-derived fibers exhibited more severe fiber fragmentation, resulting in shorter fiber length and higher short fiber content. These findings confirm that different degradation mechanisms dominate depending on fabric structure. Among the evaluated parameters, short fiber content was identified as the most critical factor affecting recycled fiber quality and processability. High SFC(n) levels, particularly in post-consumer groups, are expected to negatively influence spinning performance by reducing drafting stability and increasing yarn irregularity.

Overall, the results indicate that recycled cotton cannot be treated as a homogeneous raw material and must be evaluated based on feedstock origin and fabric type. AFIS-based multi-parameter analysis provides a practical and reliable approach for industrial monitoring and quality assessment of recycled cotton fibers. Future studies should focus on defining threshold values for acceptable fiber quality and establishing direct correlations between AFIS parameters and yarn performance in recycled fiber systems.

This study contributes to bridging the gap between academic research and industrial applications in recycled fiber characterization.

#### ACKNOWLEDGMENT

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## COMPARATIVE MICROSTRUCTURAL ANALYSIS OF LYOCELL FILAMENTS ACROSS DIFFERENT PROCESSING STAGES

Merve Bulut<sup>1,\*</sup>, Merve Küçükali Öztürk<sup>2</sup>

<sup>1</sup> Istanbul Technical University, Department of Textile Engineering, Istanbul, Türkiye

<sup>2</sup> Istanbul Bilgi University, Department of Textile and Fashion Design, Istanbul, Türkiye

\* [merve.bulut@itu.edu.tr](mailto:merve.bulut@itu.edu.tr)

### ABSTRACT

Lyocell fibers are widely used in textile applications due to their uniform morphology and semi-crystalline polymer structure. However, structural variations may occur during their transformation into future forms, and these variations may depend on the intrinsic properties of the raw material. This study investigates the microstructural characteristics of two different lyocell materials across different states, with a focus on filament morphology and crystallinity.

Two lyocell knitted fabrics were analyzed in their untreated fabric and dyed fabric forms. Filaments were extracted and analyzed using scanning electron microscopy (SEM) at 1000×, 2500×, and 5000× magnifications to evaluate cross-sectional morphology. Filament diameters were measured from high-magnification images to quantify dimensional consistency. Crystalline structure was investigated using X-ray diffraction (XRD) to determine crystallinity levels in each state. The comparison focused on identifying structural variation between materials and across textile forms.

SEM observations confirmed that both lyocell materials preserved their characteristic circular cross-sections across textile states, with minor variations in surface definition and diameter distribution. Diameter measurements indicated that one group showed slightly finer and more uniform fibers (~9.7–10.2 µm), while the other exhibited larger and more variable diameters (~10.2–12.1 µm). Differences between the two lyocell groups were more pronounced than differences between textile states, suggesting material-dependent structural behavior. XRD results revealed that crystallinity varied among both materials and textile states. While filament samples exhibited similar crystallinity values (32% and 33.6%), different trends were observed after textile processing. One fabric group showed a decrease in crystallinity (26.9%), whereas the other exhibited the highest crystallinity (34.3%), indicating a material-dependent structural response to textile conversion.

The combined SEM–XRD analysis demonstrates that filament microstructure remains largely stable during textile conversion, while crystallinity variations reflect intrinsic material differences. The findings highlight the importance of raw material selection in determining structural behavior of lyocell-based textiles. The results contribute to a deeper understanding of structure–processing relationships in filament-based fabrics and offer insight for optimizing finishing treatments to maintain structural integrity.

**Keywords:** *crystallinity, fiber morphology, filament microstructure, Lyocell fibers*

### 1. INTRODUCTION

The global textile industry is currently navigating a significant strategic transition toward sustainable man-made cellulosic fibers. Lyocell technology emerged as the definitive response to this supply deficit and the inherent environmental liabilities of the traditional viscose process. Lyocell fibers are regenerated cellulose fibers widely used in textile applications due to their uniform morphology, relatively high crystallinity, and environmentally sustainable production process. It also provides the thermo-physiological comfort and

biodegradability of natural fibers alongside the high resistance, low contraction, and technical durability typically belonging to synthetic chemical fibers. This unique position makes Lyocell indispensable for modern applications, transitioning from high-fashion apparel to industrial technical textiles. Their semi-crystalline structure plays a key role in determining their mechanical and physical performance [1]. For this reason, understanding the relationship between fiber structure and textile processing is essential for optimizing material performance.

During the conversion of filaments into textile forms such as knitted and dyed fabrics, structural changes may occur at both the morphological and molecular levels. Previous studies have shown that crystallinity variations can significantly influence the behavior of cellulose-based fibers; however, these changes are not always consistent and may depend on the intrinsic properties of the raw material [2,3].

In this context, the present study aims to comparatively investigate the microstructural characteristics of two different lyocell materials, focusing on both filament morphology and crystallinity. The aim is to determine whether observed structural variations are primarily driven by processing conditions or by intrinsic material characteristics.

## 2. EXPERIMENTAL STUDY

Two different lyocell materials manufactured from different raw materials were investigated. Each material was analyzed in raw knitted fabric and dyed knitted fabric. Sample codes and explanations are given below at Table 1.

Filament samples were examined using scanning electron microscopy (SEM) at magnifications of 1000×, 2500×, and 5000×. All samples were coated with an Au/Pd layer prior to imaging. Cross-sectional images were used to evaluate fiber morphology and to measure filament diameters. X-ray diffraction (XRD) analysis was conducted to determine the crystallinity and amorphous content of all samples. Measurements were performed in the range of  $2\theta = 5-75^\circ$  with a Bruker AXS D8 Advance diffractometer (42 kV, 30 mA, CuK $\alpha$  radiation, 1.540 Å).

**Table 1.** Sample codes.

| SAMPLE CODE | EXPLANATION             |
|-------------|-------------------------|
| U-1         | Untreated – Type 1      |
| U-2         | Untreated – Type 2      |
| D-1         | Treated & Dyed – Type 1 |
| D-2         | Treated & Dyed – Type 2 |

## 3. RESULTS

Crystallinity and amorphous ratios obtained from the XRD analysis is given at Table 2 below.

**Table 2.** XRD results.

|     | CRYSTAL (%) | AMORPHOUS (%) |
|-----|-------------|---------------|
| U-1 | 32          | 68            |
| U-2 | 33,6        | 66,4          |
| D-1 | 26,9        | 73,1          |
| D-2 | 34,3        | 65,1          |

XRD analysis revealed that the crystallinity values of the samples varied within a relatively narrow but meaningful range, indicating differences in molecular ordering among the lyocell groups and textile states. While U-1 and U-2 exhibited similar crystallinity values of 32% and 33.6%, respectively, the transition to treated and dyed fabric form resulted in different structural responses. D-1 showed the lowest crystallinity (26.9%) and the highest amorphous fraction (73.1%), suggesting a reduction in ordered regions. In contrast,

D-2 exhibited the highest crystallinity value (34.3%), indicating a comparatively more preserved or enhanced structural order.

XRD diffractograms are also given below at Figure 1. To better evaluate the effect of textile processing, XRD patterns were compared within each material group by pairing untreated and dyed samples. Additionally, comparisons between the two material groups were performed to provide a secondary insight.

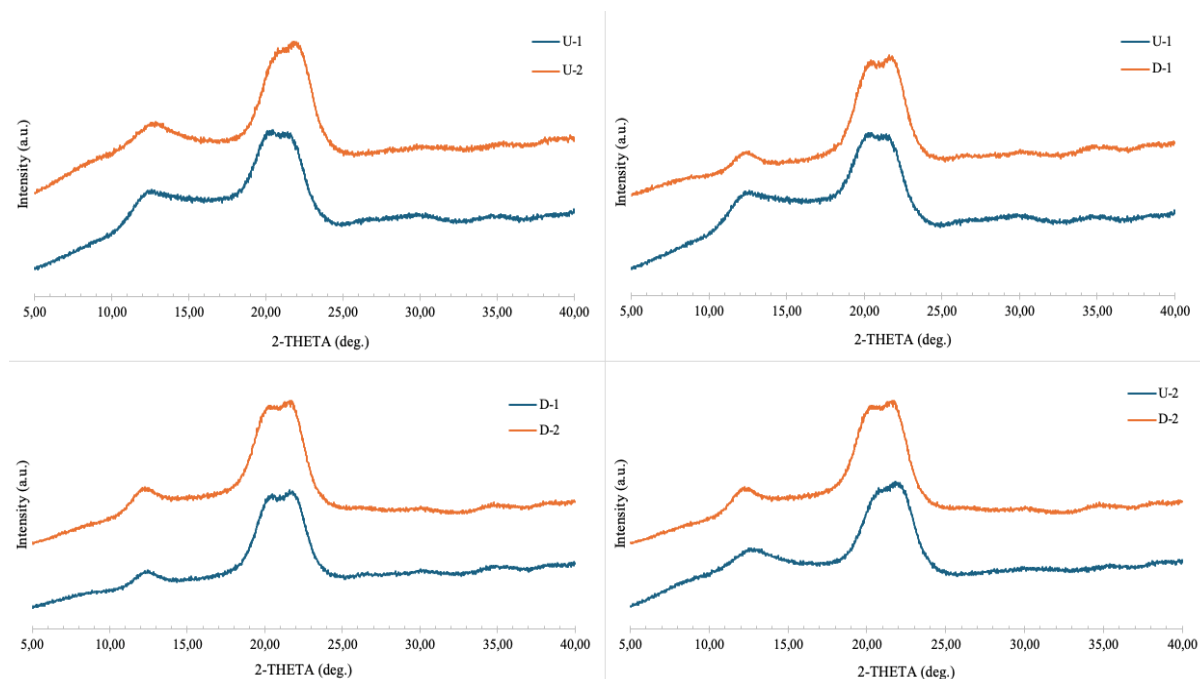


**Figure 1.** XRD Diffractograms.

The XRD diffractograms of all samples show the same general regenerated-cellulose pattern, with the main reflections concentrated roughly around 12–13° and 20–22° (2 $\theta$ ). In the lyocell/regenerated-cellulose literature, those peaks are commonly associated with a cellulose II structure, which is exactly what would be expected for lyocell rather than native cellulose I. Reported lyocell/cellulose II reflections are typically found near 12°, 20–20.6°, and about 21.4°–22° [4]. In the graphs, the cellulose II signature appears to be retained in all samples, thus it can be commented that the main structural change is in the relative degree of order/disorder. The variation in peak intensity and sharpness indicates differences in the degree of molecular ordering among the samples. This also correlates with the crystallinity results given in Table 2. The lower peak intensity observed in D-1 is consistent with its reduced crystallinity, while the sharper and more pronounced peaks in D-2 indicate a higher degree of crystalline order.

The decrease in crystallinity, particularly in the D-1 sample, indicates that this group exhibits a more sensitive structural response to knitting and/or post-dyeing processes. In contrast, the fact that the D-2 sample has the highest crystallinity value at 34.3% suggests that the second lyocell group better retains its crystalline order after being converted into textile form or develops a more regular molecular organization after processing. These findings suggest that the structural evolution of lyocell during textile conversion is both raw material-dependent and treatment-dependent rather than uniform for all groups. This finding is consistent with prior studies showing that regenerated cellulose fibers may undergo crystallinity changes without losing the cellulose II character, depending on treatment conditions, raw-material source, and physical form [5].

SEM images obtained from the extracted lyocell filaments (pulp state) from samples U-1 and U-2 are presented in Figure 2.

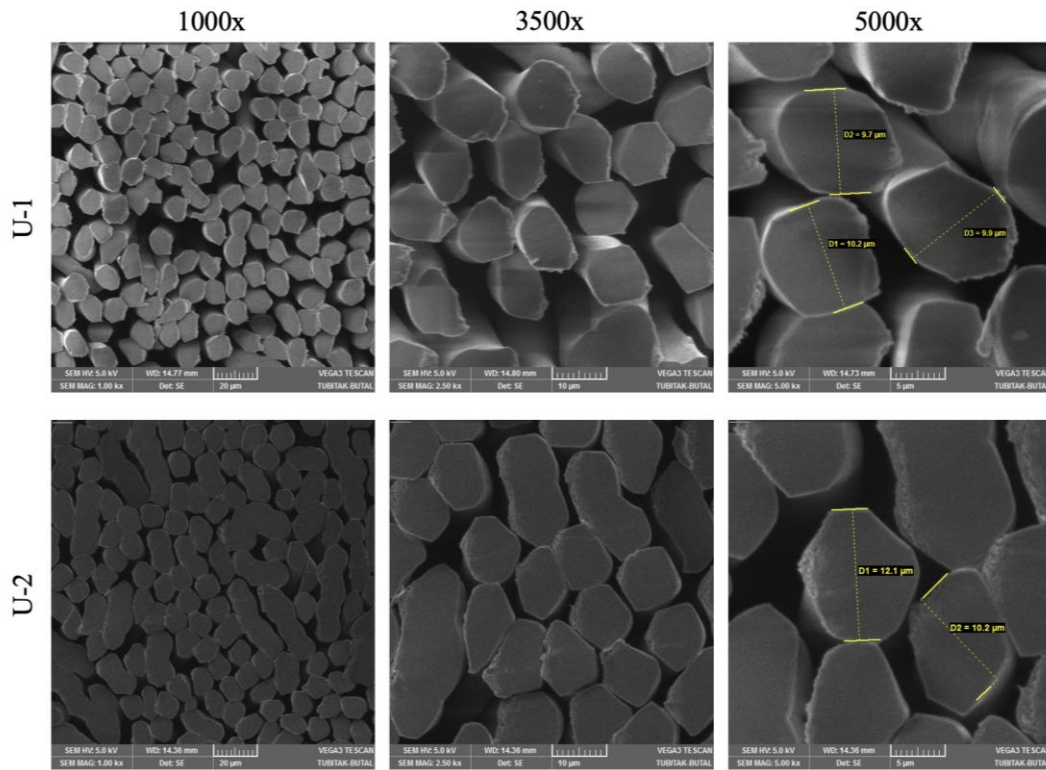


**Figure 2.** SEM images of lyocell filaments in pulp form.

SEM observations of the raw lyocell filaments showed generally regular and compact cross-sectional geometries, with no severe deformation or collapse. Diameter measurements further indicated that U-1 fibers were slightly finer and more uniform, with measured values around 9.7–10.2  $\mu\text{m}$  (with an average of 9.93  $\mu\text{m}$ ), whereas U-2 fibers showed a somewhat larger diameter range of 10.2–12.1  $\mu\text{m}$  (with an average of 11.15  $\mu\text{m}$ ). Accordingly, U-2 fibers can be characterized as slightly coarser with a broader diameter distribution compared to U-1. Although the morphological differences were limited, the slightly coarser and more heterogeneous structure of U-2 suggests that the two lyocell groups possess distinct initial filament characteristics, primarily governed by raw material properties.. Since the SEM analysis was performed on filaments extracted from the fabric in their pulp-like state, the results reflect the intrinsic filament morphology rather than fabric-level structural effects. When considered together with the XRD findings, the SEM results support the notion that the observed structural differences between the samples are predominantly influenced by inherent material characteristics rather than solely by textile processing.

#### 4. CONCLUSION

This study has studied two types of Lyocell materials in their untreated fabric and treated & dyed fabric states. Overall, the combined SEM and XRD findings indicate that the filament cross-sectional morphology of lyocell filaments remains stable during textile processing, whereas the crystallinity values show more pronounced variation among the samples depending on both material type and processing stage. The diffractograms revealed that all samples preserved the characteristic cellulose II pattern of lyocell, with the main reflections remaining in the expected  $2\theta$  regions reported for regenerated cellulose. However, variations in peak intensity and sharpness were observed among the samples, indicating differences in crystalline order rather than a change in crystal structure. The results highlight that structural changes in lyocell-based textiles are not solely process-driven but are strongly influenced by the intrinsic properties of the raw material. SEM observations performed on filaments extracted in their pulp-like state further support that the observed morphological characteristics reflect intrinsic filament properties rather than fabric-level effects. This suggests that internal molecular organization is more sensitive than apparent filament geometry in distinguishing structural differences between lyocell groups and textile states. Consequently, crystallinity emerges as a more discriminating parameter compared to morphological features. Overall, the study provides valuable insight for optimizing material selection and processing conditions in lyocell-based textile applications.



Future work could expand this study by incorporating detailed analysis of fabric-level morphology and evaluating the influence of processing parameters such as knitting and dyeing conditions. Furthermore, correlating crystallinity changes with mechanical or functional properties would provide deeper insight into structure–property relationships in lyocell-based materials.

#### **ACKNOWLEDGMENT**

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# CONCEPTUAL COSTUME DESIGN FOR CONTEMPORARY FESTIVALS: AN INNOVATIVE APPROACH TO LIGHTING TECHNOLOGIES, 3D PRINTING, AND ORNAMENTATION TECHNIQUES

Parinaz Mehri Kahnemouei<sup>1\*</sup>, Ayben Pakolpakçıl<sup>2</sup>

<sup>1</sup> Istanbul Nişantaşı University, Institute of Graduate Education, Istanbul, Türkiye

<sup>2</sup> Istanbul Nişantaşı University, Faculty of Art and Design, Istanbul, Türkiye

\* parinaz.mehri.ka@gmail.com

## ABSTRACT

This study presents application-based research examining the impact of digital technologies on contemporary fashion design within the context of conceptual costume design. Specifically, the integration of wearable technologies, 3D printing, and digital production methods transform clothing from passive objects into active and interactive systems. The research employs an application-based methodology, employing an iterative design process encompassing concept development, sketching, digital modeling, material experimentation, prototyping, and final production. Transparent textiles such as tulle and organza are combined with metal structures and 3D-printed components to emphasize the contrast between fragility and strength. The integration of LED and fiber optic systems adds a dynamic and performative dimension to the garments. The results are presented through a collection of five looks representing the transformation of the female body from oppression to liberation. The first two looks represent fear, silence, and restraint, while the third looks question trauma and exposure. The fourth aspect represents resistance and rebirth, while the final aspect signifies cosmic freedom and the transcendence of boundaries. The study demonstrates how technological innovations can integrate with traditional craftsmanship to create multisensory, interactive, and narrative-oriented clothing systems. In this respect, the research offers an interdisciplinary contribution at the intersection of fashion, technology, and cultural discourse. Alongside the conceptual and aesthetic framework, the produced prototypes were also evaluated in terms of structural stability, wearability, ergonomic comfort, and the integration of lighting systems. These evaluations helped assess the practical performance and usability of the garments.

**Keywords:** *conceptual costume design, 3D printing, lighting systems, interactive fashion, festival performance*

## 1. INTRODUCTION

The rapid development of digital technologies has significantly transformed contemporary fashion design, enabling new forms of interaction between the body, garment, and environment. In particular, the integration of wearable technologies and digital fabrication methods has shifted garments from passive objects to active, responsive systems [1].

Within this evolving context, conceptual costume design has emerged as a critical field where fashion intersects with performance, technology, and cultural discourse. As Roland Barthes argues, fashion operates as a system of signs through which social meanings are constructed and communicated [2]. This semiotic perspective allows garments to function as narrative media rather than merely aesthetic forms.

Furthermore, feminist theory provides a crucial framework for understanding the body as a site of cultural inscription. Judith Butler's concept of performativity emphasizes that identity is not fixed but continuously

produced through repeated acts [3]. In fashion design, this suggests that garments can actively participate in the construction and transformation of identity.

In parallel, technological developments have introduced new possibilities for material and structural innovation. 3D printing enables designers to produce complex geometries and customized forms that extend beyond traditional textile techniques [4]. Similarly, wearable lighting technologies allow garments to interact dynamically with their surroundings, enhancing their performative and experiential qualities [5].

This study investigates how these technological and theoretical frameworks can be integrated into conceptual costume design. Through a five-look collection, the research explores the transformation of the female body from oppression to empowerment, using fashion as a medium for narrative expression and socio-cultural critique.

## **2. EXPERIMENTAL STUDY**

### **2.1 Design Methodology**

This study adopts an application-based research approach that integrates the theoretical framework with creative production. The design process is a multi-layered and iterative structure including concept development, visual research, sketching, digital modeling, material selection, prototyping, and final garment production. Each stage has been systematically evaluated and optimized according to both aesthetic and technical performance criteria. This approach addresses the interaction between conceptual design decisions and materials and production techniques in a holistic manner [6, 7].

### **2.2. Materials and Technologies**

Textile materials used in garment production were selected from synthetic fabrics such as tulle and organza to provide lightness, translucency, and layered visual depth. Metal components and polymer-based 3D-printed elements were used together to create structural integrity and conceptual contrast [4].

The structural components were developed via three-dimensional digital modeling prior to fabrication, as shown in Figure 1a. Polylactic acid (PLA) filament was used due to its low processing temperature, dimensional stability, and surface quality. Fabrication was performed using a desktop FDM-type Anycubic 3D printer (Figure 1b).

Printing parameters were experimentally optimized based on geometric complexity and mechanical requirements. Layer height was set to 0.1–0.2 mm, infill to 15–40%, and printing speed to 40–60 mm/s. The nozzle temperature was maintained at 190–210°C for PLA, while the print bed was kept at 50–60°C to enhance adhesion.

For lighting integration, LedNeon LED systems were used, providing flexible, low-energy consumption and homogeneous light distribution. The electronic system's energy needs were met by a CPH brand 12V, 3.2Ah lithium-ion battery. The LED systems, integrated into the garment structure, both enhanced the visual impact and offered a performative and interactive experience [5].

### **2.3. Garment Development and Techniques**

The garments were constructed using a hybrid approach that combines traditional tailoring with experimental techniques (Figure 1c and 1d). Draping, layering, and sculptural construction were employed to create complex silhouettes. Digital ornamentation methods, such as 3D pen applications and printed elements, were incorporated to reinforce the conceptual themes. This hybridization of manual and digital techniques reflects current trends in fashion innovation [8].

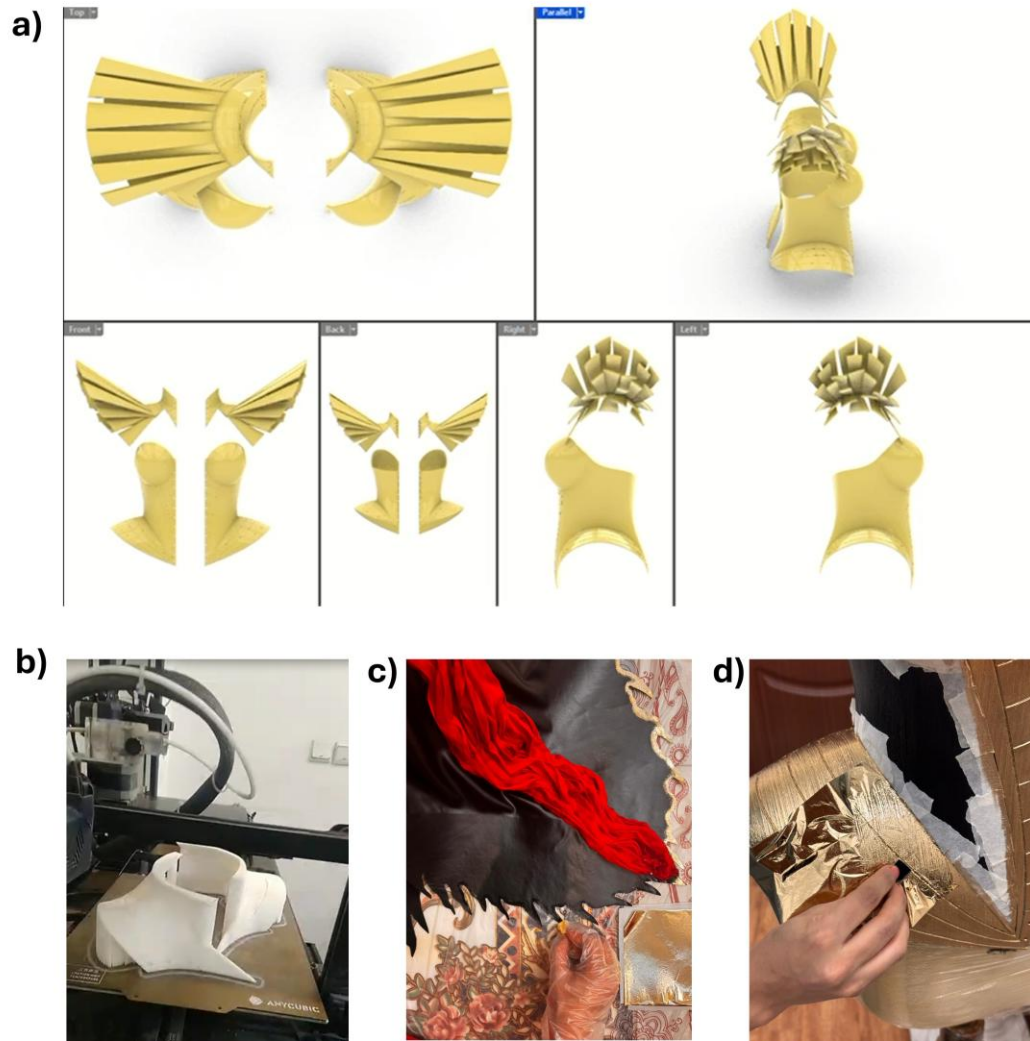


**Figure 1.** The design, fabrication, and material integration process of the conceptual costume components is illustrated. **(a)** presents the digital modeling and multi-view visualization of the 3D printed structural elements, highlighting their geometric configuration. **(b)** shows the fabrication of PLA-based components using FDM 3D printing. **(c)** demonstrates the application of textile materials and surface detailing during the garment assembly process. **(d)** illustrates the integration of metallic surface elements and the final finishing procedures, emphasizing the transition from digital design to a fully realized, material-based wearable structure.

#### 2.4. Prototype Evaluation

The produced costume prototypes were examined in terms of wearability, structural stability, ergonomic comfort, and the integration of lighting systems. Observations were carried out during fitting sessions and movement-based performances. Attention was particularly given to the behavior of the 3D-printed connections, the flexibility of illuminated components, weight distribution, and the relationship between rigid and soft materials. These observations provided a better understanding of how the proposed designs functioned in practice.

### 3. RESULTS and DISCUSSION

The findings of this study were evaluated through a collection of five consecutive appearances representing a conceptual transformation process. The results show that design is not only an aesthetic production but also a multidimensional means of expression where socio-cultural, theoretical and technological layers are combined. In particular, the integration of digital production techniques and wearable technologies enables clothing to transform from passive objects into active and narrative-oriented systems [1,5].

**Look 1 – Fear, Silence, and Constraint:** This look represents the initial stage of oppression, where the body is enclosed within restrictive forms (Figure 2a). Dark color palettes and layered structures symbolize invisibility and suppression. Such representations align with feminist critiques of how social norms regulate and control the female body [9].

**Look 2 – Captivity and Limitation:** The second look introduces cage-like structures that physically and symbolically confine the body (Figure 2b). This reflects the concept of disciplinary power described by Michel Foucault, where the body becomes an object of control within social systems [10]. In this respect, the design embodies a theoretical concept through structural form.

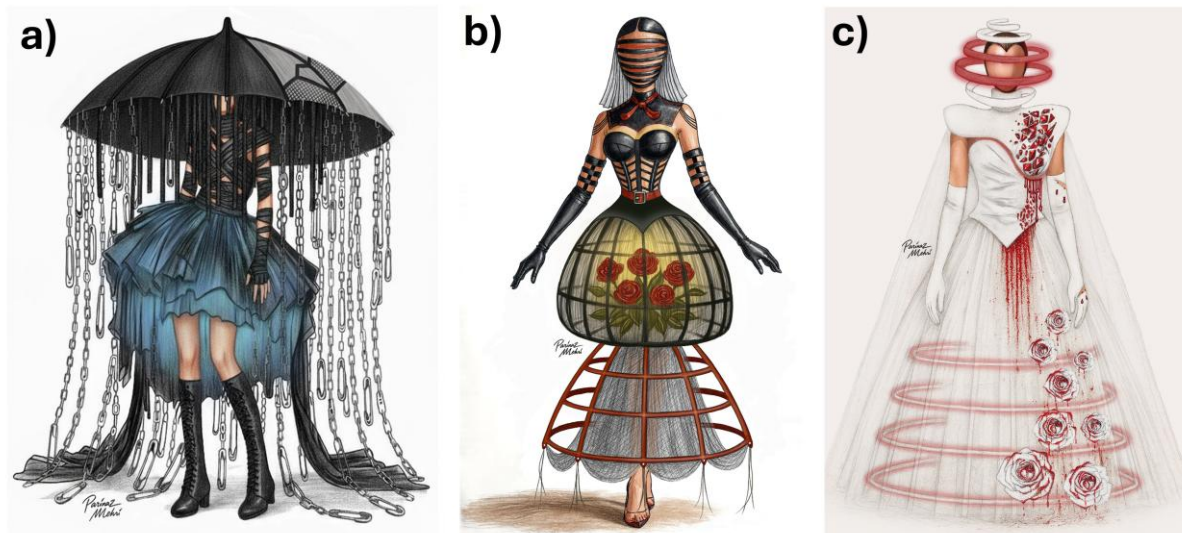


**Figure 2.** Conceptual design development illustrates the narrative progression of the collection. **(a)** represents the initial stage of fear, silence, and restriction through layered dark textiles, enclosing forms, and the use of chain elements symbolizing physical and psychological constraint. **(b)** visualizes confinement and controlled agency via structured corsetry and cage-like skirt forms, emphasizing tension between restriction and movement. **(c)** reflects trauma and exposure through a reinterpretation of the traditional bridal silhouette, incorporating symbolic surface elements and fluid red accents to convey emotional rupture and transformation.

**Look 3 – Trauma and Exposure:** This look reinterprets the traditional bridal garment as a site of symbolic violence. By subverting established meanings, the design reveals hidden structures of inequality. Pierre Bourdieu defines symbolic violence as the internalization of social hierarchies that appear natural but reinforce domination [9]. Thus, clothing is positioned as a narrative surface that makes visible invisible power relations. The conceptual design development presented in Figure 2c clearly demonstrates how these three stages were visually and structurally conceived. Throughout the design process, the relationship between form, material, and symbolic meaning was systematically developed.



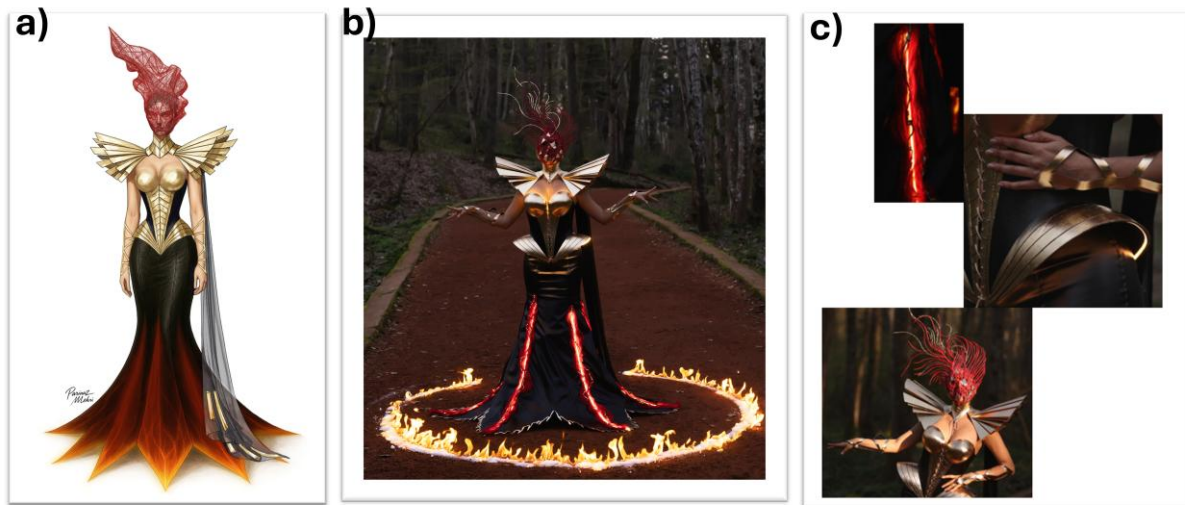


**Figure 3.** Conceptual development, final realization, and detail analysis of the costume representing resistance and rebirth. **(a)** presents the initial design illustration highlighting the symbolic use of flame-inspired forms and structural elements. **(b)** shows the fully realized garment worn in a performative context, emphasizing the integration of illuminated elements and the embodiment of transformation. **(c)** provides detailed views of material applications, including illuminated textile channels and metallic structural components, demonstrating the interaction between digital fabrication, wearable technology, and surface design.

**Look 4 – Resistance, Power, and Rebirth:** Inspired by the Phoenix mythology, this look represents transformation and empowerment. The use of metallic materials, structured silhouettes, and integrated lighting systems convey strength and renewal. This demonstrates that technology has become not only a supporting tool but also a meaning-producing component in fashion design. As Sabine Seymour states, wearable technologies transform garments into dynamic systems that can interact with the environment [5]. The results shown in Figure 3 reveal that digital production, material selection, and electronic integration work together to create a powerful narrative.

**Look 5 – Liberation and Cosmic Unity:** The final look represents transcendence and freedom through fluid forms and luminous materials. The dissolution of rigid structures reflects a shift from constraint to openness. This approach can be associated with Donna Haraway's posthumanist perspective, where the body is considered not as a human-centered structure, but as an entity integrated with technology, the environment, and other systems [11]. The results presented in Figure 4 demonstrate how this integration occurs at both the aesthetic and technological levels.

Beyond their conceptual and visual aspects, the garments were evaluated during fitting and movement-based use. The integrated LED systems and 3D-printed elements functioned consistently throughout the performance simulations. It was also observed that the combined use of flexible textiles and rigid structural components allowed movement while maintaining the intended silhouette of the garments

#### 4. CONCLUSION

This study demonstrates that the integration of digital technologies and conceptual design methodologies can significantly expand the expressive potential of fashion. By combining 3D printing, wearable lighting, and traditional craftsmanship, garments can function as interactive and narrative systems.

The five-look collection illustrates a transformation from oppression to empowerment, highlighting the role of fashion as a medium for cultural critique and emotional storytelling. The findings suggest that technologically enhanced garments can engage audiences on multiple sensory levels while maintaining strong conceptual foundations. The study demonstrates that theoretical frameworks (semiotics, feminist, and posthumanist approaches) can be effectively integrated into design practice, enabling garments to



develop a narrative language and engage viewers through multi-sensory communication. Future research may explore the development of more responsive systems and the application of such designs in broader performance and exhibition contexts.



**Figure 4.** Design realization and interactive material performance of the garment. **(a)** presents the initial conceptual illustration, highlighting the sculptural form and integration of layered textile structures. **(b)** shows the realized garment in a performative context, demonstrating fit, movement, and overall aesthetic translation from design to physical form. **(c)** provides detailed views of material applications and embedded lighting systems, emphasizing the integration of 3D printed elements, metallic surfaces, and LED-based illumination to create a dynamic and interactive visual effect.

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## CONSUMER BEHAVIOR TOWARDS AUGMENTED REALITY APPLICATIONS IN PRODUCT TRIALS AND SHOPPING

Canan Saricam<sup>1\*</sup>, Enes Tatli<sup>1</sup>, Nazan Okur<sup>1</sup>, Sinem Birsen<sup>1</sup>,

<sup>1</sup> Istanbul Technical University, Department of Textile Engineering, Istanbul, Turkey

\* saricamc@itu.edu.tr

### ABSTRACT

The rapid development and implementation of augmented reality (AR) technologies, which integrates the physical environment with virtual content, have attracted considerable interest within the retail sector due to their potential to enhance consumer experience and decision-making processes. Despite increasing improvement of AR applications, limited research has focused on consumer perceptions, experiential responses, and motivational drivers. The primary objective of this study is to investigate and evaluate the attitudes of consumers in their engagement with AR applications. For this purpose, a qualitative methodology, two focus group sessions were conducted to assess participants' levels of familiarity with AR, their cognitive and affective responses to AR interactions, and their intentions regarding future use. In the first focus group, participants' knowledge, perceptions, and attitudes regarding AR technology were examined. Participants were purposively selected to include individuals both with and without prior experience using AR applications. In the second focus group, participants were asked questions concerning their experience after using an AR application. The findings of the study revealed that participants generally hold positive attitudes towards AR applications and describe AR applications as useful, entertaining, and informative, and therefore they have a high intention to use such applications in the future even though some limitations in responsiveness were noted. Nevertheless, it was observed that the participants still exhibited a preference for traditional applications, attributable both to habitual use and to skepticism about getting inaccurate responses. The results contribute to a deeper understanding of consumer engagement with AR retail applications and highlight implications for retailers seeking to leverage AR to enhance shopping experiences.

**Keywords:** *Consumer Behavior, Augmented Reality, Product Trial, Retail Industry*

### 1. INTRODUCTION

With the rapid advancement of digital technologies, augmented reality (AR) applications have become increasingly integrated into various domains of everyday life. Augmented reality can be conceptualized as the practice of augmenting a real-time, direct, or indirect view of the physical world with virtual information [1]. Contemporary AR technologies are employed across a diverse array of sectors, including education, gaming, retail, tourism, and healthcare, where they serve distinct functional and experiential purposes[2]. In the retail context, for example, AR facilitates consumers' decision-making processes by enabling virtual product trials—such as visualizing furniture in a home environment or trying on clothing and cosmetics through interactive interfaces—which can lead to more informed and confident purchase behaviors[3]. As the use of augmented reality applications spreads rapidly, consumer attitudes and reactions are also becoming worthy of investigation. Consumer attitudes toward AR are recognized as a critical determinant of both adoption and continued use, influencing not only individual engagement but also broader patterns of market diffusion and technological acceptance. Accordingly, a systematic evaluation of consumer perceptions, expectations, and motivations can yield valuable insights for both researchers and industry practitioners seeking to optimize AR implementation strategies. The primary aim of the present study is to examine and evaluate consumer attitudes toward augmented reality applications. To achieve this objective, consumers' levels of knowledge, perceptions, and expectations regarding augmented reality technology, as

well as the consumers' thought and beliefs in relation to the performance characteristics of the technology after experiencing with these applications have been investigated. The data obtained will be subjected to statistical analysis and interpreted within the context of relevant industry applications to provide comprehensive insights into consumer engagement with augmented reality.

## **2. METHODOLOGY**

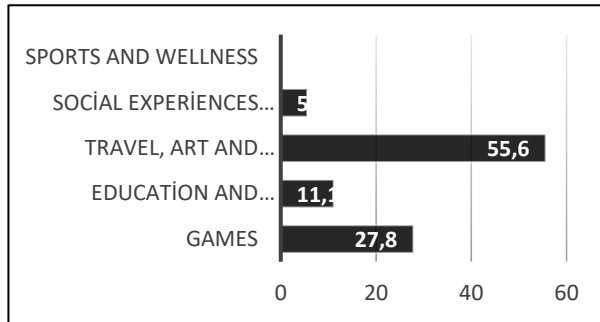
In the study, two focus group studies were implemented. In the first focus group session, participants' knowledge and prior experience with augmented reality were assessed through a series of targeted questions. Within this session, distinct question sets were administered to participants who had previously used AR applications and those who had not, allowing for comparative insights into familiarity and preconceptions. In the second focus group session, participants were instructed to interact with an augmented reality application developed by a shoe retailer, after which they responded to questions designed to explore their experiential perceptions and affective responses. The data collected from both focus group studies were analyzed using appropriate statistical methods, and visual representations, including pie charts, histograms, and tabular summaries, to facilitate comprehensive analysis and interpretation of consumer attitudes and experiential outcomes.

## **3. RESULTS**

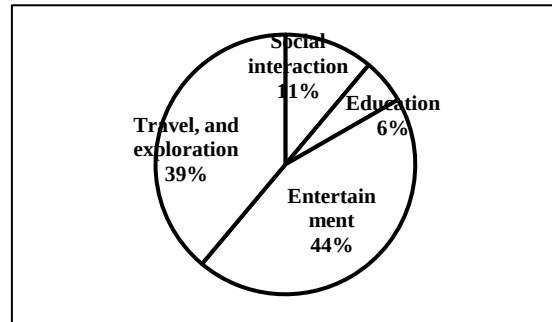
The findings of the study are discussed in detail below. In the first focus group study, the knowledge and experience of 31 participants regarding augmented reality were assessed through a series of structured questions. The content of these questions varied according to participants' prior experience with AR applications; therefore, the results of this phase are presented separately in Sections 3.1 and 3.2. In the second focus group study, a uniform set of questions was administered to all participants following their interaction with an AR application. The responses obtained in this phase are reported in Section 3.3.

### **3.1 Views and Opinions of Participants Without AR Experience Regarding AR**

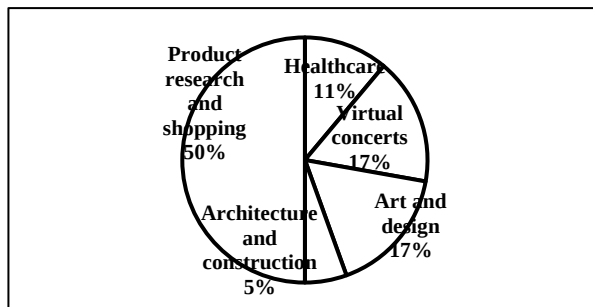
Among the 31 participants in the first focus group, 18 reported having no prior experience with augmented reality (AR); however, all of these individuals indicated a desire to engage with AR products and applications. The majority of respondents expressed a strong interest in exploring AR applications related to travel, art, and exploration, followed by AR gaming applications. In contrast, sports and wellness applications received comparatively low interest from the participants. When asked about the potential benefits of AR applications, a substantial portion of respondents identified entertainment (44.4 %) and travel and exploration (38.9 %) as key areas in which AR could provide value. Specifically, half of the participants (50 %) perceived AR as advantageous for product search and shopping, while smaller percentages associated benefits with virtual concerts (16.7 %), art and design (16.7 %), and healthcare (11.1 %). Furthermore, approximately 61 % of all participants reported a favorable attitude toward the use of VR/AR/Metaverse applications for product presentation and shopping. Regarding emotional responses to AR technology, 61.1 % of participants reported curiosity about trying AR applications, while 27.8 % stated that they felt excitement about the experience. Additionally, 11.1 % indicated that they expected to enjoy the experience, and notably, none of the participants reported feelings of panic or bias toward AR applications. Despite these generally positive affective responses, concerns were also evident: 50 % of participants expressed worries about the potential for AR applications to foster addiction, followed by concerns regarding security risks (27.8 %), reduced attention (16.7 %), and dizziness (5.5 %). Finally, a significant proportion of respondents anticipated broader future adoption of AR technologies. Specifically, 77.7 % of participants implied that AR applications are likely to become widespread in the future, and 88.9 % expressed that AR would be beneficial for product search and shopping.



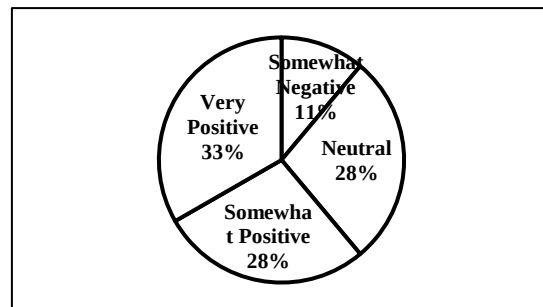
(a) The areas for AR products to be experienced



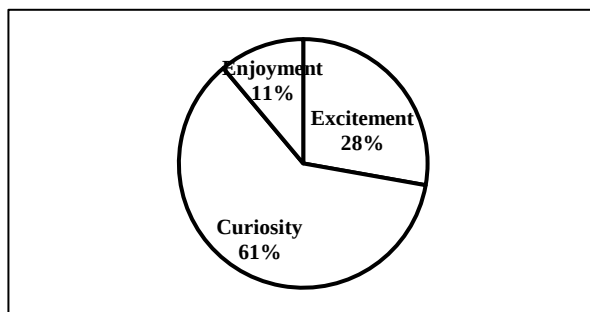
(b) Benefits AR app. could provide



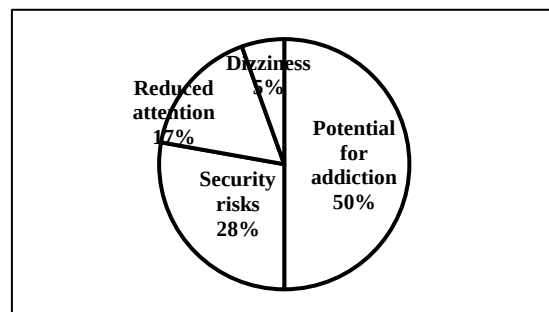
(c) The areas AR app. could be used in the future



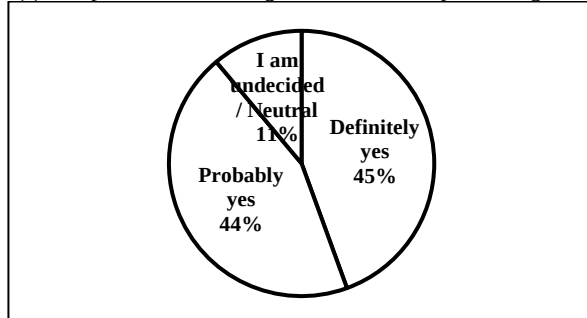
(d) VR/AR/Metaverse app. in product presentation



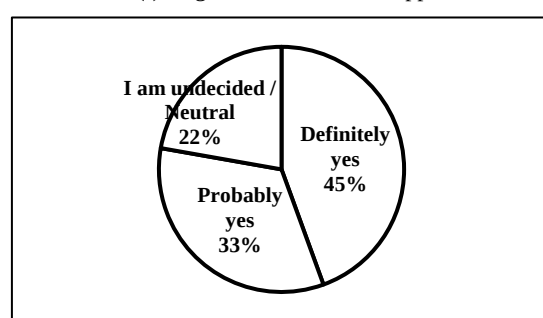
(e) Best possible describing attitude when experiencing AR app.



(f) Negative effects of AR app.



(g) Would you like AR app. to be used more widely in product presentation and sales in the footwear industry in the future?



(h) Would you like AR app. to become more widespread in the future

**Figure 1.** The evaluation of first group of respondents having no experience with AR

### 3.2 Views and Opinions of Participants With AR Experience Regarding AR

Of the 31 participants in the first focus group, 13 reported having prior experience with augmented reality (AR) applications. Among these experienced users, only 30.8 % indicated that they possessed a moderate to high level of knowledge about AR technologies, whereas 61.5 % reported having only limited familiarity with AR applications. Furthermore, less than half of the experienced participants (46.2 %) stated that they engaged with AR applications on a regular basis (i.e., several times per week or month). When asked about their actual use of AR applications, the majority of respondents (69.2 %) indicated that they had utilized AR primarily for entertainment purposes, such as playing games or watching films and videos, while 30.8 % reported using AR for educational activities. These proportions were mirrored in participants'



28-29 April 2026, Istanbul, Turkey

perceptions of the benefits associated with AR, with equivalent percentages acknowledging the value of AR for both entertainment and educational functions. Additionally, a notable proportion of participants (38.5 %) recognized the potential for AR applications to support work-related collaboration and social interaction, suggesting a broader range of perceived utility beyond leisure and learning. Regarding future adoption, an overwhelming majority (92.3 %) of experienced users anticipated that AR applications would become more widespread in the future. Despite this optimism, participants also identified several limitations associated with current AR technologies. The most frequently cited concern (69.2 %) was the inability of AR representations to fully match the characteristics of real products, followed by potential health-related issues (e.g., headaches and nausea) reported by 30.8 %, and concerns about social isolation noted by 23.1 %. Finally, 23.1 % of participants indicated that they found using AR applications challenging, highlighting usability issues as a barrier to engagement.

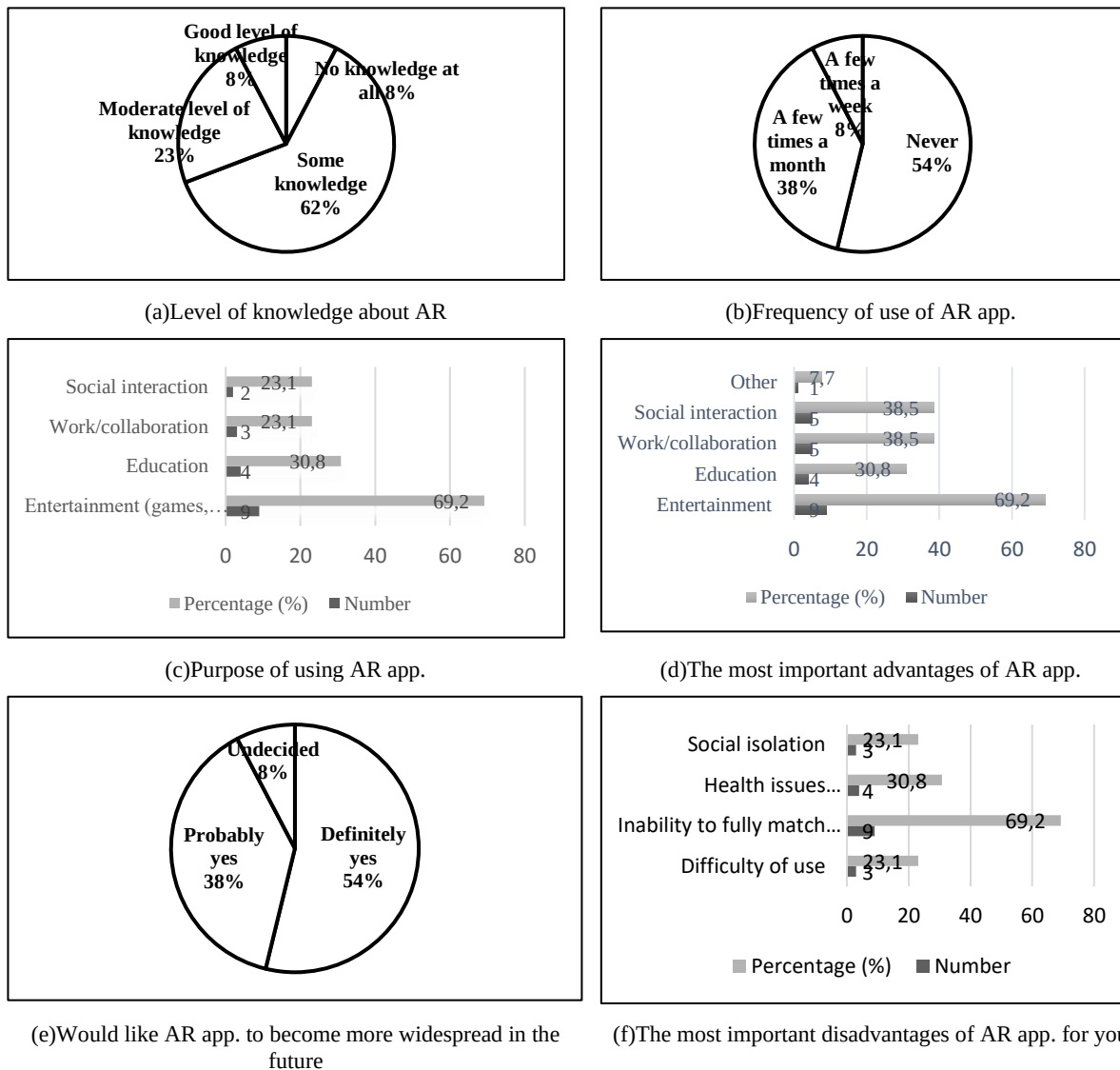


**Figure 2.** The evaluation of first group of respondents having an experience with AR

### 3.3 Participants' Views and Thoughts After Using the AR Application

In the second focus group, participants were asked to articulate their views and reflections after interacting with an augmented reality application provided by a shoe retailer. Participants evaluated the AR application across multiple dimensions, including usability, consumer engagement, and perceived utility. The aggregated results of these evaluations are presented in Table 1 below, which summarises the key responses and thematic patterns identified during the session.



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**Table 1.** The evaluation of AR application in different aspects (*SD: strongly disagree, D: Disagree, UND: Undecided, A: Agree, SA: Strongly Agree*)

| The Relevant Statement                                                                      | SD   | D     | UND   | A     | SA    |
|---------------------------------------------------------------------------------------------|------|-------|-------|-------|-------|
| The interface of AR app. offers an appealing presentation.                                  | 7,69 | 0,00  | 7,69  | 53,85 | 30,77 |
| AR app. interfaces are highly aesthetic in terms of design.                                 | 0,00 | 0,00  | 15,38 | 53,85 | 30,77 |
| The interface design of AR app. is functional and appealing.                                | 0,00 | 0,00  | 0,00  | 69,23 | 30,77 |
| <b>Average of Aesthetic</b>                                                                 | 2,56 | 0,00  | 7,69  | 58,97 | 30,77 |
| Using AR, I can virtually try on the shoes I intend to buy.                                 | 0,00 | 7,69  | 0,00  | 30,77 | 61,54 |
| Using AR, I can easily find and try on the footwear I am looking for.                       | 0,00 | 0,00  | 15,38 | 30,77 | 53,85 |
| Using AR, I can ignore the footwear I am not interested in.                                 | 7,69 | 0,00  | 46,15 | 15,38 | 30,77 |
| <b>Average of Perceived control requirement</b>                                             | 2,56 | 2,56  | 20,51 | 25,64 | 48,72 |
| I can receive immediate feedback when I interact with AR.                                   | 0,00 | 0,00  | 53,85 | 46,15 | 0,00  |
| The feedback I received when interacting with AR met my expectations.                       | 0,00 | 0,00  | 30,77 | 61,54 | 7,69  |
| I received helpful feedback while interacting with AR.                                      | 0,00 | 0,00  | 38,46 | 53,85 | 7,69  |
| <b>Average of Perceived responsiveness</b>                                                  | 0,00 | 0,00  | 41,03 | 53,85 | 5,13  |
| The AR app. is personalized to a certain extent.                                            | 0,00 | 7,69  | 23,08 | 69,23 | 0,00  |
| I can use the AR app. the way I want.                                                       | 0,00 | 0,00  | 23,08 | 69,23 | 7,69  |
| The AR app. meets my individual needs.                                                      | 0,00 | 0,00  | 23,08 | 53,85 | 23,08 |
| <b>Average of Perceived personalization</b>                                                 | 0,00 | 2,56  | 23,08 | 64,10 | 10,26 |
| I find the AR app. useful for footwear shopping.                                            | 7,69 | 0,00  | 0,00  | 30,77 | 61,54 |
| The AR app. makes footwear shopping easier.                                                 | 0,00 | 0,00  | 0,00  | 30,77 | 69,23 |
| AR app. increase my chances of making the right decisions in online shopping.               | 0,00 | 0,00  | 15,38 | 30,77 | 53,85 |
| AR app. speed up footwear shopping.                                                         | 0,00 | 7,69  | 0,00  | 38,46 | 53,85 |
| AR app. make footwear shopping more effective.                                              | 0,00 | 0,00  | 15,38 | 30,77 | 53,85 |
| <b>Average of Performance expectancy</b>                                                    | 1,54 | 1,54  | 6,15  | 32,31 | 58,46 |
| The AR app. provided me with the information I expected.                                    | 0,00 | 0,00  | 7,69  | 76,92 | 15,38 |
| The AR app. provided detailed information about the topic I wanted to learn about.          | 0,00 | 7,69  | 15,38 | 76,92 | 0,00  |
| The AR app. provided complete information about the topic I wanted to learn about.          | 0,00 | 15,38 | 30,77 | 53,85 | 0,00  |
| The AR app. provided me with information that helped me make decisions.                     | 0,00 | 0,00  | 7,69  | 69,23 | 23,08 |
| The AR app. provided sufficient information for comparing products.                         | 0,00 | 0,00  | 7,69  | 69,23 | 23,08 |
| <b>Average of Perceived informativeness</b>                                                 | 0,00 | 4,62  | 13,85 | 69,23 | 12,31 |
| I am curious about the AR app.                                                              | 0,00 | 0,00  | 7,69  | 30,77 | 61,54 |
| The AR app. is very interesting to me.                                                      | 0,00 | 0,00  | 15,38 | 23,08 | 61,54 |
| I didn't notice the passage of time while using the AR app.                                 | 0,00 | 7,69  | 15,38 | 46,15 | 30,77 |
| <b>Average of Perceived enjoyment</b>                                                       | 0,00 | 2,56  | 12,82 | 33,33 | 51,28 |
| After using the AR app., I have a positive opinion about it.                                | 0,00 | 0,00  | 0,00  | 61,54 | 38,46 |
| The AR app. offers valuable services.                                                       | 0,00 | 0,00  | 0,00  | 61,54 | 38,46 |
| The AR app. offers valuable services.                                                       | 0,00 | 0,00  | 0,00  | 61,54 | 38,46 |
| Using the AR app. was an enjoyable experience.                                              | 0,00 | 0,00  | 0,00  | 53,85 | 46,15 |
| <b>Average of Attitudes</b>                                                                 | 0,00 | 0,00  | 0,00  | 59,62 | 40,38 |
| I intend to use the AR app. regularly.                                                      | 0,00 | 0,00  | 15,38 | 76,92 | 7,69  |
| I intend to use the AR app. more frequently.                                                | 0,00 | 0,00  | 0,00  | 92,31 | 7,69  |
| I plan to use the AR app. in my next footwear shopping.                                     | 0,00 | 0,00  | 15,38 | 61,54 | 23,08 |
| <b>Average of Intention and Continuation to use</b>                                         | 0,00 | 0,00  | 10,26 | 76,92 | 12,82 |
| I will say positive things to others about the brand that has the AR app.                   | 0,00 | 0,00  | 7,69  | 76,92 | 15,38 |
| I will defend the brand that has the AR app. when others criticize it.                      | 0,00 | 15,38 | 15,38 | 69,23 | 0,00  |
| I want to recommend the brand that offers the AR app. to people planning to buy shoes.      | 0,00 | 0,00  | 7,69  | 84,62 | 7,69  |
| I want to share my experience with the AR app. with my friends on my social media accounts. | 7,69 | 30,77 | 23,08 | 30,77 | 7,69  |
| I want to post my experience with the AR app. on my social media accounts.                  | 7,69 | 30,77 | 30,77 | 23,08 | 7,69  |
| <b>Average of Impact on Brand advocacy</b>                                                  | 3,08 | 15,38 | 16,92 | 56,92 | 7,69  |

The majority of participants (89.6 %) indicated that the AR application possessed both a functional and visually appealing design, suggesting positive initial impressions of its aesthetic and structural attributes. A substantial proportion of respondents (74.36 %) also reported that the application's ease of use reduced the need for extensive control effort, particularly when searching for products and interacting with virtual try-on features. However, the responsiveness of the system did not meet user expectations, as 41.03 % of participants reported difficulties receiving immediate feedback during interaction, which may indicate performance limitations in real-time processing or interface responsiveness. In terms of informational value, 81.54 % of respondents perceived that the AR application provided detailed, sufficient, and comprehensive information to support decision-making, aligning with research suggesting that augmented reality can enhance both utilitarian and hedonic consumer outcomes such as perceived usefulness and enjoyment. Moreover, 84.61 % of participants reported that using the AR application was enjoyable, indicating a strong hedonic element to the user experience. The ability to personalize content or interactions within the AR environment was likewise acknowledged by a majority (74.36 %) of respondents, emphasizing the importance of customization as a user-centered design feature. Overall, a considerable proportion of participants (90.77 %) affirmed that the AR application met or exceeded their expectations in terms of usefulness, ease of use, functionality, versatility, and overall effectiveness. After experiencing the

AR tool, all participants reported a positive attitude toward AR technologies, and 89.74 % expressed an intention to use similar tools more frequently in the near future. However, despite generally favorable attitudes and intentions, participants were less inclined to engage in advocacy behaviors; although they stated they *would recommend* AR tools and brands utilizing such tools, they were reluctant to actively defend a brand on this basis or to share their experiences with others, either socially or via digital platforms.

#### **4. CONCLUSION**

This study investigated consumer attitudes and experiential responses toward augmented reality applications within the context of shoe retail.

The findings indicate that, there is generally positive perceptions of AR potential across entertainment, education, and retail domains. After direct engagement with the application, users evaluated the technology positively in terms of design and functional performance. Despite certain limitations related to system responsiveness and accuracy, the majority of respondents affirmed that the AR experience met or exceeded their expectations with respect to ease of use, functionality, and perceived utility. Moreover, nearly all participants reported favorable attitudes toward AR technologies and expressed an intention to use similar tools more frequently in the future.

However, while participants were willing to recommend AR applications and acknowledge their benefits for product search and shopping, they were less inclined to engage in active brand advocacy or share their experiences socially. This pattern might suggest that although AR can positively influence individual attitudes and perceived experiential value, the translation of these attitudes into broader promotional behaviors may be limited without further enhancements in engagement features or social integration. In summary, this research contributes to the growing body of literature on AR in retail by providing empirical evidence that AR applications can enhance consumer experience and positive attitudes, while also highlighting areas for improvement, such as responsiveness and accuracy to foster brand advocacy. Future studies should examine the long-term effects of repeated AR interactions on consumer engagement and investigate how specific design features might drive stronger social sharing and loyalty outcomes.

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## DESIGN OF A LEGGING WITH THERAPEUTIC EFFECT

Sinem Birsen<sup>1,\*</sup>, Nazan Okur<sup>1</sup>, Canan Sarıçam<sup>1</sup>, Fatma Sude Güllüoğlu<sup>1</sup>, Elif Işık<sup>1</sup>, Sıla Çelik<sup>1</sup>

<sup>1</sup> Istanbul Technical University, Department of Textile Engineering, Istanbul, Türkiye

\* [birsen15@itu.edu.tr](mailto:birsen15@itu.edu.tr)

### ABSTRACT

Recent developments in textile engineering and advanced manufacturing technologies have enabled the creation of garments capable of delivering targeted functional and therapeutic performance. Therapeutic tools such as kinesio tapes, adhesive bands, and conventional compression garments are widely used to alleviate muscle soreness, enhance circulation, and support muscle recovery. Despite their proven effectiveness, these solutions often have practical limitations, including the need for manual application, limited customization, and potential discomfort with prolonged use. Such constraints highlight the demand for integrated wearable alternatives that provide localized therapeutic effects without compromising user comfort or mobility. In response to these challenges, this study presents the design and development of compression leggings that incorporate region-specific pressure zones, achieved through three-dimensional (3D) printing technology. Flexible thermoplastic polyurethane structures were directly integrated onto textile substrates using optimized additive manufacturing parameters to enable controlled and anatomically aligned compression. Three distinct TPU structure designs were developed and applied to the leggings to investigate the influence of pattern geometry. The therapeutic leggings prototype was produced using TPU filament and evaluated against five key criteria: flexibility, lightweight construction, filament-to-textile adhesion, pressure application effectiveness, and manufacturing feasibility. In addition to structural and material assessments, the functional performance of the developed garment was evaluated using established biomechanical methods, including the Gastrocnemius Shortness Test, Soleus Shortness Test, and Knee-to-Wall Test. These tests were selected to assess the garment's influence on lower limb muscle flexibility and mobility, which are critical parameters in both sports performance and rehabilitation contexts. The results indicate that the proposed 3D-printed compression leggings provide muscle support comparable to traditional therapeutic products while offering enhanced adaptability through customizable pressure distribution. By integrating manufacturing with functional textile design, this study demonstrates a promising approach to developing next-generation sportswear and healthcare garments that combine comfort, performance, and therapeutic functionality within a single wearable system.

**Keywords:** 3D-Printing, Biomechanical Compression, Customizable Pressure Application, Muscle-Supporting Textiles, Therapeutic Compression Legging

### 1. INTRODUCTION

Advancements in textile technology and manufacturing processes have enabled the development of garments that provide both functional and therapeutic benefits, particularly in sports performance, rehabilitation, and preventive healthcare. Various approaches, including kinesio taping, adhesive therapeutic bands, and compression garments, are commonly used to support muscles and enhance recovery.

Kinesio taping is widely applied to improve circulation, reduce pain, and support muscle function [2]. However, existing studies have reported several limitations, including generally short-term effects [3], greater effectiveness when combined with other therapeutic interventions rather than used alone [4], dependence on proper application technique, and the potential for skin irritation from direct contact [6]. Similarly, compression garments are designed to apply graduated pressure to enhance venous return and circulation, potentially reducing muscle soreness and accelerating recovery [1]. While some studies report

benefits such as improved performance [5] and proprioception [7], the overall effectiveness of these garments remains inconsistent [8] and highly dependent on factors such as material properties, garment fit, and individual body morphology [9]. Therefore, without careful application and proper customization of kinesio tapes or compression garments, the performance may be compromised. These limitations highlight the need for integrated wearable solutions capable of delivering localized therapeutic effects while maintaining comfort and mobility.

Recent advances in three-dimensional (3D) printing offer significant potential for producing customized and functional textile-based products. Additive manufacturing enables the direct integration of personalized, body-contoured structures tailored to specific needs onto textile surfaces [11,12] and also allows controlled, targeted pressure applications [10]. In this context, the present study proposes the design and development of compression leggings with region-specific pressure zones and distinguishes itself by embedding therapeutic functionalities directly into the textile structure via 3D printing. Three Thermoplastic Polyurethane (TPU) structures with different geometries were developed and evaluated for geometry, flexibility, adhesion, pressure effectiveness, and manufacturability. In addition, biomechanical tests were conducted to assess the effects of developed garments on lower-limb flexibility and mobility. The findings demonstrate that 3D-printed compression leggings have the potential to provide effective muscle support while offering enhanced adaptability through customizable pressure distribution, presenting a promising approach for next-generation therapeutic and performance-oriented wearable systems.

## **2. EXPERIMENTAL STUDY**

### **2.1 Material Selection**

TPU filament was selected due to its flexibility, durability, cost-effectiveness, and wide commercial availability [13]. In addition, TPU offers advantages in processability, compatibility with additive manufacturing, and recyclability, contributing to environmental sustainability [13,14]. Its high adhesion capability enables strong bonding to textile surfaces [19], resulting in flexible, durable printed structures with a low risk of delamination and long-term sustainability. The textile substrate was selected as a polyester-elastane knitted fabric chosen for its elasticity, comfort, and suitability for close-fitting garments. The fabric has a mass per unit area of approximately 201.7 g/m<sup>2</sup>, with a wale density of 27 wales/cm and a course density of 17 courses/cm. This combination of TPU and elastic fabric supports both functional performance and wearer comfort, making it appropriate for therapeutic sportswear applications.

### **2.2 3D-Printing Model Designs**

The three TPU designs used in this study were selected based on textile compatibility, therapeutic functionality, manufacturability, and user comfort. Each design was optimized for specific mechanical properties and application requirements. The selection process was guided by Gibson-Ashby's [15] cellular material mechanics model and by Bauer et al.'s [16] findings on the superior energy-dissipation performance of hexagonal geometries.

The first design is a Y-shaped configuration with vertically stacked circular TPU filaments. The circular geometry enables a homogeneous stress distribution under tensile and compressive loads [17], resulting in uniform and comfortable compression of the calf muscles. This graduated compression (15-20 mmHg) can enhance venous return by 40% [18], while the Y-shaped layout provides directional support aligned with muscle fibers and maintains flexibility during movement (Figure 1.a1). The second design is a Y-shaped configuration composed of vertically stacked hollow hexagonal TPU filaments. Hexagonal geometries are widely recognized for their high strength-to-weight ratios. Bauer et al. [16] reported that hexagonal cellular structures exhibit 35% greater energy-dissipation capacity than square lattices, while also enabling approximately 40% material savings. The hollow structure enhances flexibility while maintaining structural integrity [16], and the vertical Y-pattern provides targeted support and compression, as well as improved breathability (ISO 9237) (Figure 1.b1). The third design is a Y-shaped configuration with multidirectional hollow hexagonal TPU filaments. This structure forms an omnidirectional support network on the textile substrate, improving pressure distribution and support during multiplanar movements (Figure 1.c1). Overall, the three designs were selected to achieve an optimal balance between flexibility, support, and manufacturing efficiency. Literature and experimental evidence indicate that the selected geometries enhance mechanical performance and comfort in therapeutic leggings. In combination with TPU's strong adhesion to textiles, these structures provide a solid scientific basis for this research.

### 2.3 3D Model Application on Textile Material

The 3D models were imported into Ultimaker Cura slicing software. Key slicing parameters were carefully defined, including model orientation and positioning on the build plate, layer thickness, filament type, printing temperature, infill density, and printing speed. Printing was conducted at a nozzle temperature of 220°C, a bed temperature of 60°C, and a low print speed of 30 mm/s. The nozzle-to-fabric distance was adjusted to ensure direct contact, with parameters selected to prevent fabric deformation and tearing. To mitigate issues, the Z-offset was increased, and the bed temperature was raised by 5°C to improve adhesion. The fabric was fixed to the print bed with bonds to prevent movement during printing, particularly given its flexible structure, thereby reducing shifting and wrinkling. Optimization enabled a stable and durable TPU-fabric bond without the use of additional adhesives or surface treatments, relying solely on controlled bed leveling and extrusion settings. As a result, the TPU designs were applied in the back lower region of the leggings. Figure 1.a2, b2, and c2 demonstrates the three TPU designs applied to textile material.

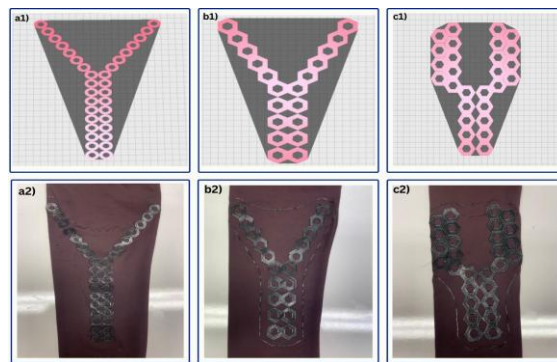


**Figure 1.** Designed & 3D Printed Y-shaped configurations: (a) vertically stacked circular, (b) vertically stacked hollow hexagonal, (c) multidirectional hollow hexagonal.

### 2.4 Three Established Biomechanical Testing

The functional performance of the developed leggings was assessed using established tests from the literature that assess ankle dorsiflexion range of motion: Gastrocnemius-Soleus Shortness Tests and the Knee-to-Wall Test. As ankle dorsiflexion range of motion is closely related to elasticity and length of muscles that are located in posterior lower leg [20,21], where the TPU designs were applied, these tests were selected as the assessment methods. In the gastrocnemius shortness test, the knee is kept in full extension, while the ankle is forced into dorsiflexion. In the soleus shortness test, the knee is kept in slight flexion, while the ankle is forced into dorsiflexion. The ankle dorsiflexion range of motion in both the knee-extended and knee-flexed positions was measured while participants sat on a table with their legs extended and feet positioned off the edge [20]. The knee-to-wall test requires the participant to lunge toward the wall with the toes positioned approximately 10 cm away, moving forward until the knee touches the wall without lifting the heel; the resulting angle between the leg and the floor was measured [22]. All measurements were conducted under the supervision of a senior physiotherapy student using goniometer to take measurements. Measurements could have been obtained using more advanced digital alternatives, such as an inclinometer [23], or recording-based methods [24]. However, due to cost constraints, the present tests and measurement techniques were selected for implementation.

## 3. RESULTS

The therapeutic leggings were first evaluated against five key criteria: flexibility, lightweight design, filament adhesion, pressure application, and ease of manufacturing. The leggings demonstrated flexibility, retaining their original elasticity after 3D printing, with no noticeable stiffness or constraint during movement. They were found to be lightweight since no significant increase in weight was observed. TPU filament adhered strongly to the textile surface, with no delamination or detachment observed during or after use, demonstrating the adhesion to fabric. 3D-printed leggings delivered targeted compression while preserving mobility, demonstrating more efficient and adaptive pressure distribution than conventional garments as observed in biomechanical testing. Although the initial optimization of printing parameters posed challenges, the final process proved reproducible, scalable, and efficient, producing results with



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minimal material waste. Additionally, the method enabled a high degree of design flexibility, supporting the development of customized therapeutic wearables.

In addition to the initial evaluations, the performance of the developed leggings was assessed using three methods: the Gastrocnemius Shortness Test, the Soleus Shortness Test, and the Knee-to-Wall Test. The results were obtained by comparing the 3D-printed leg with the non-printed right leg, and all values were calculated as the difference between post- and pre-test measurements of three participants, which were then averaged. Negative values indicate a decrease in flexibility, while positive values indicate an increase. The average results for each test are presented in Table 1.

**Table 1.** Biomechanical test results.

| PARTICIPANT                         | TEST<br>DESIGN NO | GASTROCNEMIUS<br>SHORTNESS   |                                | SOLEUS SHORTNESS             |                                | KNEE-TO-WALL                 |                                |
|-------------------------------------|-------------------|------------------------------|--------------------------------|------------------------------|--------------------------------|------------------------------|--------------------------------|
|                                     |                   | LEFT LEG<br>(3D-<br>PRINTED) | RIGHT LEG<br>(NON-<br>PRINTED) | LEFT LEG<br>(3D-<br>PRINTED) | RIGHT LEG<br>(NON-<br>PRINTED) | LEFT LEG<br>(3D-<br>PRINTED) | RIGHT LEG<br>(NON-<br>PRINTED) |
| AVERAGE OF<br>THREE<br>PARTICIPANTS | 1                 | -2.00°                       | -8.33°                         | -1.00°                       | -6.11°                         | +3.33°                       | +4.00°                         |
|                                     | 2                 | +2.00°                       |                                | +1.33°                       |                                | +2.00°                       |                                |
|                                     | 3                 | -5.33°                       |                                | -2.33°                       |                                | +2.33°                       |                                |

In the Gastrocnemius Shortness test, the right leg without a 3D-printed design showed an average decrease of 8.33° in joint angle, indicating a reduction in flexibility. In contrast, the left leg with the 3D-printed designs showed smaller changes: Design 1 resulted in an average decrease of 2°, Design 2 showed an increase of 2°, and Design 3 showed an average decrease of 5.33°. Since all these changes are more favorable than the decrease observed in the non-printed leg, it can be concluded that the 3D-printed designs helped maintain or improve muscle flexibility.

In the Soleus shortness test, the right leg without the 3D-printed design showed an average decrease of 6.11° in joint angle, indicating reduced flexibility. In contrast, the left leg with the 3D-printed design showed smaller changes: Design 1 resulted in an average decrease of 1°, Design 2 showed an average increase of 1.33°, and Design 3 showed an average decrease of 2.33°. Since these challenges are more favorable than the decrease observed in the non-printed leg, it can be concluded that the 3D-printed design helped maintain or improve muscle flexibility.

In the Knee-to-Wall Test, the right leg without the 3D-printed design showed an average 4° increase in angle, indicating reduced forward movement and therefore lower mobility when wearing standard leggings compared to a bare leg. In contrast, the left leg with the 3D-printed designs showed smaller, or even improved, changes: Design 1 showed a 3.33° increase, while Designs 2 and 3 showed increases of 2.00° and 2.33°, respectively. Since all 3D-printed designs showed less restriction than the non-printed condition, it can be concluded that the printed structures reduced movement limitations, with Designs 2 and 3 showing the greatest improvement in mobility.

The performance outcomes from functional mobility and flexibility assessments indicate that, among the evaluated design configurations, Design 2 offers the optimal balance between effective pressure application and unimpeded joint movement. While all three designs exhibited improvements in muscle flexibility and mobility metrics, Design 2 consistently demonstrated superior performance in minimizing motion restriction, particularly in tests such as the knee-to-wall test, where the limitation was notably reduced. The moderate-to-high consistency across multiple participants further strengthens its candidacy as a user-adaptable solution. These findings support the feasibility of 3D-printed therapeutic garments as functionally responsive, user-specific wearables, capable of delivering targeted biomechanical interventions without compromising comfort or mobility.

#### 4. CONCLUSION

This study addressed the limitations of existing muscle-support strategies in sportswear and rehabilitation, such as kinesio taping and conventional compression garments, which often pose challenges, including reliance on technique, skin irritation, and limited customization. To overcome these challenges, the



potential of 3D printing was explored for developing functionalized compression leggings with region-specific pressure zones.

Three TPU structures were designed, integrated into textile substrates, and evaluated for geometry, flexibility, lightweight construction, filament-to-textile adhesion, pressure-application effectiveness, and manufacturing feasibility. In addition, the developed leggings were assessed using three established biomechanical tests to determine their effects on lower-limb flexibility and mobility. The results demonstrated that all 3D-printed designs maintained or improved muscle flexibility compared to non-printed conditions, while also reducing movement restrictions during functional testing. Among the tested structures, Design 2 showed the most consistent performance across all evaluations, providing improvements in both flexibility and mobility. Despite its contributions, this study has several limitations. The biomechanical testing was conducted with a small sample size of three participants. In addition, durability under real-world conditions, such as repeated use and washing, was not evaluated. The study also focused only on the calf region, limiting its anatomical scope. Future work should include a larger participant group, durability testing under practical conditions, and the development of multi-region or modular designs targeting other lower-limb areas.

Overall, the findings indicate that 3D-printed TPU-based compression leggings can deliver effective and localized muscle support while preserving mobility and comfort. This approach offers a promising direction for developing next-generation wearable systems that integrate therapeutic functionality, performance enhancement, and user-specific customization within a single textile platform.

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## DESIGN OF AN INNOVATIVE AND SUSTAINABLE UNDERARM PAD WITH ENHANCED FUNCTIONALITY

Ceren Karaarslan<sup>1</sup>, İpek Bengü Varol<sup>1</sup>, Emir Bilgin<sup>1</sup>, Banu Nergis<sup>1</sup>, Cevza Candan<sup>1</sup>, Seda Kızıl<sup>2</sup>

<sup>1</sup> Technical University of Istanbul, Textile Engineering Department, Istanbul, Türkiye

<sup>2</sup> ÇGS Çetinkaya Giyim Sanayi, Tasarım Merkezi, Istanbul, Türkiye

\* [uygunf@itu.edu.tr](mailto:uygunf@itu.edu.tr)

### ABSTRACT

Throughout the lifecycle of a textile product, the most significant environmental impact typically occurs during the user phase. Existing research characterizes the ideal consumer as one who launders garments infrequently, at lower temperatures, with environmentally friendly detergents, air-dries them, and minimizes the use of ironing. However, because the underarm region becomes soiled rapidly due to perspiration, shirts often require washing after each wear. The present study seeks to address this issue by developing an underarm pad with enhanced absorbency and functional performance, designed to delay the onset of soiling in the underarm area of garments and thereby reduce laundering frequency. The primary objective has been to provide users with a hygienic and comfortable wearing experience over an extended period, while simultaneously mitigating environmental impact through decreased water, energy, and detergent consumption. In this respect, the study aims to generate benefits for both individual consumers and the broader environment. The work's innovative dimension and technological value lie in proposing a washable, reusable, and high-performance alternative to existing single-use underarm pads, which typically offer limited absorbency. The incorporation of layered textile arrangements and specialized fabric structures is intended to facilitate rapid sweat absorption and evaporation, thereby prolonging garment cleanliness. Moreover, the selection of eco-friendly and recyclable materials aligns with the study's overarching commitment to sustainability. A utility model has also been obtained for the underarm pad design that includes at least one fastening section allowing it to be easily attached to and removed from a shirt, and features a curved shape created by a circular cut in the middle section to ensure comfortable arm movement and prevent tightening in the underarm area.

**Keywords:** *Underarm Pad, Absorbency, Functionality, Sustainability*

### 1. INTRODUCTION

Sweat is a clear, salty fluid produced by the sweat glands to help regulate body temperature. Although sweating is a normal physiological process, it can cause wetness, discomfort, and discoloration on clothing, particularly in the underarm area. When combined with skin bacteria, sweat may also lead to unpleasant odor. Sweat production varies depending on gland activity, which is influenced by factors such as puberty, sex, and the autonomic nervous system and can be managed through hygiene practices and products such as antiperspirants, deodorants, and sweat pads [1]. Beyond personal discomfort, prolonged exposure of textiles to sweat can accelerate fabric discoloration, weaken fiber structure, and reduce garment service life. These effects are especially significant in products worn in close contact with the skin, where both moisture management and user comfort are critical performance requirements.

To address these issues, underarm sweat pads—also referred to as sweat shields or sweat absorbers—have been developed as functional personal hygiene products designed to absorb perspiration before it reaches outer garments. Such products provide both physiological and psychological benefits by improving wearer comfort, minimizing odor and stain formation, and increasing user confidence in daily, professional, and social environments. Sweat pads are generally classified into two main groups: disposable and reusable.

Disposable products are convenient and widely available, but their single-use nature contributes to post-consumer waste and limits their long-term sustainability. Reusable alternatives, by contrast, offer a more environmentally responsible solution by allowing repeated washing and prolonged use, aligning with the growing global demand for sustainable personal care and hygiene products.

The functional performance of a reusable sweat pad depends strongly on the moisture-related behavior of the textile materials used in its construction. Textile fibers differ significantly in their moisture absorption, retention, transport, and drying characteristics, all of which directly influence wearer comfort and product effectiveness. Natural fibers such as cotton, wool, silk, and bamboo are widely recognized for their hydrophilic behavior and their ability to absorb perspiration efficiently [2-4]. Cotton, for example, is known for its high moisture absorbency and breathability, while bamboo offers additional softness and antibacterial potential. Wool provides excellent moisture buffering and thermal regulation, whereas silk offers moderate moisture management with superior skin comfort. However, high moisture retention in natural fibers may also lead to slower drying, discomfort in humid environments, and, in some cases, increased microbial growth or reduced long-term durability. In contrast, synthetic fibers such as polyester, nylon, and acrylic are generally hydrophobic and exhibit low moisture regain, quick drying, and superior dimensional stability [5]. Although these fibers do not absorb moisture to the same extent as natural fibers, they can support effective sweat management when engineered for moisture transport or treated with functional finishes. Among these, advanced functional materials such as 37.5®-enhanced polyester have gained increasing attention due to their ability to accelerate moisture vapor evaporation and regulate the microclimate around the skin through embedded active particles [6]. In addition, regenerated fibers such as viscose contribute softness, absorbency, and comfort, bridging the performance gap between natural and synthetic materials. Consequently, blended textile systems are often preferred in moisture-management applications because they can combine the absorbency of natural fibers with the durability and fast-drying properties of synthetic fibers [2,5]. The interaction between textile materials and sweat is governed not only by fiber type but also by fundamental moisture-management properties such as hydrophilicity/hydrophobicity, moisture regain, hygroscopicity, moisture vapor transmission, absorbency, and capillary liquid transport [7, 8]. Effective sweat management requires more than simply absorbing moisture; it also involves transferring liquid away from the skin, distributing it across the textile structure, and enabling rapid evaporation. Therefore, textile structures intended for underarm sweat management must be designed to balance liquid uptake, transport efficiency, drying behavior, and tactile comfort.

Among the structural approaches proposed for advanced moisture management, dual-layer textile systems have shown considerable potential. These systems typically combine an inner hydrophilic layer that absorbs sweat from the skin with an outer hydrophobic or low-absorbency layer that promotes outward moisture transfer and evaporation while simultaneously protecting the outer garment [9, 10]. Such structures can create a directional moisture transport mechanism, improving both wearer comfort and clothing protection. For reusable underarm sweat pads, this approach is particularly relevant because the product must not only absorb sweat but also remain comfortable, washable, lightweight, discreet under clothing, and durable over repeated use cycles.

Previous studies [11-17] have investigated underarm sweat pad designs from both disposable and reusable perspectives.

**Disposable underarm pad development:** Some studies proposed single-use underarm pads designed to prevent sweat stains and odor transfer to garments through the use of absorbent textile or nonwoven structures combined with hydrophobic barrier layers.

**Use of natural fibers in disposable pads:** Research has explored the incorporation of biodegradable natural fibers such as kenaf, jute, and banana into disposable underarm pads, emphasizing their moisture absorption potential and environmental advantages.

**Composite structures for improved moisture management:** Advanced disposable pad designs have included nonwoven/nanomembrane composite structures with hydrophilic and breathable layers to improve liquid retention, moisture transport, and drying performance.

**Reusable multilayer textile pad systems:** Reusable sweat pad concepts have been developed using multilayer textile assemblies to combine absorbency, comfort, and garment protection within a washable structure.

**Antimicrobial and odor-control functionality:** Some reusable designs incorporated antimicrobial or aromatherapeutic finishes, such as essential oil microcapsules, to enhance odor control and hygienic performance.

**Ergonomic and wearer-oriented design features:** Studies have also highlighted the importance of flexibility, low profile thickness, fit, and wearer comfort in the development of reusable underarm sweat pads for daily use.

**Patent-based functional solutions:** Existing patented designs have focused on washable, moisture-managing underarm products with hydrophilic cores, ergonomic shaping, and discreet construction for repeated use under garments.

Although these studies have demonstrated promising developments, the existing literature still reveals several important limitations. A large proportion of previous work has focused either on disposable absorbent products or on general moisture-management concepts rather than on structurally optimized reusable underarm pads intended for practical daily wear. In addition, many available solutions prioritize absorbency alone without sufficiently addressing the combined requirements of directional moisture transfer, wearer comfort, garment protection, washability, low profile thickness, and sustainable material selection within a single integrated textile system. This indicates a clear need for product-oriented textile design studies that evaluate reusable underarm pads not only as absorbent materials but also as engineered moisture-management systems. In this context, the present study aims to develop a reusable underarm sweat pad with improved moisture management performance through the strategic use of textile raw materials and multilayer fabric design. The study specifically investigates how different textile materials with distinct hydrophilic and hydrophobic characteristics can be combined in a functional layered structure to enhance sweat absorption, reduce moisture transfer to garments, and improve comfort during wear. By integrating sustainability considerations with textile performance requirements, this work seeks to contribute to the development of practical, washable, and user-friendly sweat pad alternatives to conventional disposable products.

## 2. EXPERIMENTAL STUDY

### 2.1 Method and Materials

In this study, two different types of shirting fabrics commonly used in garment production were selected as the outer layers of the underarm pad prototypes: 100% cotton and a 60/40% cotton/polyester blend. In addition to these shirting fabrics, a knitted fabric produced from yarns containing 37.5® technology was used as a high moisture-absorbing intermediate layer. Furthermore, a microfiber woven fabric was used as an outer layer in one of the multilayer prototypes to evaluate its effect on moisture management and drying performance.

Four different underarm pad structures were designed and tested, with the following configurations:

- \* Structure I: Single-layer shirting fabric, either 100% cotton (coded as I – Cotton) or 60/40 cotton/polyester blend (coded as I – C/P).
- \* Structure II: A three-layer pad composed entirely of shirting fabric, using either three layers of 100% cotton (II – Cotton) or three layers of cotton/polyester blend (II – C/P).
- \* Structure III: A multilayer configuration consisting of shirting fabric on both the skin-facing and garment-facing sides, with a 37.5® knitted fabric placed as an intermediate moisture-absorbing layer (coded as III – Cotton or III – C/P).
- \* Structure IV: A complex multilayer structure featuring a skin-facing shirting fabric, a middle layer of 37.5® knitted fabric, and a garment-facing outer layer made of microfiber woven fabric (coded as IV – Cotton or IV – C/P).

In addition to these composite pad structures, individual tests were also performed on stand alone fabrics namely, the 37.5® knitted fabric and the microfiber woven fabric to obtain reference data regarding their intrinsic moisture and air management properties. Each sample was labeled using a code in the format “Structure Number – Sample Number” (e.g., I-Cotton, III-C/P), ensuring traceability during testing and analysis. The samples were conditioned (65% RH, 20°C) for 24 hours before testing and then were tested for some of their properties such as weight (ISO 3801), fabric thickness (TS 7128 EN ISO 5084), drying



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rate (AATCC 201-2020), Water Vapor Permeability (ASTM E96-00), Air Permeability (ASTM D737-18), Transfer Wicking, Moisture Absorption (ISO 20158) and Ommc-MMT (AATCC TM195).

### 3. RESULTS AND DISCUSSION

The structural properties of each fabric and tested properties of the single and layered samples are summarized in Tables 1-3.

In Figure 1, on the other hand, transfer wicking behaviour of samples based on dry fabric weight is presented.

**Table 1.** Structural Properties of the Samples.

|                                                       | Weave/Knit Type   | Weight (g/m <sup>2</sup> ) | Thickness (mm) | Moisture Absorption (%) |
|-------------------------------------------------------|-------------------|----------------------------|----------------|-------------------------|
| <b>100% Cotton</b>                                    | Plain weave       | 117.43                     | 0.34           | 7.89                    |
|                                                       | Plain weave       | 108.30                     | 0.35           | 4.23                    |
|                                                       | Plain weave       | 80.00                      | 0.64           | 3.60                    |
| <b>60/40 Cotton/Polyester Microfiber Woven Fabric</b> |                   |                            |                |                         |
| <b>37.5® Knitted Fabric</b>                           | Plain jersey knit | 1003.63                    | 0.19           | 2.45                    |

**Table 2.** Tested Properties of the Samples.

|                             | Air Permeability (cm <sup>3</sup> /cm <sup>2</sup> /s) | Drying Rate (g/m <sup>2</sup> /h) | Water Vapor Transmission (g/ m <sup>2</sup> /day) |
|-----------------------------|--------------------------------------------------------|-----------------------------------|---------------------------------------------------|
| <b>I - Cotton</b>           | 228.46                                                 | 47.60                             | 3312                                              |
| <b>I - C/P</b>              | 338.88                                                 | 51.86                             | 3657.6                                            |
| <b>II - Cotton</b>          | 152.94                                                 | 137.51                            | 3072                                              |
| <b>II - C/P</b>             | 218.26                                                 | 152.85                            | 3532,8                                            |
| <b>III - Cotton</b>         | 206.60                                                 | 166.80                            | 4032                                              |
| <b>III - C/P</b>            | 310.40                                                 | 163.67                            | 3868.8                                            |
| <b>IV - Cotton</b>          | 80.00                                                  | 163.36                            | 4185.6                                            |
| <b>IV - C/P</b>             | 84.70                                                  | 133.48                            | 3830.4                                            |
| <b>37.5® Knitted Fabric</b> | 707.76                                                 | 123.78                            | 4108.8                                            |
| <b>Microfiber Fabric</b>    | 87.98                                                  | 171.38                            | 4425.6                                            |

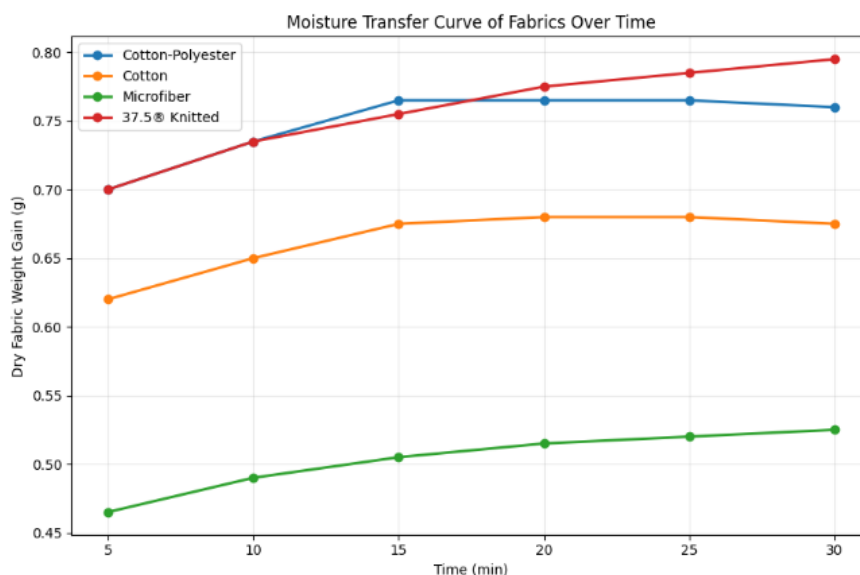


**Figure 1.** Transfer Wicking based on Dry Fabric Weight



In table 3, the Alambeta and OMMC test results for samples are presented. These data provide a comprehensive assessment of the thermal transport characteristics and overall moisture management capacity of the samples and the sample layer arrangement (e.g., Cotton+Cotton+Cotton), the first-listed material corresponds to the skin-facing side of the underarm pad.

**Table 3.** OMMC and Alambeta thermal comfort test results

| Sample Layers                  | Th. Cond.<br>$\lambda$<br>(mW/m·K)<br>$\times 10^{-3}$ | Th. Diff.<br>(mm <sup>2</sup> /s)<br>$\times 10^{-6}$ | Th. Abs.<br>(W·s <sup>1/2</sup> /m <sup>2</sup> ·K) | Th. Res.<br>(Km <sup>2</sup> /W)<br>$\times 10^{-3}$ | Heat Flow<br>Ratex10 <sup>3</sup> | qmax<br>(W/m <sup>2</sup> ) | OMMC |
|--------------------------------|--------------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------|------------------------------------------------------|-----------------------------------|-----------------------------|------|
| Cotton+Cotton+Cotton           | 43,48                                                  | 0,0968                                                | 143                                                 | 24,1                                                 | 2,342                             | 396,8                       | 0,55 |
| C/P+C/P+ C/P                   | 45,66                                                  | 0,0812                                                | 161                                                 | 19,64                                                | 2,062                             | 486,2                       | 0,33 |
| Cotton+37,5 knitted+Cotton     | 44,7                                                   | 0,123                                                 | 127                                                 | 30,8                                                 | 3,16                              | 489                         | 1,24 |
| C/P+37,5 knitted + C/P         | 42,3                                                   | 0,144                                                 | 111                                                 | 29,4                                                 | 3,24                              | 519                         | 1,33 |
| Cotton+37,5 knitted+Microfiber | 45,8                                                   | 0,103                                                 | 142                                                 | 27,9                                                 | 3,26                              | 558                         | 0,55 |
| C/P+37,5 knitted+Microfiber    | 42,5                                                   | 0,201                                                 | 95                                                  | 27,4                                                 | 2,69                              | 458                         | 0,46 |

### 3.1 Moisture Absorption of the Samples

Considering the moisture absorption values (Table 1), clear differences were observed among the tested fabrics. The 100% cotton fabric exhibited the highest moisture absorption (7.89%), which is consistent with the hydrophilic nature of cellulose-based fibers and their strong affinity for liquid water. The cotton/polyester blend showed a lower absorption value (4.23%), reflecting the reduced moisture affinity of polyester. Although the cotton component contributes to moisture uptake, the presence of polyester lowers the overall absorption capacity of the fabric. The 37.5® knitted fabric demonstrated a moderate moisture absorption value (3.60%), which is consistent with its functional role in facilitating moisture transfer rather than moisture retention. Its knitted structure allows some liquid interaction despite its relatively hydrophobic composition. Among all tested samples, the microfiber woven fabric exhibited the lowest moisture absorption (2.45%). This can be attributed to its compact structure and the hydrophobic characteristics of the synthetic fibers, both of which limit liquid uptake. Overall, the results indicate that fiber composition and fabric structure strongly influence moisture absorption behavior. For underarm pad applications, an optimal balance is essential, since excessive absorption may delay drying and reduce comfort, whereas insufficient absorption may limit effective sweat capture.

### 3.2 Air Permeability of the Samples

Considering the air permeability values, distinct differences were observed among the tested pad structures. As expected, the single-layer 37.5® knitted fabric showed the highest air permeability (707.76 mm/s) due to its open knit structure and high porosity, which facilitate airflow with minimal resistance. Among the multilayer pad structures, the incorporation of the 37.5® knitted layer generally improved air permeability compared to structures composed solely of woven shirting fabrics. For example, Structure III - C/P (310.40 mm/s) exhibited higher air permeability than II - C/P (218.26 mm/s), while Structure III - Cotton (206.60 mm/s) also outperformed II - Cotton (152.94 mm/s). These findings indicate that the 37.5® layer contributes positively to airflow within multilayer constructions. In contrast, Structures IV - Cotton (80.00 mm/s) and IV - C/P (84.70 mm/s), which include a microfiber outer layer, exhibited the lowest air permeability values. This reduction is mainly attributed to the dense and tightly woven structure of microfiber, which restricts airflow and lowers the overall breathability of the pad. A comparison of the single-layer shirting fabrics also showed that I - C/P (338.88 mm/s) had higher air permeability than I - Cotton (228.46 mm/s). This difference can be associated with the smoother and more uniform structure of polyester fibers, which allows easier airflow than the more irregular and moisture-retentive cotton fibers. Taken together, the results indicate that layer number, fabric thickness, and material structure strongly influence air permeability. While the inclusion of 37.5® fabric helps maintain airflow in multilayer pads, the addition of microfiber layers and increased thickness significantly reduce breathability.

### 3.3 Drying Rate of the Samples

Considering the drying rate values, clear differences were observed among the tested pad structures. The single-layer shirting fabrics (Structure I) showed the lowest drying performance, with 100% cotton (47.60 g/m<sup>2</sup>/h) drying slightly more slowly than the cotton/polyester blend (51.86 g/m<sup>2</sup>/h). This can be attributed to the higher moisture retention capacity of cotton fibers compared to polyester. A marked improvement was observed in the three-layer structures (Structure II), where both cotton (137.51 g/m<sup>2</sup>/h) and C/P (152.85 g/m<sup>2</sup>/h) versions exhibited considerably higher drying rates. This enhancement is likely due to the increased surface area and capillary pathways created by the multilayer configuration, which support faster moisture evaporation. The incorporation of the 37.5® knitted fabric in Structures III and IV further improved drying performance. Structure III - Cotton (166.80 g/m<sup>2</sup>/h) showed the highest drying rate among the pad assemblies, followed closely by Structure III - C/P (163.67 g/m<sup>2</sup>/h), demonstrating the strong moisture transfer and evaporation capability of the 37.5® layer. This is also consistent with the standalone drying performance of the 37.5® knitted fabric (123.78 g/m<sup>2</sup>/h). A different trend was observed in Structure IV, which includes a microfiber outer layer. While IV - Cotton (163.36 g/m<sup>2</sup>/h) maintained a drying rate comparable to Structure III, IV - C/P (133.48 g/m<sup>2</sup>/h) showed a noticeable decrease. This suggests that the combination of polyester shirting and microfiber may restrict moisture escape due to their relatively dense and less porous structures. This interpretation is also supported by the static moisture absorption results. Interestingly, the standalone microfiber fabric exhibited the highest drying rate overall (171.38 g/m<sup>2</sup>/h), indicating that drying behavior is influenced not only by airflow but also by fiber type and fabric structure. In general, the results show that multilayer configurations and functional fabrics such as 37.5® and microfiber markedly enhance drying performance compared to single-layer shirting fabrics.

### 3.4 Water Vapour Permeability of the Samples

Considering the water vapor permeability values, clear differences were observed among the tested pad structures. The single-layer shirting fabrics (Structure I) showed the lowest water vapor transmission values, with 100% cotton performing slightly lower than the cotton/polyester blend. This can be attributed to the higher moisture regain of cotton, which tends to retain vapor more than polyester. The three-layer structures (Structure II) exhibited values close to those of Structure I, with II - Cotton showing a slight decrease and II - C/P remaining relatively similar. This suggests that multilayering introduces some resistance to vapor transfer, although the effect remained limited due to the relatively thin fabric layers used. A clear improvement was observed in Structures III and IV, where the incorporation of the 37.5® knitted fabric enhanced water vapor permeability. Structure III - Cotton and Structure IV - Cotton outperformed both single- and three-layer counterparts, confirming the effectiveness of the 37.5® layer in promoting vapor diffusion through its open knitted structure and moisture management properties. Similarly, Structure III - C/P and Structure IV - C/P also showed improved water vapor permeability compared to their respective Structure I and II versions. However, these values remained slightly lower than those of the corresponding cotton-based structures, which contrasts with the trend observed in drying rate performance. This suggests that while polyester and microfiber components may support faster surface drying, they may also create a more compact structure that restricts steady-state vapor transmission. The standalone results of the 37.5® knitted fabric and microfiber fabric further confirm their strong vapor transfer capability, with microfiber showing the highest water vapor permeability overall. On the whole, the findings suggest that functional layers such as 37.5® knitted fabric and microfiber improve water vapor permeability, while fiber type, structural compactness, and total thickness play important roles in determining the final vapor transport behavior of multilayer underarm pad systems.

### 3.5 Transfer Wicking of the Samples

Considering the transfer wicking results (Fig. 1), clear differences were observed in the moisture transfer efficiency of the tested fabrics. The 37.5® knitted fabric exhibited the most rapid and sustained moisture transfer, as reflected by the continuous weight loss in the wet fabric and corresponding weight gain in the dry fabric throughout the test period. This performance can be attributed to its high porosity and effective capillary structure, which promote efficient moisture movement under pressure. In contrast, the microfiber fabric showed the lowest transfer wicking performance. Its dense and tightly woven structure restricts moisture migration, resulting in lower weight loss in the wet fabric and minimal weight gain in the dry fabric. This behavior is consistent with the moisture-retentive nature of microfiber fabrics. When

comparing the shirting fabrics, the cotton/polyester blend demonstrated better transfer performance than 100% cotton. This can be explained by the smoother and less hydrophilic nature of polyester fibers, which support more effective capillary-driven moisture transport than the more moisture-retentive cotton fibers. This difference was particularly noticeable during the first 10–15 minutes of the test. The  $\Delta$  values for both wet and dry fabrics further indicated that most moisture transfer occurred during the initial stage of contact, after which the transfer rate gradually plateaued. This suggests that capillary channels become increasingly saturated over time, thereby limiting further moisture migration. Taken together, the results show that fabric structure and fiber composition strongly influence transfer wicking performance. Fabrics incorporating 37.5® technology exhibited the most efficient moisture transfer, while microfiber fabrics showed the lowest. The cotton/polyester blend also outperformed pure cotton in facilitating capillary-driven moisture transport, particularly at the early stage of contact.

### **3.6 Thermophysiological Comfort and Moisture Management Properties**

The results indicate that the six multilayer underarm pad samples exhibit different thermo-physiological comfort profiles depending on their fiber composition and layer arrangement. Since underarm pads are expected to provide both thermal comfort and effective sweat management, the relationship between thermal conductivity, thermal absorptivity, thermal resistance, heat flow rate, and OMMC is particularly important.

In general, the incorporation of the 37.5® knitted layer improved moisture management performance, while the outer layer composition (cotton, cotton/polyester, or microfiber) played a major role in determining the thermal sensation and heat transfer behavior of the pad structures. The best moisture management performance was achieved by the 37.5®-containing structures without microfiber outer layers. In particular, the C/P+37.5 knitted+C/P structure provided the most effective combination of liquid transport, spreading, and one-way moisture movement, all of which are essential for a high OMMC value. By contrast, structures containing microfiber showed lower OMMC values, even though microfiber improved some other comfort-related parameters such as drying rate or cool touch sensation. This suggests that microfiber may help with surface-level moisture release, but not necessarily with through-thickness moisture transport, which is critical for efficient sweat management in underarm pads

The Cotton+Cotton+Cotton structure showed a moderate thermal conductivity (43.48) and low thermal diffusivity (0.0968), indicating that heat transfer through the structure occurs relatively slowly. Its thermal absorptivity (143) and  $q_{\max}$  (396.8 W/m<sup>2</sup>) suggest a moderate-to-soft initial warm feeling when first touched. In addition, its thermal resistance (24.1) was lower than the 37.5®-containing structures, meaning that its insulation performance was relatively limited.

Compared to the all-cotton version, the C/P+C/P+C/P structure exhibited higher thermal conductivity (45.66) and higher thermal absorptivity (161), together with a noticeably higher  $q_{\max}$  (486.2 W/m<sup>2</sup>). This indicates that the structure may feel cooler at first contact, since more heat is drawn rapidly from the skin surface.

The Cotton+37.5 knitted+Cotton structure exhibited a highly favorable comfort profile. Its thermal conductivity (44.7) remained moderate, while its thermal diffusivity (0.123) was higher than the fully cotton structures, suggesting more efficient heat distribution through the pad. Its thermal resistance (30.8) and thickness (3.16 mm) were also relatively high, indicating improved insulation and structural bulk.

Among all samples, C/P+37.5 knitted+C/P showed the highest OMMC value (1.33), indicating the best overall moisture management performance. This strongly confirms the positive contribution of the 37.5® knitted layer, as well as the ability of the cotton/polyester layers to facilitate liquid spreading and transfer more efficiently than pure cotton. Thermally, this structure also exhibited one of the most interesting profiles: it had the lowest thermal conductivity (42.3) among the six samples, but a relatively high thermal diffusivity (0.144) and high thermal resistance (29.4). This suggests that the structure may not conduct heat aggressively in steady-state conditions, but can still redistribute transient heat efficiently while also providing a degree of insulation. Its  $q_{\max}$  value (519 W/m<sup>2</sup>) indicates a cool and refreshing initial touch sensation. Therefore, this sample stands out as the most successful balanced structure in terms of both cool touch sensation and moisture management, making it especially promising for underarm pad applications where rapid sweat transfer and wearer freshness are important.

The Cotton + 37.5® knitted + Microfiber structure exhibited a distinct thermal and moisture management profile. It showed the highest thermal conductivity (45.8) and the highest  $q_{\max}$  value (558 W/m<sup>2</sup>) among all tested structures, indicating a strong capacity for heat transfer through the multilayer assembly. Since the skin-facing layer in this structure is cotton, the initial thermal sensation perceived by the wearer is primarily governed by the cotton surface rather than the microfiber layer itself. Therefore, the high  $q_{\max}$  value should be interpreted not as a direct surface effect of microfiber on the skin, but rather as a consequence of the overall thermal behavior of the entire multilayer structure. The elevated  $q_{\max}$  may be attributed to the combined influence of the cotton inner layer, the 37.5® knitted intermediate layer, and the microfiber outer layer, which together appear to facilitate efficient transient heat transfer across the structure. In this sense, the microfiber layer likely contributes indirectly by modifying the total thermal pathway and structural compactness of the pad rather than by directly affecting skin contact sensation.

Despite this favorable thermal response, the OMMC value (0.55) remained only moderate, similar to that of the all-cotton multilayer structure. This suggests that although the structure supports effective heat transfer, it does not achieve equally strong overall moisture management. This interpretation is consistent with earlier transfer wicking and moisture absorption findings, where microfiber-containing systems showed limited liquid transport despite favorable drying behavior. Therefore, this structure may provide a thermally responsive and relatively dry-feeling performance, but it appears less efficient in sustaining continuous sweat transport over time.

The C/P + 37.5® knitted + Microfiber structure, on the other hand, displayed one of the most distinctive thermal profiles among the tested samples. It exhibited the highest thermal diffusivity (0.201) and the lowest thermal absorptivity (95), indicating that heat can be redistributed relatively rapidly through the structure, while the initial warm/cool sensation at the skin-facing surface remains comparatively moderate. Since the skin-contacting layer is C/P, the wearer's initial tactile thermal sensation is mainly determined by the cotton/polyester surface rather than the microfiber outer layer. Its  $q_{\max}$  value (458 W/m<sup>2</sup>) was lower than that of Cotton + 37.5® knitted + Microfiber and also lower than C/P + 37.5® knitted + C/P, suggesting that although the structure supports heat diffusion, it does not generate as strong a transient cooling effect as some of the other multilayer assemblies. This may be related to the specific interaction between the C/P inner layer, the 37.5® knitted layer, and the dense microfiber outer layer, which together influence the heat flow behavior of the structure.

From a moisture management perspective, this sample showed a relatively low OMMC value (0.46), indicating that the combination of C/P and microfiber creates a more compact and less moisture-efficient multilayer assembly. The dense microfiber layer likely limits effective liquid spreading and interlayer transfer, even though it may contribute to certain aspects of drying or thermal responsiveness. As a result, this structure appears less effective in dynamic sweat management compared to the 37.5®-containing structures without microfiber.

Although a formal statistical analysis was not performed due to the preliminary proof-of-concept and prototype-design nature of this study, the performance deltas observed among the structures exhibit highly distinct and conclusive trends. For example, the C/P + 37.5® knitted + C/P assembly demonstrated an OMMC value of 1.33, which is more than double the values obtained from microfiber-containing counterparts (0.46–0.55). Such substantial margins clearly differentiate the performance capabilities of the proposed material combinations.

### **3.7 Underarm Pad Design**

Finally, the multilayer structure has been implemented in the design of a reusable underarm pad, for which a utility model has been registered under the title “Innovation in Outer Garments” (Registration No. 2024 003076). The design incorporates at least one fastening section to allow easy attachment to and removal from a shirt, and features a curved shape achieved through a circular cut in the middle section to ensure comfortable arm movement and prevent tightness in the underarm area.



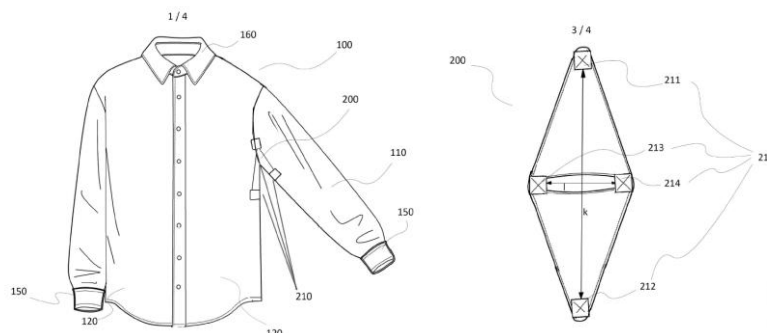


**Figure 2.** The underarm pad design covered by the utility model

#### 4. CONCLUSION

The present study systematically evaluated the impact of fiber composition and multilayer structure on the moisture management, drying behavior, air and vapor permeability, and thermophysiological comfort of underarm pad assemblies. Among the tested configurations, the inclusion of the 37.5® knitted layer consistently enhanced moisture transfer, drying rate, and water vapor permeability, demonstrating its critical role in facilitating effective sweat management. While microfiber layers contributed to rapid surface drying and thermal responsiveness, they restricted through-thickness moisture transport, resulting in lower overall moisture management performance (OMMC). The C/P + 37.5® knitted + C/P structure emerged as the most balanced and effective assembly, achieving the highest OMMC value (1.33) and providing an optimal combination of rapid sweat absorption, efficient moisture transfer, and favorable thermophysiological comfort. This structure seem to benefit from the synergistic effect of the 37.5® layer's high porosity and capillary action, combined with the liquid spreading capacity of cotton/polyester layers, without the restrictive influence of dense microfiber. Overall, these findings highlight the importance of integrating functional knitted layers such as 37.5® in multilayer underarm pad designs to maximize moisture management while maintaining breathability and thermal comfort. The results provide a clear framework for the development of high-performance, wearer-comfort-oriented underarm pads that efficiently manage sweat under dynamic conditions.

#### ACKNOWLEDGMENT

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## DESIGN OF HOME-TYPE KNEE PADS FROM AUXETIC KNITTED FABRICS WITH SUSTAINABLE FIBERS FOR ELDERLY PEOPLE

Aydes Korubay<sup>1,\*</sup>, Sude Akyüz<sup>1</sup>, Ezgi Aydın<sup>1</sup>, Cevza Candan<sup>1</sup>, Sena Duru<sup>1</sup>, Fatma Banu Nergis<sup>1</sup>, Evren Eski<sup>2</sup>, Hakan Doğan<sup>1</sup>

<sup>1</sup> Istanbul Technical University, Textile Engineering Department, Istanbul, Türkiye

<sup>2</sup> İntem Triko, Istanbul, Türkiye

\* a.korubay.6@gmail.com

### ABSTRACT

The aging process leads to changes such as weakening of the musculoskeletal system, decreased bone density, and loss of joint flexibility; as a result, older individuals face a higher risk of injuries from falls and impacts. Since the knee is one of the critical joints that support the body's load, knee injuries and joint degradation are commonly observed in elderly individuals. Such injuries not only affect physical health but also reduce quality of life by impacting individuals' psychological and social well-being. Protective clothing solutions such as knee pads which are developed to reduce the risk of injury, are generally thick and rigid in structure. So, they can limit user's comfort and mobility. Particularly for elderly users, there is a need for protective solutions made of relatively lightweight, comfortable materials that enhance mobility. Accordingly, in this study, we introduce auxetic fabrics that are developed using flat knitting technology to address the aforementioned limitations of the commercial knee pads for elderly people. Moreover, in order to ensure sustainability of the targeted product, Ne 8/1 and Ne 12/1 yarns made from Refibra/hemp and r-PET sustainable blends were employed for fabric development. These blends provide excellent durability and breathability while maintaining a smooth, comfortable touch. The study systematically investigates how variations in auxetic knit structures and loop density settings influence the performance and design suitability of home-type knee pads. In addition to auxetic performance of the developed fabrics, their mechanical performance is evaluated in accordance with relevant textile standards. The findings demonstrate that auxetic knitted fabrics can be designed and optimized through the strategic selection of manufacturing related variables for sustainable, cost-effective and comfortable protective knee pads tailored to the needs of the aging population.

**Keywords:** *Auxetic knitted fabric, comfort, hemp, knee pad, Refibra, elderly care.*

### INTRODUCTION

Aging is characterized by a progressive decline in bone mineral density, cartilage integrity, and joint flexibility, rendering the musculoskeletal system increasingly susceptible to mechanical trauma [1, 2]. The knee joint, as a critical load-bearing articulation, is disproportionately affected by age-related degeneration and constitutes one of the most common sites of fall-related injuries in the elderly population [3]. According to the World Health Organization, falls are the second leading cause of unintentional injury deaths worldwide, with adults over 60 years facing the greatest risk [4]. Consequently, the development of effective, wearable protective solutions that maintain comfort and mobility is of significant clinical and engineering importance.

Auxetic materials, defined by their negative Poisson's ratio (NPR) behavior, exhibit the counterintuitive property of lateral expansion under longitudinal tension and lateral contraction under compression [5, 6]. This unique deformation mechanism endows auxetic structures with several mechanically advantageous properties, including enhanced indentation resistance, superior energy absorption capacity, synclastic curvature, and variable porosity under strain [7, 8]. These characteristics make auxetic textiles particularly promising candidates for impact-protective applications such as knee pads, where conformability to complex anatomical geometries and effective load distribution are essential design criteria [9, 10].

Among the various textile manufacturing techniques, weft knitting offers exceptional versatility for producing auxetic structures through strategic manipulation of loop transfer sequences and stitch geometry [11, 12]. Previous studies have demonstrated that weft-knitted auxetic fabrics based on zigzag, re-entrant, and foldable architectures can achieve significant NPR values while maintaining the inherent flexibility and drapeability required for wearable applications [13, 14]. The mechanical performance of these structures is governed by several interdependent parameters, including yarn material properties, stitch density, loop

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length, and the specific auxetic pattern employed [15]. Coarser yarns and optimized loop transfer sequences have been shown to enhance the auxetic response by providing sufficient structural rigidity to resist loop collapse during deformation [9, 16].

The growing emphasis on environmental sustainability in the textile industry has prompted increasing interest in bio-based and recycled fiber alternatives [17]. Refibra™, a regenerated cellulosic fiber produced by Lenzing AG using recycled cotton scraps and wood pulp through the lyocell process, offers a reduced environmental footprint compared to conventional viscose and virgin cotton [18]. Similarly, hemp fibers provide excellent mechanical strength and moisture management properties while requiring minimal pesticide and irrigation inputs during cultivation. Recycled polyethylene terephthalate (r-PET), derived from post-consumer plastic waste, addresses the dual challenges of plastic pollution reduction and resource conservation in textile manufacturing [19].

Despite the extensive research on auxetic textile structures and sustainable fibers independently, studies investigating the integration of sustainable fiber blends into auxetic weft-knitted constructions for protective applications remain limited [7, 20]. Furthermore, existing commercial knee pad solutions for the elderly predominantly rely on conventional rigid thermoplastic or viscoelastic foam materials that compromise breathability and ergonomic conformity. Accordingly, this study aims to explore the mechanical, dimensional, and thermophysiological comfort properties of auxetic weft-knitted fabrics developed from sustainable Refibra/hemp and r-PET fiber blends as alternatives to commercial knee pads for elderly people. The specific objectives are to: (i) develop and characterize 86 auxetic knitted fabric samples with varying structural parameters, (ii) evaluate the auxetic behavior, air permeability, and thermal performance of the most promising configurations, and (iii) identify the optimal fabric construction that balances protective functionality with thermophysiological comfort for home-use knee pad applications.

## EXPERIMENTAL STUDY

### 2.1. Materials

The auxetic weft-knitted fabrics for knee pad prototypes were developed in cooperation with İntem Triko using sustainable yarn blends. Two yarn counts were employed: 8/1 Ne (6-ply construction) and 12/1 Ne (8-ply construction), formulated from Refibra/hemp and r-PET blends at varying composition ratios. Each yarn configuration incorporated 70-denier 2-ply elastane–polyamide gimped yarns to provide the necessary elastomeric recovery for auxetic deformation. The detailed yarn specifications and corresponding codes are presented in Table 1.

**Table 1. Yarn compositions and corresponding codes used in auxetic fabric production.**

| Yarn Code | Yarn Type                   |
|-----------|-----------------------------|
| 1         | 8/1 Ne 80/20% Refibra/Hemp  |
| 2         | 8/1 Ne 50/50% r-PET/Hemp    |
| 3         | 8/1 Ne 100% r-PET           |
| 4         | 8/1 Ne 80/20% r-PET/Hemp    |
| 5         | 8/1 Ne 50/50% Refibra/Hemp  |
| 6         | 12/1 Ne 80/20% r-PET/Hemp   |
| 7         | 12/1 Ne 80/20% Refibra/Hemp |
| 8         | 12/1 Ne 100% r-PET          |

### 2.2. Fabrication Method

Three distinct auxetic knitting structures, designated as Patterns A, B, and C, were designed using the Apex4 Design System based on a comprehensive literature survey of established auxetic weft-knit architectures [5, 11, 14]. All samples were fabricated on a Shima Seiki 112SVR E7-gauge computerized flat knitting machine using the sustainable 2-ply elastane–polyamide gimp yarn constructions described in Section 2.1. Each of the three patterns was knitted at four stitch densities (40, 43, 46, and 49 stitch/cm settings), yielding a total of 86 unique fabric samples (3 patterns × 8 yarn types × ~4 stitch densities, accounting for production constraints). The digital knitting patterns and structural representations of Patterns A, B, and C are illustrated in Figures 1–3.



**Figure 1.** APEX Digital Knitting Pattern and Structural Representation of Sample A



**Figure 2.** APEX Digital Knitting Pattern and Structural Representation of Sample B



**Figure 3.** APEX Digital Knitting Pattern and Structural Representation of Sample C

### 2.3. Characterization Methods

All fabric samples were subjected to dry conditioning for 72 hours at  $20 \pm 2$  °C and  $65 \pm 2\%$  relative humidity in accordance with ISO 139:2005, followed by wet relaxation to achieve dimensional stability prior to testing. The following structural, dimensional, and comfort properties were systematically measured: stitch density (courses and wales per cm), fabric areal density (TS EN 12127), thickness (TS 7128 / EN ISO 5084), dimensional change after washing (ISO 6330), air permeability at 200 Pa pressure differential (TS 391 EN ISO 9237), water absorption time (AATCC 79), and porosity (calculated from fabric density and fiber density). The auxetic behavior was quantified in accordance with the literature [18].

Thermophysiological comfort properties were evaluated using the Alambeta instrument, which measures thermal conductivity ( $\lambda$ , mW/m·K), thermal diffusivity ( $a$ , mm<sup>2</sup>/s), thermal absorptivity ( $b$ , W·s<sup>1/2</sup>/m<sup>2</sup>·K), and thermal resistance ( $r$ , m·K/W·m<sup>2</sup>) under steady-state and transient heat flow conditions [21]. The heat flow rate ( $P = q_{\max}/q_{\text{steady}}$ ) and maximum heat flow density ( $q_{\max}$ , W/m<sup>2</sup>) were also recorded to evaluate the warm-cool feeling upon initial skin contact.



## RESULTS AND DISCUSSION

### 3.1. Structural and Auxetic Properties

The structural and dimensional properties of the seven best-performing auxetic samples (selected from the initial 86 based on confirmed NPR behavior) are summarized in Table 2. All seven samples exhibited positive auxeticity values ranging from 2.06% to 5.49%, confirming the successful development of NPR behavior through the designed knitting architectures.

**Table 2. Structural and comfort properties of the seven highest-performing auxetic samples.**

| Sample Code | Weight (g/m <sup>2</sup> ) | Thickness (mm) | Porosity (%) | Water Abs. (s) | Air Perm. (cm <sup>3</sup> /cm <sup>2</sup> /s) | Auxeticity (%) |
|-------------|----------------------------|----------------|--------------|----------------|-------------------------------------------------|----------------|
| 40C.7       | 125                        | 4.87           | 80.6         | 38             | 31.93                                           | 3.00           |
| 43C.3       | 151                        | 5.64           | 79.4         | 5              | 55.77                                           | 2.11           |
| 43C.5       | 156                        | 4.53           | 77.2         | 12             | 45.80                                           | 2.11           |
| 46C.2       | 148                        | 5.41           | 81.0         | 0              | 53.40                                           | 2.38           |
| 46C.8       | 137                        | 3.96           | 77.0         | 43             | 77.77                                           | 2.90           |
| 40C.4       | 162                        | 3.12           | 59.9         | 40             | 48.96                                           | 5.49           |
| 46C.7       | 160                        | 4.75           | 82.4         | 4              | 39.27                                           | 2.06           |

Among all evaluated configurations, the C-coded zigzag pattern demonstrated the most pronounced auxetic response, which is attributable to the strategic loop transfer sequences inherent in this architecture that facilitate superior three-dimensional deformation under tensile strain [9, 14]. This observation is consistent with Aghazadeh et al. [9], who reported that zigzag-based auxetic weft-knitted structures exhibit enhanced formability and NPR characteristics compared to re-entrant and foldable configurations. Sample 40C.4 (80/20% r-PET/Hemp, 8/1 Ne, Pattern C, 40 stitch cam setting) achieved the maximum auxeticity of 5.49%, which represents a notable magnitude for weft-knitted textile structures and exceeds the NPR values reported for similar constructions in prior studies [5, 10].

Comparative analysis of yarn parameters revealed that the coarser 8/1 Ne yarns produced a higher auxetic response than the finer 12/1 Ne yarns across all pattern types. This behavior is attributed to the increased structural rigidity of coarser yarns, which resists loop collapse during deformation and thereby promotes the lateral expansion mechanism essential for NPR behavior [15]. Furthermore, a critical relationship was observed between yarn twist level and auxeticity: the lower twist values characteristic of the Refibra/hemp blends provided the structural flexibility required for geometric rearrangement of loop elements, whereas higher twist levels in certain r-PET formulations constrained loop mobility and reduced the auxetic response. This twist-dependent behavior is consistent with the theoretical framework described by Nguyen et al. [7], who identified yarn flexibility as a key determinant of NPR magnitude in textile structures.

### 3.2. Thermophysiological Comfort Properties

The Alambeta test results for the seven auxetic samples with the highest NPR performance are presented in Table 3. These data provide a comprehensive assessment of the thermal transport characteristics relevant to skin-contact comfort in knee pad applications.

**Table 3. Alambeta thermal comfort test results for the highest-performing auxetic samples.**

| Sample Code | Ther. Cond. $\lambda$ (mW/m·K) | Ther. Diff. $a$ (mm <sup>2</sup> /s) | Ther. Abs. $b$ (W·s <sup>1/2</sup> /m <sup>2</sup> ·K) | Ther. Res. $r$ (m·K/W·m <sup>2</sup> ) | Thickness $h$ (mm) | Heat Flow Rate P | qmax (W/m <sup>2</sup> ) |
|-------------|--------------------------------|--------------------------------------|--------------------------------------------------------|----------------------------------------|--------------------|------------------|--------------------------|
| 40C.7       | 82.4                           | 0.797                                | 92.3                                                   | 98.4                                   | 8.106              | 271.8            | 2.209                    |
| 43C.3       | 66.1                           | 1.709                                | 50.6                                                   | 158.4                                  | 10.479             | 157.5            | 1.919                    |
| 43C.5       | 81.0                           | 0.950                                | 83.1                                                   | 109.4                                  | 8.857              | 189.3            | 1.785                    |
| 46C.2       | 80.2                           | 2.234                                | 53.6                                                   | 123.7                                  | 9.917              | 172.8            | 1.718                    |
| 46C.8       | 61.0                           | 1.064                                | 59.1                                                   | 165.2                                  | 10.078             | 161.5            | 1.943                    |
| 40C.4       | 71.5                           | 0.492                                | 101.9                                                  | 139.2                                  | 9.949              | 294.8            | 2.912                    |
| 46C.7       | 70.0                           | 0.607                                | 91.0                                                   | 119.8                                  | 8.490              | 240.7            | 1.884                    |



The high porosity inherent in the auxetic structures (ranging from 59.9% to 82.4%) ensures effective air circulation through the fabric cross-section, which is a critical requirement for prolonged skin-contact wear in home environments. Sample 46C.8 exhibited notably favorable thermal characteristics, with the lowest thermal conductivity ( $61.0 \text{ mW/m}\cdot\text{K}$ ) and the highest thermal resistance ( $165.2 \text{ m}\cdot\text{K/W}\cdot\text{m}^2$ ) among all tested samples. This combination indicates superior thermal insulation capability, attributable to the high entrapped air volume within the 100% r-PET fiber structure at the 12/1 Ne count. The relatively low thermal absorptivity ( $59.1 \text{ W}\cdot\text{s}^{1/2}/\text{m}^2\cdot\text{K}$ ) of sample 46C.8 further suggests a warm tactile sensation upon initial contact, which is desirable for elderly users in domestic settings [21, 22].

Conversely, sample 40C.4, despite achieving the highest auxeticity (5.49%), exhibited the highest thermal absorptivity ( $101.9 \text{ W}\cdot\text{s}^{1/2}/\text{m}^2\cdot\text{K}$ ) and the maximum heat flow rate ( $P = 294.8$ ), indicating a relatively cooler initial contact sensation. This is explained by the lower porosity (59.9%) and more compact structure of this sample, which promotes conductive heat transfer from the skin surface. The thermal conductivity of 40C.4 ( $71.5 \text{ mW/m}\cdot\text{K}$ ) falls within the intermediate range, suggesting that while the high auxetic response provides excellent mechanical protection, the thermal comfort profile requires careful optimization of structural parameters.

### 3.3. Air Permeability and Moisture Management

Air permeability, measured at a pressure differential of 200 Pa, ranged from  $31.93$  to  $77.77 \text{ cm}^3/\text{cm}^2/\text{s}$  across the seven auxetic samples (Table 2). Sample 46C.8 achieved the highest air permeability ( $77.77 \text{ cm}^3/\text{cm}^2/\text{s}$ ), which is attributable to the combination of the finer 12/1 Ne yarn count that produces a more open fabric structure with well-connected interpore channels [23]. This value substantially exceeds the air permeability of conventional foam-based knee pads, which typically exhibit negligible breathability due to their closed-cell structure [3].

The relationship between water absorption, porosity, and thickness in the auxetic weft-knitted fabrics is closely interconnected, though non-linear due to the additional influence of loop geometry, yarn characteristics, and fiber hygroscopicity [24]. Higher porosity generally facilitates greater water uptake through enhanced capillary action across interconnected pore networks. Samples 40C.7 (porosity: 80.6%, water absorption: 38 s) and 46C.8 (porosity: 77.0%, water absorption: 43 s) exemplify this relationship, exhibiting moderate-to-high porosity with correspondingly longer water absorption times, indicating that water is retained within the fabric structure rather than rapidly passing through.

However, when pores become excessively large or insufficiently interconnected, water may transit through the structure without retention, reducing the overall moisture-holding capacity. Samples 46C.7 (porosity: 82.4%, water absorption: 4 s) and 46C.2 (porosity: 81.0%, water absorption: 0 s) demonstrate this phenomenon, suggesting a fundamentally different pore geometry characterized by large, interconnected channels that facilitate rapid throughflow rather than absorption. Thickness influences the total water storage capacity, as thicker fabrics contain more fiber material and greater internal volume for moisture retention. Samples 43C.3 (thickness: 5.64 mm, water absorption: 5 s) and 46C.2 (thickness: 5.41 mm, water absorption: 0 s) demonstrate that increased thickness with high porosity can yield rapid uptake with limited retention in loose structures [22, 24]. Overall, moisture management performance in auxetic weft-knitted fabrics is governed by a complex interplay between porosity, thickness, fiber hygroscopicity, and structural configuration.

These results collectively demonstrate that by optimizing stitch length, pattern geometry, and fiber composition, sustainable r-PET and Refibra/hemp blends can effectively replace conventional synthetic materials, providing a lightweight, breathable, and ergonomic protective solution tailored for the aging population. The superior overall performance of sample 46C.8 (100% r-PET, 12/1 Ne, Pattern C, 46 stitch length setting) confirms the feasibility of achieving a balanced configuration that simultaneously addresses auxetic protection, air permeability, and thermal comfort requirements for home-use knee pad applications.

## CONCLUSION

This study systematically developed and characterized 86 seamless, eco-friendly knee pad fabrics incorporating auxetic weft-knitted architectures produced from sustainable Refibra, hemp, and r-PET fiber blends. The comprehensive evaluation revealed that fabric structural parameters, yarn composition, and stitch density exert significant influences on auxetic behavior, air permeability, and thermal comfort performance.

The zigzag-based Pattern C consistently outperformed Patterns A and B in terms of NPR magnitude, confirming the superiority of zigzag loop transfer architectures for achieving pronounced auxetic behavior in weft-knitted textiles. Although sample 40C.4 demonstrated the maximum auxeticity (5.49%), its relatively low porosity (59.9%) and elevated thermal absorptivity limit its suitability for prolonged domestic wear. Sample 46C.8 (100% r-PET, Pattern C, 46 loops) emerged as the most balanced sustainable configuration, combining a robust auxetic response (2.90%) with the highest air permeability (77.77 cm<sup>3</sup>/cm<sup>2</sup>/s), favorable thermal resistance (165.2 m·K/W·m<sup>2</sup>), and a warm contact sensation suitable for elderly home use.

The findings establish that optimal knee pad design for the elderly requires a multi-objective optimization approach balancing auxetic expansion, breathability, and thermal comfort. Future research directions may include: (i) dynamic impact testing under simulated fall conditions to quantify energy absorption performance, (ii) integration of shear-thickening fluid (STF) layers to enhance impact mitigation [20], (iii) extended wear trials with elderly participants to validate subjective comfort assessments, and (iv) life-cycle assessment (LCA) of the sustainable fiber blends to comprehensively evaluate the environmental benefits of the proposed material system.

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## DESIGNING STRENGTH AT THE SEAM: JOINING STRATEGIES FOR WOOL–CORDURA HYBRID TEXTILES

Nur Seçgin<sup>1</sup>, Özge Çolak Yıldırım<sup>1</sup>, Melike Çavdar<sup>1</sup>, Nursema Pala Avcı<sup>2</sup>, Özgür Atalay<sup>3</sup>, Emine Dilara Koçak<sup>2</sup>

<sup>1</sup>Aymarka Mağazıcılık A.Ş.

<sup>2</sup>Marmara University

<sup>3</sup>Istanbul Technical University

### ABSTRACT

Seam performance is a critical parameter determining the durability and functional integrity of textile products, especially in high-performance fabrics such as Cordura-based materials. This study investigates the effect of different joining techniques, including ultrasonic welding and conventional sewing methods, on the seam strength of a woven fabric composed of 69% wool, 29% Cordura (polyamide), and 2% elastane. Ultrasonic bonding was applied at 140°C, 20 seconds, and 5 bar pressure, while conventional seams were produced using polyester sewing threads of different linear densities (Tex 120 and Tex 50) and stitch configurations (single and double needle). Seam strength tests were conducted according to ISO 13935-2, and tensile strength and tear strength tests were performed in accordance with ISO 13934-1 and ISO 13937-1, respectively. Results revealed that ultrasonic seams exhibited significantly lower seam strength values (5.62–7.94 kgf), failing to meet the required minimum threshold of 10 kgf. In contrast, conventional sewn seams demonstrated superior performance, with seam strengths ranging from 39.46 to 58.4 kgf. The highest values were obtained from double-needle sewing configurations, highlighting the importance of stitch structure. Failure analysis indicated that seam failure predominantly occurred due to sewing thread breakage rather than fabric rupture, suggesting that the fabric strength exceeded seam strength. The results confirm that ultrasonic welding is not suitable for fabrics with high non-thermoplastic fiber content such as wool. The findings provide important insights for optimizing seam performance in hybrid textile structures and contribute to the understanding of joining technologies in technical textiles.

**Keywords:** Cordura fabric, Hybrid textile structures, Seam strength, Sewing parameters, Ultrasonic welding

## DEVELOPMENT AND ENVIRONMENTAL EVALUATION OF REUSABLE WOVEN FILTERS FOR MICROFIBER EMISSION REDUCTION

Gokce Sakmar<sup>1</sup>, Hande Sezgin<sup>1</sup>, Ipek Yalcin-Enis<sup>1</sup>

<sup>1</sup> Istanbul Technical University, Faculty of Textile Technologies and Design, Textile Engineering Department, Istanbul, Türkiye.

\*sakmar15@itu.edu.tr

### ABSTRACT

The increase in the occurrence of microplastic pollution in both water and land ecosystems has become a major concern in the field of environmental science. The main contributor to microfiber pollution in water bodies is domestic laundry, and most sewage treatment plants do not filter these micro-sized fibers, causing them to flow into natural water resources. To filter these microplastic pollutants at their source, this research aims to design and test filters made from woven polyester fabric, which can be used in household washing machines. The research method in this project involved creating plain woven fabrics with two different weft densities (17 and 33 picks per cm) to investigate their effect on filter efficiency. The prototypes designed in this research were first physically tested and then their filtration performance was assessed using a vacuum filtration test. The research further discussed the importance of the sustainability of the filter, and using the Higg Materials Sustainability Index method, the carbon footprint of the most efficient filter was calculated. The results demonstrate that plain weave fabric with a higher weft density of 33 picks per cm achieved a microplastic filtration efficiency of 96.60%, significantly outperforming fabric with lower weft density. Life cycle assessment results indicate that the high-performance woven polyester filter exhibited a low carbon footprint due to its reusability. Moreover, its long-term contribution to mitigating microplastic pollution suggests substantial environmental benefits.

**Keywords:** *Microfiber, Filtration, Laundry machine, Woven fabric*

### 1. INTRODUCTION

The presence of microscopic pollutants in ecosystems has come to represent an important environmental crisis over the last few years [1]. Specifically, microplastics and synthetic textile materials have received significant scientific attention owing to their widespread presence and adverse effects on biological health [2]. Researchers have been able to identify these microfibers in various ecosystems, ranging from urban wastewater to the Arctic environment [3]. Although the plastic waste is currently being effectively managed on land, studies have shown that the concentration of microplastics in the ocean is expected to double by 2030, thus calling for immediate intervention by scientists and regulatory authorities [4].

The breakdown of plastic waste in marine ecosystems gives rise to microplastics, which measure between 1 mm and 5 mm, and nanoplastics, which measure between 1 nm and 1 mm, and have significant impacts on living organisms [5, 6, 7]. The source of microplastics is varied, including the use of microbeads in personal care items and the release of synthetic fibers during washing [8]. The textile industry is one of the primary contributors to microplastic pollution, with microfibers making up between 15% and 31% of the total 9.5 million tons of plastic waste that enter the ocean annually [8, 9]. Synthetic clothing, which makes up almost half of global clothing production, releases microplastic fibers during regular laundry cycles [10]. The released fibers move through the wastewater treatment system, often evading filtration systems because of their small size, and eventually enter the marine ecosystem [11]. A single laundry cycle can release up to 700,000 individual fibers, and it is projected that between 2015 and 2050, 22 million tons of microfibers will enter the marine ecosystem if the current trend is allowed to persist [11, 12].

Investigation into household laundering as a primary source of microplastics documented more than a decade ago, showing that specific washing parameters significantly influence the volume of fiber release [13]. A typical 6 kg laundry load can generate over 700,000 particles, a number that can surge to six million under certain conditions [11, 14]. Consequently, laundry wastewater that is either unfiltered or inadequately treated is recognized as a major factor in the buildup of microplastics within marine environments [11].



Although the initial scientific investigation mainly focused on synthetic materials, emerging research has revealed that natural fibers, such as cotton and wool, also remain in the environment and pose ecological risks [3]. While fibers composed of cellulose tend to degrade at a faster rate, they also tend to be dyed with toxic chemicals, which can be harmful to aquatic life [2, 3]. Laboratory tests have also revealed that natural cotton fibers can interfere with the physiological development of aquatic life [2]. Additionally, natural fibers tend to lose a higher number of fibers during the washing cycle, owing to their intrinsic structural properties, as opposed to their synthetic counterparts [15].

Until such time as source reduction is improved, the installation of specialized microfiber filters in washing machines is still a top priority [9]. The effectiveness of such a filter is dependent upon a complex interrelation of various properties, including fibers, yarn composition, and overall textile architecture [16]. Factors such as cross-sectional shape and fiber diameter play a crucial role in balancing the effectiveness of the filter, water flow rates, and power consumption [17, 18]. The shape of the fibers also plays a role, as does the type of yarn used, whether monofilament or multifilament, which poses the challenge of balancing throughput rates with entrapment effectiveness [16, 19]. Furthermore, the weave pattern also has a significant role to play, requiring a comprehensive approach to achieve optimal mechanical effectiveness [19].

The objective of this study is to design woven textile filters using draw texturized polyester multifilaments with two different weft densities (17 and 33 picks per cm) to control microfiber emissions during the laundering process. The novelty of the study lies in the design of reusable and washable filter that can be easily integrated into washing machine designs and evaluation of its environmental impact.

## **2. EXPERIMENTAL STUDY**

### **2.1 Materials**

In the current research, 36 filament, 100 denier, draw texturized 100% polyester yarns were provided by Tepar Textile. In order to model the microfibers commonly shed by textiles during laundering, the study utilized 20-micron flock fibers provided by Flokcan.

### **2.2 Methods**

#### **2.2.1 Physical Tests**

The mass per unit area of the fabric specimens was determined in compliance with the TS ISO 3801 standard. The measurements were taken at three distinct locations on each specimen and results were documented as the mean and standard deviation for each respective group.

#### **2.2.2 Vacuum Filtration Test**

To replicate the filtration environment of a domestic washing machine, a custom laboratory-scale vacuum filtration assembly was developed. The apparatus utilized a water ejector driven by a vacuum pump maintained at a constant pressure of 2 bar. To ensure a stable vacuum and prevent atmospheric interference, the filtration fluid was fed through a hermetically sealed intake. Circular fabric specimens, 45 mm in diameter, served as the filtration membranes, with triplicate testing conducted for each fabric variant. The experimental filtration medium comprised 0.5 g of 20-micron flock fibers dispersed in 100 mL of water, serving as a proxy for microplastic pollutants. Following the vacuum-assisted filtration of this mixture, the captured fibers were harvested on the fabric's surface. The specimens then underwent a drying stage at 120°C for 60 minutes, followed by a conditioning period to reach moisture equilibrium. The actual amount of fiber retained was then determined using a high-precision balance (Sartorius TE313S). Finally, the filtration efficiency and hence the capability of each fabric to filter microfiber was determined by the gravimetric difference between the two measurements.

### **2.3 Environmental Impact Assessment**

Following the approach to the analysis of the filtration performance, the ecological profile of the selected filter was also considered. The study was conducted according to ISO 14067:2018, and a solid foundation for calculating the carbon footprint of the product was developed. The study had a cradle-to-gate scope, covering the production of raw PET materials, yarn production, transport, and weaving. As the filters were only produced by weaving, without any additional chemical treatment, dyeing, or finishing, the use phase,

packaging, or end-of-life phase were not considered in the study. The functional unit (FU) was defined as a single reusable woven filter measuring 100 cm<sup>2</sup> with a mass of 0.79 g (Configuration PET-33), serving as the primary reference for all inventory scaling and impact modelling. Given that the production process yielded a singular output, allocation procedures were unnecessary. Life cycle inventory (LCI) data were synthesized from Ecoinvent v3.11, DEFRA (2025) emission factors, and electricity grid datasets from the Republic of Türkiye Ministry of Energy and Natural Resources. Logistics were calculated based on a cumulative road distance of 705 km, accounting for the transport of polyester yarn from Istanbul to Bursa (289 km) and the subsequent delivery of finished fabric to Kırklareli (416 km). The energy demand was restricted to the electricity consumed during the weaving process, to the extent that heat energy and water were not considered. In order to maintain consistency with the industry standard, the study was complemented by the Higg Materials Sustainability Index (Higg MSI) and the Higg Product Module. The overall structure was provided by ISO 14067, while the standardized secondary inventory values for polyester materials were provided by Higg MSI. The study focused on four key environmental impact categories: global warming potential, water scarcity, eutrophication potential, and fossil resource depletion.

## **1. RESULTS**

### **1.1 Physical Test Results**

Increasing the weft density from 17 to 33 picks/cm significantly raised the basis weight of 36-filament samples from 60.50 g/m<sup>2</sup> in PET-17 to 79.00 g/m<sup>2</sup> in PET-33. An increase in weft density clearly results in a higher cover effect, since more yarns per unit length contribute to greater surface occupation and structural compactness [20].

### **1.2 Vacuum Filtration Protocol**

The filtration analysis indicates that the PET-33 specimen, characterized by a 36-filament yarn, plain weave structure, and high weft density, achieved the highest filtration efficiency (96.60%), outperforming the PET-17 specimen, which exhibited a filtration efficiency of 92.30%. It is demonstrated that a textile's filtration performance is enhanced when the material possesses a high yarn count and a compact physical structure that minimizes gaps in the weave [21, 22].

## **3.3. Environmental Performance of the Woven Microplastic Filter**

### **3.3.1. Environmental Impact Assessment and Life Cycle Results**

In accordance with the Higg MSI inventory benchmarks for polyester textiles, the global warming potential was established at 14.1 kg CO<sub>2</sub>-eq per kilogram of material. When adjusted to the specific functional unit of this study, the initial manufacturing impact is approximately 0.011 kg CO<sub>2</sub>-eq per reusable filter. Further environmental indicators derived from the Higg MSI dataset revealed an eutrophication potential of 0.005 kg PO<sub>4</sub><sup>3-</sup>-eq/kg, a water scarcity index of 4.34 m<sup>3</sup> H<sub>2</sub>O-eq/kg, and fossil resource depletion valued at 198 MJ/kg. On an individual unit basis, these metrics translate to 3.9 mg PO<sub>4</sub><sup>3-</sup>-eq, 3.4 L H<sub>2</sub>O-eq, and 0.156 MJ, respectively.

Operational data indicated that producing 300 m<sup>2</sup> of woven fabric required 68 kWh of electricity, enabling the manufacture of approximately 30,000 filters over a 7.6-hour weaving period. The comprehensive environmental profile suggests that the impacts during the production stage are minimal and primarily driven by the synthesis of the polyester raw material. Conversely, the weaving process accounts for a significantly lower proportion of the total impact, a direct consequence of eliminating energy-intensive finishing and chemical treatment stages.

### **3.3.2. Interpretation of Environmental Performance in Relation to Filtration Efficiency and Microplastic Mitigation**

The Life Cycle Assessment (LCA) demonstrates that the majority of the environmental impact associated with the production of the single filter comes from the production of the raw materials, but the filter's excellent efficiency and its ability to be reused contribute to its positive environmental impact. The optimized PET-33 configuration achieved a microplastic retention rate of 96.60% in laboratory trials. Such high performance facilitates the effective sequestration of synthetic microfibers during laundering, which is a process identified as a primary contributor to aquatic microplastic contamination. Research suggests that microfiber shedding during washing ranges from 124 to 308 mg per kilogram of textile, which

translates to the release of roughly 640,000 to 1,500,000 individual fibers [23]. Consequently, even a partial interception of these discharges constitutes a substantial and measurable environmental intervention.

In contrast to disposable mitigation strategies, this filter is engineered for prolonged, repeated application without compromising structural stability or filtration capacity. The mechanical resilience of the woven polyester architecture ensures that the initial production impacts are amortized over numerous washing cycles, thereby drastically lowering the environmental footprint per use. Consequently, the production-phase impact of approximately 0.011 kg CO<sub>2</sub>-eq per unit serves as a one-time environmental investment that provides continuous prevention of microfiber leakage throughout its functional lifespan.

Methodologically, the ISO 14067 standard indicates that avoided emissions should not be deducted from a product's carbon footprint. Therefore, the reported numbers account only for direct emissions from the production process. Nonetheless, preventing microfiber emissions provides an additional environmental benefit, slightly improving the LCA results. This decision is also supported by the Higg MSI framework, which suggests considering the multi-impact approach to material efficiency and longevity.

The decision to use polyester as the primary material is critical in achieving the balance between the initial environmental impact and the product's longevity. Although it is derived from fossil fuels, the polyester fabric's resistance to mechanical, chemical, and wet environmental exposure makes it suitable for long-lasting filtration processes [24]. On the other hand, natural materials may be biodegradable, but their tendency to degrade easily when wet may compromise the filtration process and require frequent replacement [25].

At a systemic level, the ecological ramifications of the broad-scale implementation of these filters are notably profound. Manufacturing data reveal that a 7.6-hour production window, requiring only 68 kWh of electrical energy, yields approximately 30,000 filter units. Integrating these reusable membranes, capable of sequestering over 96% of liberated microfibers, into an equivalent volume of domestic washing machines would drastically curtail the influx of microplastics into wastewater infrastructure and subsequent aquatic ecosystems. This inherent scalability, coupled with the minimal per-unit environmental footprint of production, underscores the filter's viability as a pragmatic and potent source-control strategy for mitigating microplastic contamination.

#### **4. CONCLUSION**

In this research, two different polyester plain woven textiles were fabricated to assess the effect of weft density on the efficacy of microfiber filtration media for domestic laundering. The experimental outcomes indicate that higher weft density specimen (PET-33) demonstrated the higher filtration efficiency at 96.60%. While this fabric emerged as the most effective candidate, in-situ testing within functional washing machine environments was outside the current research scope. Given that optimal filtration must be equilibrated with hydraulic permeability and pressure drop, subsequent evaluations under authentic laundering conditions are warranted. From the environmental assessment, it can be determined that the woven microplastic filter has a minimal ecological footprint during the production phase, as indicated by the cradle-to-gate life cycle analysis. The carbon footprint per unit is also low, primarily because of the production of the polyester substrate. The fact that processes such as dyeing, finishing, and chemical modifications are not required in the production of this filter also helps in reducing the overall energy and materials used in the production phase. When the high efficiency of the filter in retaining pollutants is combined with its reusability, the results suggest that there is a favorable balance between the production phase and the overall reduction in the discharge of pollutants. Thus, this polyester filter can be considered an ecologically viable source-control measure for reducing microfiber discharge from domestic washing machines.

While in-situ testing within fully functional domestic washing machines was outside the immediate scope of this preliminary study, the custom laboratory-scale vacuum filtration protocol was rigorously designed to simulate real-world operating conditions. Specifically, the operating pressure was maintained at a constant 2 bar, directly referencing the average hydraulic pressure values encountered in standard domestic washing cycles, thereby ensuring the practical relevance and baseline validity of the filtration efficiency results. Nevertheless, to comprehensively transition from laboratory-scale prototyping to real-world integration, subsequent evaluations under authentic laundering environments are essential. Future research directions will expand upon these findings by explicitly focusing on long-term structural durability, in-situ

pressure drop profiles, and continuous hydraulic performance under realistic, multi-cycle domestic operating conditions.

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## DEVELOPMENT OF A CAPACITIVE SLIDING-ELECTRODE TEXTILE SENSOR FOR JOINT MOTION MONITORING

Serenay Zeynep Eğriboyun<sup>1,\*</sup>, İbrahim Adel Khamis Ahmed<sup>1</sup>, Münire Sibel Çetin<sup>1</sup>, Kadir Özlem<sup>2</sup>, Ash Tunçay Atalay<sup>1</sup>, Özgür Atalay<sup>1</sup>

<sup>1</sup> Istanbul Technical University, Department of Textile Engineering, Istanbul, Türkiye

<sup>2</sup> Istanbul Technical University, Department of Computer Engineering, Istanbul, Türkiye

\* [egriboyun19@itu.edu.tr](mailto:egriboyun19@itu.edu.tr)

### ABSTRACT

Wearable textile-based sensors are promising for continuous human motion monitoring due to their flexibility, comfort, and garment compatibility. In this study, a textile-based capacitive sensor with a layered sliding-electrode architecture was developed for joint motion monitoring. The sensor consists of two face-to-face comb-like textile electrodes separated by a dielectric layer and initially positioned without overlap. During joint motion, relative sliding between the electrode layers increases the effective overlap area, resulting in a measurable capacitance change. The sensor was characterized using a tensile tester and a customized fixture that simulates joint-like deformation. The results showed stable and repeatable electromechanical behavior, with a clear increase in normalized capacitance response as a function of crosshead displacement and high fitting accuracy in the effective response region ( $R^2 = 0.99$ ). The response delay was approximately 0.08 s, and cyclic testing over 1000 cycles indicated no significant signal degradation. Wearable demonstrations during squat motion further confirmed that the sensor can monitor repetitive lower-body movements, with a stronger response at the knee than at the hip. Overall, the proposed sensor offers a simple and promising approach for garment-integrated joint motion monitoring.

**Keywords:** *Textile sensor, Capacitive sensor, Wearable motion monitoring, Sliding-overlap, Smart textiles*

### 1. INTRODUCTION

Wearable textile-based sensor systems have attracted increasing attention for real-time monitoring of human motion due to their flexibility, comfort, and ability to be directly integrated into garments [1–3]. Compared with conventional motion monitoring systems, textile-based sensors offer a more suitable approach for long-term and unobtrusive monitoring, particularly around joints where repeated bending and deformation occur [2–4]. Among wearable sensing mechanisms, capacitive sensors are promising because they respond to geometric and dielectric changes and can provide stable and repeatable signals for motion tracking applications [1,5–7]. Textile-based capacitive sensors can be designed using different structural configurations, including planar and layered architectures [8]. Planar interdigital structures mainly rely on in-plane electric field modulation [7,9], whereas layered structures typically consist of opposing electrodes separated by a dielectric layer, where capacitance changes are associated with variations in electrode spacing or effective overlap area [8,10]. Previous studies have also shown that relative displacement between conductive layers can modulate capacitance through changes in electrode overlap area [11,12]. Based on this principle, this study proposes a textile-based capacitive sensor with a layered sliding-electrode architecture. The sensor consists of two face-to-face comb-like textile electrode layers that are initially positioned without overlap. During joint-like motion, relative sliding between the layers increases the effective overlap area, producing a measurable capacitance change. The aim of this study is to evaluate the proposed sensor in terms of electromechanical response, crosshead displacement-related capacitance behavior, cyclic durability, pressure cross-sensitivity, and wearable applicability.

## 2. EXPERIMENTAL STUDY

### 2.1 Sensor Fabrication and Working Principle

The sensor was fabricated using silver-plated polyamide woven fabric as the conductive electrode material, linear low-density polyethylene (LLDPE) film as the dielectric layer, and an elastic textile substrate. Low-extensibility yarns were placed along both sides of the electrode region to improve dimensional stability and limit undesired stretching of the sensing area. The structure consists of two face-to-face comb-like textile electrode layers separated by a dielectric layer, as shown in Figure 1. Four sensor designs with electrode finger widths of 0.3, 0.6, 1.2, and 2.4 cm were prepared to examine the effect of electrode geometry. In the initial state, the electrode fingers were positioned between the gaps of the opposite electrode layer without overlap. During joint-like deformation, the electrode layers slide in opposite directions within the unbonded sliding region, increasing the effective overlap area and therefore the capacitance.

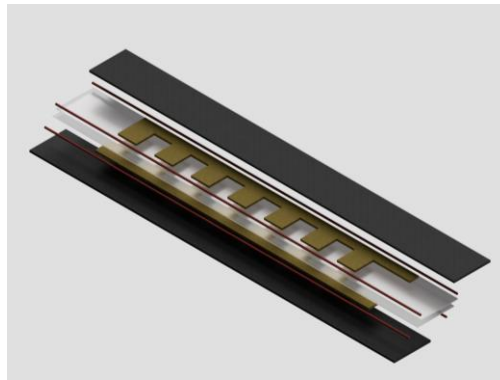


**Figure 1.** Exploded schematic illustration of the proposed textile-based sliding-electrode capacitive sensor.

### 2.2 Electromechanical Characterization

The sensor was tested using a tensile tester equipped with a customized fixture. The sensor ends were fixed, while a rigid indenter attached to the crosshead applied localized deformation to the central region. Force, crosshead displacement, and capacitance were recorded simultaneously during loading–unloading tests at 300 mm min<sup>-1</sup>. The normalized capacitance change was calculated as  $\Delta C/C_0$ .

### 2.3 Pressure, Cyclic Durability, and Wearable Demonstration

Pressure cross-sensitivity was evaluated using the 2.4 cm finger-width sensor under predefined overlap levels from 0 to 2.4 cm and external loads from 50 to 500 g. Cyclic durability was tested over 1000 loading cycles. For wearable demonstration, the sensor was integrated into leggings at the hip and knee regions, and capacitance signals were recorded during repeated squat movements.

## 3. RESULTS

### Electromechanical Response and Crosshead Displacement Behavior

Figure 2(a) shows the synchronized force, crosshead travel, and normalized capacitance response ( $\Delta C/C_0$ ) of the 1.2 cm finger-width sensor during 10 loading–unloading cycles. As the crosshead moved downward, the applied force and  $\Delta C/C_0$  increased simultaneously, confirming the electromechanical response of the sensor under joint-like deformation. During unloading, the capacitance signal returned close to its initial level, and repeated cycles showed similar response profiles, indicating reversible and repeatable sensor behavior. The relationship between  $\Delta C/C_0$  and crosshead displacement is presented in Figure 2(b). At the beginning of loading, the capacitance response remained limited up to approximately 15 mm of crosshead displacement, indicating an initial low-response region. After this stage,  $\Delta C/C_0$  increased more clearly with

further crosshead displacement, corresponding to the effective sliding-overlap response region. A second-order polynomial fit applied to this region showed high fitting accuracy ( $R^2 = 0.99$ ), demonstrating a strong relationship between crosshead displacement and the electrical response.

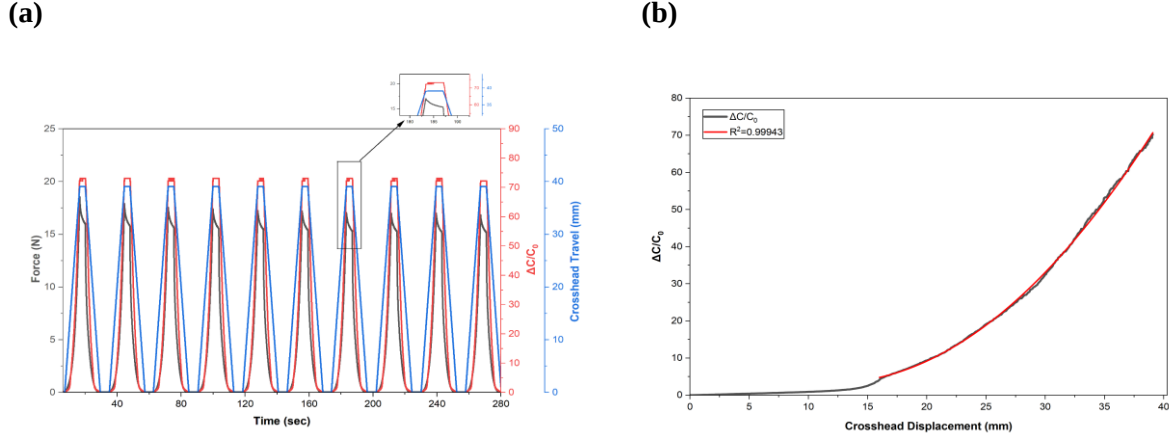


**Figure 2.** Electromechanical response of the 1.2 cm finger-width sensor: (a) synchronized force, crosshead travel, and normalized capacitance response ( $\Delta C/C_0$ ) during 10 loading–unloading cycles; (b) normalized capacitance response as a function of crosshead displacement.

### 3.2 Effect of Electrode Geometry, Response Delay, and Cyclic Durability

Figure 3(a) compares the normalized capacitance responses of sensors with electrode finger widths of 0.3, 0.6, 1.2, and 2.4 cm as a function of normalized crosshead displacement. The 2.4 cm sensor showed the highest response, followed by the 1.2 cm sensor, whereas the 0.3 cm and 0.6 cm sensors exhibited lower responses. This indicates that electrode finger width is an important design parameter for tuning the sensor response. The mechanical-to-electrical response delay was determined from the initial loading stage, as shown in Figure 3(b). The onset of crosshead motion was compared with the first  $\Delta C/C_0$  response exceeding the baseline noise band, and the delay was found to be approximately 0.08 s. Cyclic durability was evaluated over 1000 loading cycles, as shown in Figure 3(c). The sensor maintained a stable response without evident signal degradation. The initial and final peak  $\Delta C/C_0$  values were 24.15 and 24.25, respectively, corresponding to a retained response of 100.41%.

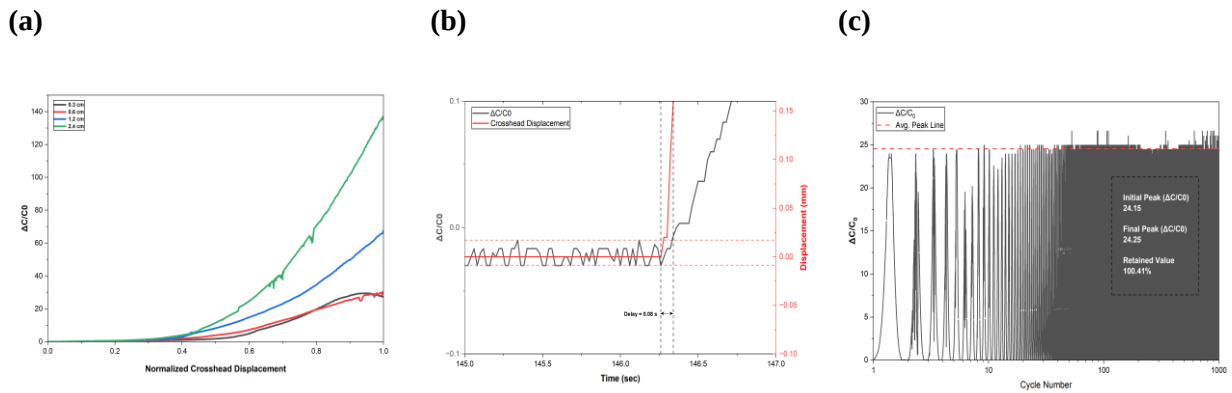


**Figure 3.** Electrode geometry effect, response delay, and cyclic durability: (a) normalized capacitance responses of sensors with different electrode finger widths as a function of normalized crosshead displacement; (b) enlarged initial loading stage used to determine the mechanical-to-electrical response delay; (c) cyclic durability of the 1.2 cm finger-width sensor over 1000 loading cycles.

### 3.3 Pressure Cross-Sensitivity and Wearable Demonstration

Pressure tests showed that  $\Delta C/C_0$  increased with normal load, especially at higher overlap levels; however, the limited response at low overlap confirms that sliding-induced overlap variation is the dominant sensing mechanism. For wearable demonstration, the sensor was integrated into leggings at the hip and knee regions. During squat tests, both sensors produced repeatable cyclic  $\Delta C/C_0$  signals, with a higher response at the knee due to larger deformation, as shown in Figure 4(a). The garment-integrated sensor configuration is shown in Figure 4(b), demonstrating the applicability of the sensor for lower-body motion monitoring.

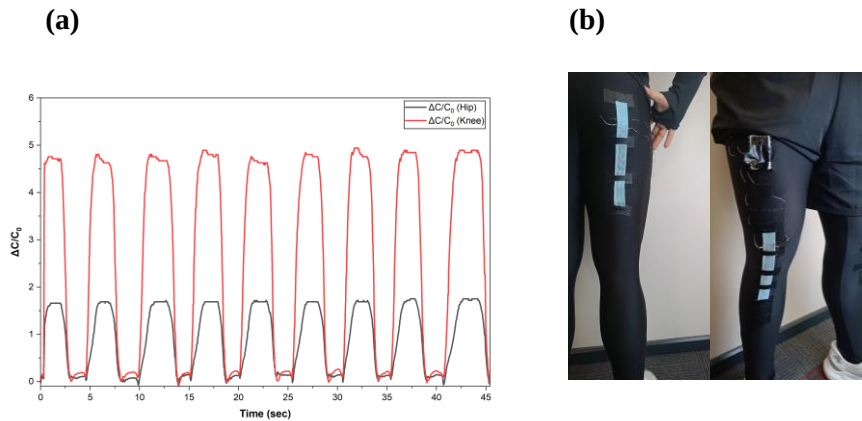


**Figure 4.** Wearable demonstration of the proposed textile sensor: **(a)** normalized capacitance responses ( $\Delta C/C_0$ ) of hip- and knee-mounted sensors during 10 squat cycles; **(b)** integration of the sensor into leggings at the hip and knee regions.

## 4. CONCLUSION

In this study, a textile-based capacitive sensor with a layered sliding-overlap architecture was developed for wearable joint motion monitoring. The sensor operates through sliding-induced overlap variation between face-to-face textile electrode layers, distinguishing it from conventional planar or tensile-deformation-based capacitive textile sensors. The experimental results demonstrated stable and repeatable electromechanical behavior, a clear relationship between crosshead displacement and normalized capacitance response, a short response delay of 0.08 s, and stable cyclic performance over 1000 loading cycles. Wearable lower-body demonstrations further confirmed that the sensor can monitor repetitive motion in a garment-integrated configuration. Overall, the proposed design offers a simple and effective approach for textile-based wearable motion sensing applications.

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## DEVELOPMENT OF A DISPERSE DYEING PROCESS FOR CELLULOSE ACETATE SOCKS AND INVESTIGATION OF FASTNESS PROPERTIES

Şeyma Nur Köseoğlu\*, İsmet Ege Kalkan<sup>2</sup>, Havva Kara Şensoy<sup>3</sup>, Umut Kıvanç Şahin<sup>4</sup>

<sup>1</sup> Bony Tekstil Tasarım Merkezi, Tekirdağ, Türkiye

<sup>2</sup> Istanbul Teknik Üniversitesi, Tekstil Teknolojileri ve Tasarım Fakültesi, İstanbul, Türkiye

<sup>3</sup> Bony Tekstil Tasarım Merkezi, Tekirdağ, Türkiye

<sup>4</sup> Istanbul Teknik Üniversitesi, Tekstil Teknolojileri ve Tasarım Fakültesi, İstanbul, Türkiye

\* seymanrkoseoglu@gmail.com

### ABSTRACT

The growing demand for sustainable textile products has increased interest in alternative fibers for hosiery applications. In this study, socks produced from secondary cellulose acetate fiber were investigated in terms of dyeing performance and color fastness properties. Dyeing was carried out at 85, 95, and 100°C for 30 and 60 min in order to determine the effect of temperature and time on product performance. After dyeing, the samples were evaluated for color fastness to washing, water, and perspiration, together with pH measurements. The results showed that dyeing conditions significantly affected fastness behavior. Among the tested parameters, the 100°C–60 min condition provided the most balanced overall performance, while lower temperature conditions gave less satisfactory results in some fastness tests. The pH values of all samples remained within the acceptable range. The findings indicate that Cellulose Acetate fiber has potential for sustainable sock production when appropriate dyeing conditions are applied.

**Keywords:** *Cellulose-Acetate, Sustainable Socks, Disperse Dyeing, Color Fastness*

### 1. INTRODUCTION

Cellulose acetate nanofibers (CANF) have received growing attention in textile research because of their notable characteristics, such as high absorption capacity, mechanical strength, and antimicrobial performance, as highlighted in previous studies [1–5]. The dyeing behavior of CANF has also been examined by several researchers using different dye classes, including disperse, vat, and reactive dyes, as well as various application methods such as pad-dry, ultrasonic, and high-temperature dyeing [6–8]. Beyond their dyeability, CA fabrics are known for properties such as softness, luster, breathability, color retention, and versatility, which make them attractive for a variety of fashion and textile uses (9). Their moisture-management capability also allows CA fibers to transport moisture away from the skin, thereby improving wearer comfort (10). Cotton, in contrast, is one of the most important and widely used natural textile fibers. It is extensively employed in textile production because of its desirable properties, including moisture absorbency, breathability, comfort, thermal insulation, and biodegradability (11,12). Its durability and ease of use have made it a preferred choice for both producers and consumers worldwide.

As the textile market continues to evolve, there is a growing demand for materials that can simultaneously offer comfort, durability, and sustainability. To address both consumer expectations and environmental concerns, textile designers and manufacturers have increasingly turned to blended fabrics as a practical alternative. In this regard, blends of CA and cotton have attracted considerable interest (13), as they combine the favorable characteristics of both fibers while minimizing their individual disadvantages. Cotton contributes softness and breathability, whereas CA enhances strength and dimensional stability (14).

Within this framework, the present study concentrates on the development of sustainable sock structures based on cellulose acetate yarns as an alternative to conventional bright sock materials. The primary aim is to examine the suitability of cellulose acetate fibers for hosiery applications, either on their own or in combination with other fibers, and to determine the most appropriate dyeing conditions for the developed sock structures. To achieve this, the study evaluates the influence of dyeing temperature and time on the color fastness performance of the socks, while also taking into account the compatibility of cellulose acetate

with disperse dyeing. In addition, the study seeks to explore the feasibility of a single-bath dyeing process for practical and sustainable production, and to identify the optimum process parameters in terms of product performance and end-use suitability. Top of Form

## 2. EXPERIMENTAL STUDY

The experimental study was planned to determine the most suitable dyeing conditions for Cellulose acetate based socks. Since Cellulose Acetate is dyed with disperse dyes, disperse dyeing was selected as the coloration route. The two main independent variables were dyeing temperature and dyeing time. Based on the project plan, three temperature levels and two time levels were studied, resulting in six dyeing conditions: 85°C/30 min, 85°C/60 min, 95°C/30 min, 95°C/60 min, 100°C/30 min, and 100°C/60 min.

This design was chosen because, although cellulose acetate fibers are generally considered dyeable at around 85°C, the optimum temperature–time combination had to be verified experimentally for sock structures containing additional components such as polyester and polyamide. Therefore, the dyeing temperature and the holding time at the target temperature were systematically varied, and the dyed samples were comparatively evaluated.

### 2.1 Materials

In this study, socks containing secondary cellulose acetate yarn were selected as the main material. Cellulose Acetate is yarn derived from renewable wood pulp and dyed with disperse dyes. The sock structure was developed as a reinforced design in which the toe and sole regions were strengthened because preliminary trials indicated that cellulose acetate alone was not sufficiently resistant to abrasion and pilling for these critical zones.

The patented sock construction describes a blended structure containing approximately 60% cellulose acetate, 30% recycled polyester, 3% elastane, and 7% polyamide.

**Table 1.** Experimental Design

|    | TEMPERATURE | DURATION |
|----|-------------|----------|
| S1 | 85          | 30       |
| S2 | 85          | 60       |
| S3 | 95          | 30       |
| S4 | 95          | 60       |
| S5 | 100         | 30       |
| S6 | 100         | 60       |

### 2.2 Dyeing Procedure

The socks were dyed by a package or piece dyeing approach using disperse dyestuffs, in accordance with the fiber characteristics of Cellulose acetate. For each trial, one of the six temperature–time combinations was applied. After dyeing, the samples were cooled, rinsed, and prepared for performance assessment. The purpose of this stage was to identify the processing window that would provide the most acceptable balance between coloration and fastness performance for sustainable sock production.

### 2.3 Testing Methods

After dyeing, the samples were tested to evaluate their end-use suitability. The response variables selected in the project were color fastness to washing, color fastness to water, color fastness to perspiration, and pH value. These properties were chosen because they directly reflect the service performance and product compliance of hosiery materials. The dyed sock samples were tested according to standardized methods. Color fastness to washing was determined in accordance with TS EN ISO 105-C08, color fastness to perspiration according to TS EN ISO 105-E04, and color fastness to water according to TS EN ISO 105-E01. The pH value of the samples was measured based on ISO 3071.

### 3. RESULTS

**Table 2.** Fastness Results

|           | WASHING                 | WATER               | PERSPIRATION<br>ACID  | PERSPIRATION<br>ALKALINE |
|-----------|-------------------------|---------------------|-----------------------|--------------------------|
| <b>S1</b> | 4/5-4/5-4/5-4/5-4/5     | 3-4-2/3-3/4-4/5-4-4 | 3-4-2/3-3-4-4-4       | 3-3/4-2/3-3/4-4/5-4-4    |
| <b>S2</b> | 4/5-4/5-4-4/5-4/5-4/5   | 3/4-4-2/3-4-4/5-4-4 | 3/4-4-3-4-4/5-4-4     | 3/4-4-3-4-4/5-4-4        |
| <b>S3</b> | 4-4/5-3-4/5-4/5-4/5     | 3/4-4-3-4-4/5-4-4   | 3/4-4-3-4-4/5-4-4     | 3/4-4-3-4-4-4-4          |
| <b>S4</b> | 4/5-4/5-4-4/5-4/5-4/5   | 4-4/5-3-4-4/5-4/5-4 | 4-4/5-3-4-4/5-4/5-4   | 4-4/5-3-4-4/5-4/5-4      |
| <b>S5</b> | 4/5-4/5-4/5-4/5-4/5-4/5 | 3/4-4/5-3-4-4/5-4-4 | 3/4-4/5-3-4-4/5-4-4   | 3/4-4/5-3-4-4/5-4-4      |
| <b>S6</b> | 4/5-4/5-4/5-4/5-4/5-4/5 | 4-4/5-3/4-4-4/5-4-4 | 4-4/5-3/4-4-4/5-4/5-4 | 4-4/5-3/4-4-4/5-4/5-4    |

The results of the dyeing trials showed that the performance of the Cellulose acetate-based sock samples was influenced by the selected temperature–time combination. In the experimental design, six dyeing conditions were applied, namely 85, 95, and 100°C for 30 and 60 min, in order to identify the most suitable processing window for the developed sock structure.

The pH measurements indicated that all samples remained within the acceptable range defined in the internal test form. The measured values were close to each other and were approximately between 6.14 and 6.50, showing that the applied dyeing conditions did not create an unfavourable pH level in the final product. Thus, pH was not found to be the limiting factor in the evaluation of the dyeing conditions.

In contrast, the fastness tests showed clearer differences between the dyeing conditions. The comparative assessment of washing, water, and perspiration fastness demonstrated that the lower-temperature conditions generally resulted in less satisfactory overall performance, whereas the higher-temperature and longer-duration condition provided more balanced results. In particular, the sample dyed at 100°C for 60 min was marked as acceptable/pass in the washing and perspiration test forms and therefore stood out as the most favourable condition among the tested alternatives.

These findings are consistent with the original project rationale. Although cellulose acetate fibres are known to be dyeable at around 85°C, the project documents already emphasized that the optimum condition had to be verified experimentally because the final sock structure also contained other components and had to meet practical fastness requirements. Therefore, the experimental results confirmed that a higher dyeing severity was necessary to obtain a more suitable overall fastness profile for the developed Cellulose acetate-based socks.

Overall, the results indicate that the main factor governing process optimization was fastness behaviour rather than pH suitability. Within the studied range, the 100°C/60 min condition gave the most promising combination of washing, water, perspiration, and pH performance for sustainable secondary cellulose acetate sock production.

### 4. CONCLUSION

This study investigated the effect of dyeing temperature and time on the performance of socks produced from sustainable secondary cellulose acetate fibre. Based on the experimental design, six dyeing conditions were examined in order to optimize the dyeing process for a sock structure containing Cellulose Acetate and supporting synthetic components.

The results showed that all samples satisfied the pH requirement, while the fastness tests were more decisive in distinguishing the suitability of the dyeing conditions. Among the tested alternatives, the 100°C for 60 min condition provided the most satisfactory overall performance and can therefore be considered the optimum dyeing condition within the investigated range.

The study also supports the practical potential of Cellulose Acetate as an alternative material for sustainable sock production. Cellulose Acetate as a disperse-dyeable yarn and position it as a more sustainable option that may help simplify processing and reduce environmental burden compared with conventional alternatives used in bright sock applications.

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In conclusion, the findings demonstrate that Cellulose acetate-based socks can be successfully processed when dyeing parameters are properly optimized. The selected optimum condition provides a useful starting point for future studies on shade depth, dimensional stability, and long-term end-use performance of sustainable cellulose acetate hosiery products.

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## DEVELOPMENT OF ANTITHROMBOTIC PCL/PVA-BASED ELECTROSPUN SURFACES FOR SMALL-DIAMETER VASCULAR GRAFTS

Janset Öztemur-Sezgin<sup>a,\*</sup>, Suzan Özdemir<sup>a</sup>, Hande Sezgin<sup>a</sup>, İpek Yalçın-Eniş<sup>a</sup>

<sup>a</sup>Istanbul Technical University, Textile Engineering Department, Istanbul, Turkey

\* oztemurj@itu.edu.tr

### ABSTRACT

Early thrombosis, initiated by rapid protein adsorption and subsequent platelet activation at the blood-material interface, remains a significant barrier to the clinical success of small-diameter synthetic vascular grafts. Systemic administration of antithrombotic agents is constrained by short half-lives, risk of bleeding, and limited efficacy at the target site. While agents such as enoxaparin and fondaparinux demonstrate improved pharmacokinetic profiles compared to unfractionated heparin, sustained and localized delivery necessitates advanced carrier systems to prevent burst release. Coaxial electrospinning represents a promising approach for fabricating biomimetic core-shell fibrous scaffolds with controllable release kinetics. The combination of polycaprolactone (PCL) for mechanical strength and durability with polyvinyl alcohol (PVA) for hydrophilicity and high drug-loading capacity yields an optimal composite for vascular applications. In this study, bicomponent core-shell fibrous matrices were developed, featuring a PCL shell and a PVA core loaded with 6% enoxaparin or fondaparinux. The physicochemical properties of these localized drug-delivery platforms were systematically characterized using morphological analysis and Fourier Transform Infrared (FTIR) spectroscopy to confirm their chemical structures.

**Keywords:** *vascular graft, antithrombotic drugs, electrospinning, biomaterials*

### 1. INTRODUCTION

Small-diameter vascular grafts are still prone to early failure, largely due to thrombus formation at the blood-material interface [1,2]. In the absence of an endothelial layer, the graft surface is directly exposed to circulating blood, leading to rapid adsorption of plasma proteins such as fibrinogen and von Willebrand factor. This is followed by platelet adhesion and activation, which initiates the coagulation cascade and can rapidly lead to graft occlusion. These early activities remain a major barrier to achieving long-term patency in small-caliber grafts [2,3].

In clinical practice, thrombotic complications are typically managed with systemic anticoagulation using agents such as unfractionated heparin, low-molecular-weight heparins, and synthetic factor Xa inhibitors [4,5]. These agents act by enhancing antithrombin-mediated inhibition of key coagulation factors, particularly factor Xa and thrombin, thereby limiting fibrin formation [5]. However, their effects are systemic rather than localized and therefore insufficient to suppress thrombosis at the graft surface. Moreover, short half-lives, rapid clearance, and bleeding risks limit their long-term use, resulting in only temporary control rather than sustained protection [6,7]. To address this limitation, localized delivery of anticoagulants from the graft surface has been investigated. Enoxaparin, a low-molecular-weight heparin, provides predictable pharmacokinetics and inhibits factor Xa via antithrombin III, with additional anti-inflammatory and antifibrotic effects [4,5]. Similarly, fondaparinux, a synthetic pentasaccharide, offers selective factor Xa inhibition with minimal interaction with platelet factor 4, reducing the risk of heparin-induced thrombocytopenia [5,9]. However, achieving sustained activity remains challenging, as conventional loading approaches often result in burst release followed by rapid drug depletion, limiting long-term efficacy [6,9]. Electrospinning has emerged as a versatile technique for developing vascular graft



surfaces, enabling the fabrication of fibrous surfaces that resemble the extracellular matrix and provide high surface area and tunable morphology [10-12]. In addition to conventional electrospinning methods, coaxial electrospinning enables the fabrication of core-shell fibers, integrating multiple material properties into a single fiber and offering enhanced control over drug encapsulation and release behavior [13]. Also, the choice of biomaterials is crucial for balancing mechanical performance and biological function. PCL is widely used in vascular applications due to its favorable mechanical strength, elasticity, and slow degradation rate, which support structural integrity over extended periods [14]. On the other hand, PVA is a hydrophilic, biocompatible polymer well suited for the incorporation and release of hydrophilic therapeutic agents [15]. The complementary properties of PCL and PVA make them a suitable combination for designing vascular graft structures with mechanical stability, biocompatibility, and controlled release behaviour [16]. Zendedel et al. (2024) incorporated enoxaparin into the inner layer of bilayer vascular grafts composed of PVA, gelatin, and hyaluronic acid, with a PCL/PLA outer layer. The enoxaparin-loaded scaffolds demonstrated resistance to platelet adhesion and sustained drug release for approximately 120 hours, highlighting their potential to improve thrombosis management in vascular graft applications [9].

Based on these considerations, this study focuses on the development of electrospun vascular graft surfaces incorporating enoxaparin and fondaparinux as localized antithrombotic agents. In particular, coaxial electrospinning is employed to fabricate core-shell fibrous structures, in which the core consists of PVA loaded with anticoagulants and the shell is formed from PCL. By combining material selection with controlled fabrication strategies, this work aims to enhance the performance of small-diameter vascular grafts.

## 2. EXPERIMENTAL STUDY

### 2.1 Materials

PCL (80,000 g/mol) and PVA (146,000-186,000 g/mol and hydrolysis degree 87-89%) were used as the main polymers. All polymers and solvents were purchased from Sigma-Aldrich. Enoxaparin sodium (Oksapar, 6000 anti-Xa IU/0.6 mL; Koçak Farma) and fondaparinux (Arixtra, 2.5 mg/0.5 mL; Eczacıbaşı) were employed as antithrombotic agents in their commercially available forms.

### 2.2 Methods

#### 2.2.1. Solution Preparation

The PVA solution (6%) was prepared by dissolving PVA in deionized water under magnetic stirring, heating to 80 °C for 2 h, and then cooling to room temperature. In parallel, an 8% (w/w) PCL solution was obtained by dissolving PCL in a chloroform/ethanol (9:1, w/w) mixture under stirring for 2 h at room temperature. Enoxaparin sodium or fondaparinux (commercial aqueous form) was then added to the PVA solution (1 injection per 10 g of polymer solution), and the mixture was stirred at 100 rpm to ensure homogeneous distribution. Drug loading was performed after cooling PVA solution to prevent thermal degradation, and final concentrations were adjusted to clinically recommended levels.

#### 2.2.2. Scaffold Fabrication

Bicomponent tubular scaffolds with a 6 mm diameter were fabricated by coaxial electrospinning using a PCL shell and a PVA core. Enoxaparin sodium or fondaparinux is incorporated into the PVA core for drug-loaded systems. Sample codes and processing parameters are provided in Table 1.

**Table 1.** Sample codes and processing parameters of the samples

| Sample Code   | Core | Shell | Incorporated Drug | Applied Voltage (kV) | Flow Rate (core/shell) (mL/h) | Tip-to-Collector Distance (cm) |
|---------------|------|-------|-------------------|----------------------|-------------------------------|--------------------------------|
| PCL/PVA       | PVA  | PCL   | -                 | 15                   | 0.08/0.8                      | 17                             |
| PCL/PVA+enox  | PVA  | PCL   | enoxaparin        | 15.5                 | 0.05/0.5                      | 17                             |
| PCL/PVA+fonda | PVA  | PCL   | fondaparinux      | 10.5                 | 0.05/0.6                      | 17                             |

The shell solution was supplied at a higher flow rate than the core to maintain a stable jet and ensure continuous core encapsulation. As the core-to-shell flow rate ratio critically influences Taylor cone stability and fiber morphology, an elevated shell flow rate is employed to prevent phase mixing and ensure uniform core-shell structure formation [17,18]. Moreover, the coaxial needle comprises inner and outer needles

with inner diameters of 0.6 and 0.8 mm, respectively. A rotational speed of 200 rpm is set for the collector to ensure the creation of randomly distributed bicomponent fibers. The fabrication process is conducted at  $13\pm 3^\circ\text{C}$  and  $60\pm 5\%$  relative humidity.

### 2.2.3. Morphological Analysis

The surface morphology was examined using scanning electron microscopy (SEM; Zeiss Evo MA10). Prior to imaging, all samples were sputter-coated with a gold-palladium (Au-Pd) layer (Quorum SC7620) to enhance conductivity. Micrographs were obtained at 2kx magnification. Fiber diameter, pore area, and porosity were quantified using ImageJ. For each sample, at least 50 randomly selected fibers were analyzed, and the results were presented as mean  $\pm$  standard deviation values. Porosity and pore size were further determined from SEM images using an ImageJ-based thresholding approach.

### 2.2.4. Fourier-Transform Infrared (FTIR) Spectroscopy Analysis

FTIR spectroscopy was employed to analyze the chemical structure of the electrospun surfaces and confirm the presence of both polymer components and incorporated antithrombotic agents. Spectra were recorded using a UATR Two spectrometer (PerkinElmer) in attenuated total reflectance (ATR) mode over the range of  $4000\text{--}400\text{ cm}^{-1}$ .

## 3. RESULTS

### 3.1 Morphological Analysis

Figure 1 presents SEM images of bicomponent electrospun surfaces composed of a PCL shell and a PVA core with varying drug incorporation. In all sample groups, continuous fibrous structures were formed. However, noticeable differences in fiber morphology emerged depending on the presence of antithrombotic agents. In the PCL/PVA bicomponent sample (Figure 1a), a slightly sticking problem of the fibers to the collector was observed. This may be due to a production-related issue; however, the fibers exhibit a relatively thin, continuous distribution. In all drug-loaded samples, thin and thick fibers coexisted; however, the fibrous structures remained bead-free and showed relatively homogeneous distributions.

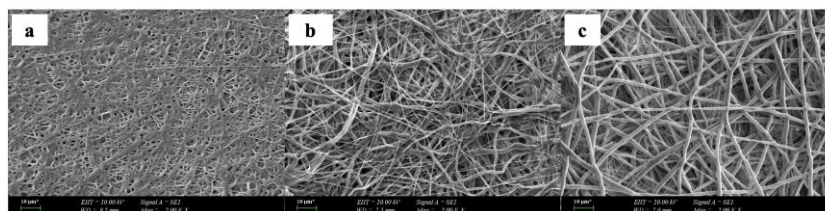


**Figure 1.** SEM images of PCL/PVA bicomponent samples at 2kx magnification: (a) PCL/PVA, (b) PCL/PVA\_enox, (c) PCL/PVA\_fonda

The fiber diameter, pore area, and porosity values of the neat PCL/PVA bicomponent and drug-loaded scaffolds are summarized in Table 2. The results demonstrated that drug incorporation significantly affects the fiber morphology and structural properties of the scaffolds. The neat PCL/PVA scaffold exhibited a relatively uniform fibrous structure, with an average fiber diameter of  $1.393\pm 0.243\text{ }\mu\text{m}$ , pore area of  $1.028\pm 0.579\text{ }\mu\text{m}^2$ , and porosity of 76%. Incorporation of enoxaparin resulted in a slight increase in fiber diameter ( $1.557\pm 0.658\text{ }\mu\text{m}$ ) and porosity (79%), with negligible changes in pore area, suggesting minimal impact on fiber formation or scaffold architecture. In contrast, fondaparinux incorporation resulted in more pronounced structural alterations, including an increase in fiber diameter ( $1.815\pm 0.816\text{ }\mu\text{m}$ ) and pore area ( $1.211\pm 0.315\text{ }\mu\text{m}^2$ ), accompanied by a decrease in porosity to 72%. These changes indicate that fondaparinux affected both fiber formation and overall scaffold organization, likely due to modifications in solution properties, such as viscosity or intermolecular interactions, that influence jet stability during electrospinning.

**Table 2.** Fiber diameters, pore areas, and porosities of neat PCL/PVA bicomponent and drug-loaded PCL/PVA bicomponent samples

| Sample Code   | Mean diameter ( $\mu\text{m}$ ) | Pore Area ( $\mu\text{m}^2$ ) | Porosity (%) |
|---------------|---------------------------------|-------------------------------|--------------|
| PCL/PVA       | 1.393 $\pm$ 0.243               | 1.028 $\pm$ 0.579             | 76           |
| PCL/PVA_enox  | 1.557 $\pm$ 0.658               | 1.03 $\pm$ 0.512              | 79           |
| PCL/PVA_fonda | 1.815 $\pm$ 0.816               | 1.211 $\pm$ 0.315             | 72           |

The relationship between fiber diameter, pore size, and porosity observed in this study is consistent with previous reports, where thicker fibers are typically associated with larger pore sizes but may also result in reduced porosity due to denser fiber packing [19]. The increase in pore area in the fondaparinux-loaded scaffold can be attributed to thicker fiber formation, while the reduced porosity indicates a more compact structure. From a tissue engineering perspective, larger pores may enhance cell infiltration and nutrient transport, whereas overall porosity governs cellular migration and tissue integration [20]. Therefore, these morphological changes may be advantageous depending on the intended application, particularly where controlled pore architecture is required.

### 3.2 FTIR Analysis

In the FTIR spectra of both drug-free and drug-loaded bicomponent fibers, the characteristic absorption bands of PCL and PVA were clearly observed, indicating that both polymers are present within the same fibrous structure (Figure 2). The simultaneous detection of PCL- and PVA-specific peaks confirms the successful formation of the bicomponent core-shell architecture. The PCL component exhibits its typical ester carbonyl (C=O) stretching band around 1720-1730  $\text{cm}^{-1}$ , along with  $\text{CH}_2$  stretching vibrations near 2940 and 2860  $\text{cm}^{-1}$ . Additional bands in the range of 1160-1240  $\text{cm}^{-1}$  and around 1290  $\text{cm}^{-1}$  are attributed to C-O-C and C-O stretching vibrations of PCL [21].

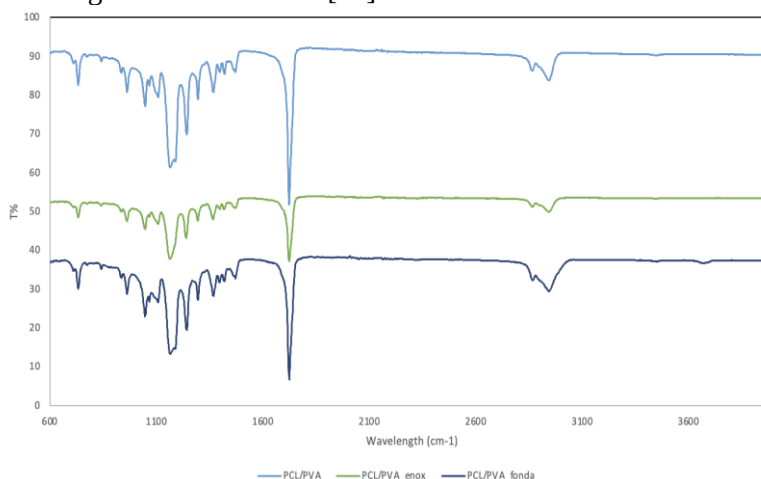


**Figure 2.** FTIR analysis of the, PCL/PVA, PCL/PVA\_enox, and PCL/PVA\_fonda bicomponent samples

On the other hand, the PVA component is identified by the broad O-H stretching band in the 3200-3500  $\text{cm}^{-1}$  region. In addition, characteristic PVA peaks were observed at around 2900  $\text{cm}^{-1}$  (C-H stretching), 1445  $\text{cm}^{-1}$  ( $\text{CH}_2$  bending), 1090  $\text{cm}^{-1}$  (C-O stretching of secondary alcohol groups), and 845  $\text{cm}^{-1}$  (skeletal C-C vibrations), which are consistent with the PVA backbone [22]. When the drug-loaded fibers were compared with the drug-free sample, no significant shifts are observed in the main PCL and PVA peaks. However, slight broadening in the hydroxyl region (3200-3500  $\text{cm}^{-1}$ ) and weak absorption bands in the range of 1600-1650  $\text{cm}^{-1}$  were detected, which can be associated with protonated amine vibrations. In addition, absorptions between 1200 and 1250  $\text{cm}^{-1}$  were attributed to sulfate (S=O) stretching vibrations [23]. The presence of these bands in both enoxaparin- and fondaparinux-loaded samples indicated that the antithrombotic agents are successfully incorporated into the fibrous structure. Despite these observations, the overall spectral differences between drug-free and drug-loaded samples remained limited. This can be explained by the overlap of the drugs' characteristic absorption bands with those of PCL and PVA, which reduces the visibility of drug-related signals in the FTIR spectra [9].

#### 4. CONCLUSION

In this study, bicomponent PCL/PVA fibrous scaffolds, both drug-free and loaded with antithrombotic agents, were successfully fabricated and characterized. Morphological analysis showed that fiber diameters ranged from approximately 1.3 to 1.8  $\mu\text{m}$ , with pore areas varying with drug incorporation, while all scaffolds exhibited high porosity ( $>70\%$ ). Moreover, FTIR analysis confirmed the presence of both PCL and PVA through their characteristic absorption bands, demonstrating the successful formation of the bicomponent structure. In addition, drug-related functional groups were detected without significant peak shifts, indicating that both enoxaparin and fondaparinux were incorporated into the fibers without chemical interaction. These findings indicate that the developed bicomponent scaffolds possess suitable structural and thermal characteristics, supporting their potential use as vascular graft materials.

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## DEVELOPMENT OF BEDROOM TEXTILES FROM SUSTAINABLE AND FUNCTIONAL YARNS

Aylin Kuşen<sup>1</sup>, Prof.Dr. Onur Balcı<sup>2</sup>, Neslihan Okyay<sup>3\*</sup>, Seda Ünal<sup>4</sup>, Ece Şevval Özcan<sup>1</sup>

<sup>1</sup>Agaoglu Textile R&D Center, Uşak, Turkey

<sup>2</sup>Kahramanmaraş Sütçü İmam University, Department of Textile Engineering Kahramanmaraş, Turkey

<sup>3</sup>Karacasu Textile R&D Center, Kahramanmaraş, Turkey

<sup>4</sup>Polyteks Textile R&D Center, Bursa, Turkey

\* nes@karacasutekstil.com.tr

### ABSTRACT

Within the scope of this study, the finishing performance and overall properties of bedroom textiles containing cellulosic and polyester-based fibers with sustainable and functional properties were compared with 100% cotton products. In this context, a total of 12 different commercially available yarns were supplied. These yarns were classified into two main groups as cellulosic-based and polyester-based. Fabric specimens were separately produced in a 5/1 warp satin construction, using 100% cotton in the warp direction and the specified yarns in the weft direction. The finishing processes of the obtained fabric specimens were carried out by rotary screen printing using pigments, followed by subsequent finishing treatments. In accordance with the relevant standards, the mechanical properties of the fabric specimens, including breaking and tear strength, abrasion resistance, pilling behaviour, and bending rigidity were evaluated. In addition, the color measurements and fastness properties were assessed. The results indicated that the new-generation fibers did not adversely affect the physical performance of the fabrics, and that optimum values in terms of performance properties were obtained for the cellulosic-based fabric specimens. Consequently, sustainable and functional fibers were shown to have significant potential for application in bedroom textiles.

**Keywords:** *Home Textile, Cellulose, Comfort, Polyester, Handle.*

### 1. INTRODUCTION

Although cotton, which is widely used in bedroom textiles, is a natural fiber, it may be insufficient on its own to optimally meet all performance requirements [1-3]. Therefore, in recent years, fabric structures developed by combining cotton fiber with natural, regenerated, and synthetic fibers have come to the forefront. In particular, regenerated cellulosic fibers make a significant contribution to sustainable textile production through advantages such as high hydrophilicity, breathability, and biodegradability [4]. Moreover, fibers obtained from recycled sources enable the reduction of environmental impacts by supporting the circular economy approach [5]. On the other hand, polyester-based functional yarns contribute to enhancing comfort properties in textile products due to their improved performance in terms of thermal management, moisture transfer, softness, and surface characteristics. In particular, modified polyester yarns can offer higher user comfort by mitigating the disadvantages of conventional polyester fibers. However, the number of studies addressing the combined evaluation of recycled cellulosic and functional polyester fibers remains limited. In this study, the performance and comfort properties of bedroom textiles produced using different cellulosic and polyester-based yarns were comprehensively investigated. The fabrics were produced using 100% cotton yarn in the warp direction, and sustainable and different functional yarns in the weft direction. The performance of the obtained fabrics was evaluated using various test methods, and the relationships between fiber type, production process, and fabric performance were investigated. As a result, it is considered that this study will contribute to the development of sustainable and functional bedroom textiles.

## 2. EXPERIMENTAL STUDY

In this study, woven fabrics were produced using Ne 40/1, %100 cotton yarn in the warp direction. The types and properties of the yarns used in the weft direction are presented in Table 1. For cellulosic-based yarns, Ne 10/1, 100% cotton yarn was taken as the reference, whereas for polyester-based yarns, Ne 40/1 100% cotton yarn was used as the reference.

**Table 1.** Types and Properties of Yarns Used in the Study

| Developer        | Yarn Code | Yarn Count    | Yarn Type   | Blend Composition               |
|------------------|-----------|---------------|-------------|---------------------------------|
| Ağaoğlu Tekstil  | W.Y.1     | 10/1 Ne       | Cotton      | %100 Cotton                     |
| Karacasu Tekstil | W.Y.2     | 10/1 Ne       | Naia        | %65 Cotton +%35 Naia            |
| Karacasu Tekstil | W.Y.3     | 10/1 Ne       | Naia Wea    | %35 Cotton +%65 Naia            |
| Karacasu Tekstil | W.Y.4     | 10/1 Ne       | Sequal Wea  | %50 Cotton +%50 Sequal          |
| Karacasu Tekstil | W.Y.5     | 10/1 Ne       | Sequal      | %50 Cotton +%30 Sequal+%20 Naia |
| Karacasu Tekstil | W.Y.6     | 12/1 Ne       | Agraloop    | %70 Cotton +%30 Agraloop        |
| Ağaoğlu Tekstil  | W.Y.7     | 40/1 Ne       | Cotton      | %100 Cotton                     |
| Polyteks         | W.Y.8     | 167/48 Denier | PES         | %100 Polyester                  |
| Polyteks         | W.Y.9     | 167/48 Denier | Polycool    | %100 Polyester                  |
| Polyteks         | W.Y.10    | 167/48 Denier | PolyShine   | %100 Polyester                  |
| Polyteks         | W.Y.11    | 167/48 Denier | PES + Soft  | %100 Polyester                  |
| Polyteks         | W.Y.12    | 167/48 Denier | ThermoBlack | %100 Polyester                  |

Within the scope of this study, all fabric samples were woven under identical production conditions in 5/1 warp satin weave structure. The weaving parameters were optimized depending on the yarn counts; accordingly, the weft density was set at 20 picks/cm for yarns coded W.Y.1– W.Y.6 and 30 picks/cm for yarns coded W.Y.7– W.Y.12, while the warp density was maintained at 50 ends/cm for all samples. The density of the produced cellulosic-based fabric samples ranged between 150–250 g/m<sup>2</sup>, whereas those of the polyester-based samples were between 130–150 g/m<sup>2</sup>. The areal density of the reference fabric samples was determined as 211 g/m<sup>2</sup> for W.Y.1 and 128 g/m<sup>2</sup> for W.Y.7. Following the weaving process, the fabric samples were subjected to conventional pre-treatment processes. The desizing process was carried out using 2 g/L desizing enzyme and 2 g/L wetting agent. The scouring and bleaching process was performed using 2.5 g/L NaOH, 2.5 g/L H<sub>2</sub>O<sub>2</sub>, 0.6 g/L wetting agent, 0.6 g/L stabilizer, and 0.3 g/L sequestering agent. After the completion of pre-treatment processes, the fabric samples were colored by means of rotary screen printing using pigments. However, due to the dark color of the yarn in the W.Y.12 coded sample, the printing process was applied using a blind paste method. In the printing paste prepared for the rotary screen printing process, 80 g/kg styrene–acrylate binder, 5 g/kg hydrophilic silicone, 5 g/kg antifoaming agent, 5 g/kg emulsifier, and 5 g/kg ammonia were used. For coloration, 2.1 g/kg carbon black pigment-based dye, 28.5 g/kg red azo pigment-based dye, and 22 g/kg yellow azo pigment-based dye were added. Following the printing process, fixation was carried out at 150 °C for 5 minutes. Subsequently, to optimize the handle, softness, and end-user comfort of the fabrics, all samples were subjected to a softening finishing process using a formulation containing 20 g/L organic and synthetic wax-based softener, 20 g/L polysiloxane-based silicone, and 3 g/L polyethylene-based softening agent, thereby completing the finishing treatments.

The mechanical properties of the fabric samples, including tensile strength, tear strength, abrasion resistance, and pilling behavior, were evaluated in accordance with the relevant standards. In addition, color fastness analyses were carried out. Furthermore, color measurements and bending rigidity performances were analyzed. In the testing of the fabric samples, the abbreviations “G (greige-raw)”, “P (printed)”, and “F (finished)” were used to represent different processing stages. All test results were comparatively evaluated by considering these three distinct processing conditions.

## 3. RESULTS

The tensile and tear strength test results of the fabric samples, determined in accordance with TS EN ISO 13934-2, are presented in Table 2.

**Table 2.** Tensile and Tear Strength Test Results

| Yarn Code | Weft Direction (N) |       |       |       |       |       | Warp Direction (N) |       |       |       |       |       |
|-----------|--------------------|-------|-------|-------|-------|-------|--------------------|-------|-------|-------|-------|-------|
|           | TENCILE            |       |       | TEAR  |       |       | TENCILE            |       |       | TEAR  |       |       |
|           | G                  | P     | F     | G     | P     | F     | G                  | P     | F     | G     | P     | F     |
| W.Y.1     | 325,9              | 366,2 | 308,3 | 37,26 | 17,79 | 33,84 | 464,9              | 445,2 | 229,8 | 25,17 | 22,44 | 27,79 |
| W.Y.2     | 492,5              | 403,4 | 378,5 | 39,37 | 18,23 | 33,15 | 383,9              | 406,5 | 342,1 | 37,78 | 27,46 | 41,19 |
| W.Y.3     | 197,3              | 98,35 | 204,7 | 36,09 | 17,54 | 29,82 | 443,5              | 391,8 | 368,3 | 44,2  | 27,58 | 40,82 |
| W.Y.4     | 861,1              | 574,3 | 703,0 | 36,75 | 19,08 | 29,1  | 432,3              | 431,4 | 366,1 | 27,38 | 52,39 | 44,87 |
| W.Y.5     | 575,7              | 406,3 | 456,6 | 38,62 | 18,45 | 23,93 | 424,0              | 427,3 | 348,1 | 44,71 | 44,7  | 40,45 |
| W.Y.6     | 297,5              | 162,5 | 244,2 | 38,67 | 19,47 | 25,96 | 430,2              | 439,9 | 326,9 | 32,08 | 25,23 | 31,71 |
| W.Y.7     | 180,2              | 175,7 | 201,0 | 12,57 | 10,67 | 21,91 | 392,0              | 343,2 | 371,6 | 12,78 | 9,66  | 18,66 |
| W.Y.8     | 657,6              | 643,0 | 625,3 | 27,19 | 13,48 | 24,07 | 415,3              | 408,8 | 397,6 | 47,51 | 29,15 | 33,9  |
| W.Y.9     | 472,9              | 512,8 | 500,1 | 24,66 | 14,28 | 25,35 | 448,4              | 449,9 | 368,7 | 38,13 | 28,24 | 30,57 |
| W.Y.10    | 537,0              | 467,2 | 516,1 | 18,22 | 15,73 | 23    | 435,2              | 412,5 | 361,8 | 17,9  | 15,94 | 27,12 |
| W.Y.11    | 624,5              | 615,5 | 615,5 | 24,27 | 8,79  | 21,63 | 401,7              | 324,6 | 324,6 | 37,54 | 22,01 | 29,84 |
| W.Y.12    | 662,5              | 370,8 | 370,8 | 18,16 | 10,16 | 24,13 | 382,5              | 386,9 | 386,9 | 38,87 | 25,33 | 32,13 |

Upon examining the tensile and tear strength results, a decreasing trend in both strength values was observed in the cellulosic-based samples (W.Y.1– W.Y.6) after processing. Compared to the reference sample A.İ.1, the reduction was found to be more pronounced particularly in sample W.Y.3. This behaviour is attributed to the structural weakening of cellulosic fibers during chemical processing [6]. In contrast, the evaluation of polyester-based samples (W.Y.8– W.Y.12) revealed that higher and more stable strength values were obtained compared to the reference sample W.Y.7. This trend was especially evident in samples W.Y.11 and W.Y.12, which can be explained by the inherently high strength properties of polyester fibers [7]. Overall, although tensile and tear strength exhibited similar trends, tear strength was observed to be more sensitive to the effects of processing.

The abrasion resistance of the fabric samples was analyzed in accordance with TS EN ISO 12947-4, and the pilling values were evaluated according to TS EN ISO 12945-2; the results are presented in Table 3.

**Table 3.** Abrasion Resistance and Pilling Test Results

| Yarn Code | Abrasion Resistance Mass Loss (%) |      |      | Pilling Rating |     |     |
|-----------|-----------------------------------|------|------|----------------|-----|-----|
|           | G                                 | P    | F    | G              | P   | F   |
| W.Y.1     | 1,27                              | 0,87 | 0,43 | 3              | 3/4 | 3/4 |
| W.Y.2     | 1,72                              | 2,70 | 0,46 | 2/3            | 4   | 3/4 |
| W.Y.3     | 7,35                              | 6,43 | 5,07 | 5              | 4/5 | 4   |
| W.Y.4     | 4,13                              | 1,23 | 0,42 | 3              | 3/4 | 3   |
| W.Y.5     | 3,48                              | 0,46 | 0,42 | 3              | 3/4 | 3   |
| W.Y.6     | 0,97                              | 2,55 | 1,52 | 2/3            | 2/3 | 2/3 |
| W.Y.7     | 27,21                             | 1,37 | 1,55 | 3/4            | 3/4 | 3/4 |
| W.Y.8     | 3,23                              | 1,30 | 0,65 | 4/5            | 5   | 5   |
| W.Y.9     | 2,72                              | 1,91 | 0,64 | 5              | 5   | 5   |
| W.Y.10    | 5,41                              | 1,91 | 4,55 | 5              | 5   | 5   |
| W.Y.11    | 3,31                              | 0,61 | 1,21 | 5              | 5   | 5   |
| W.Y.12    | 1,20                              | 1,76 | 1,21 | 5              | 5   | 5   |

When the abrasion resistance results of the samples were evaluated, it was determined that among the cellulosic-based samples (W.Y.1– W.Y.6), the lowest mass loss after weaving was observed in sample W.Y.6, while the highest loss occurred in sample W.Y.3. In contrast, the evaluation of polyester-based samples (W.Y.8– W.Y.12) revealed lower and more stable mass loss values. In general, it was observed that the mass loss values decreased after the printing process and particularly after the finishing treatment. This behavior is associated with the increased resistance of the fabric structure following processing [8]. Upon examining the pilling results, it was observed that cellulosic-based samples generally exhibited moderate ratings, whereas a higher pilling value was obtained for sample W.Y.3. In polyester-based samples (W.Y.8– W.Y.12), high pilling ratings were maintained even after processing. This behavior is attributed to the high strength of polyester fibers, which tend to remain on the fabric surface without breaking [7].

The bending rigidity of the fabric samples was analyzed in accordance with ASTM D1388, and the results are presented in Table 4.

**Table 4.** Bending Rigidity Results

| Yarn Code | Weft F.S. (mN*cm) |      |      | Warp F.S. (mN*cm) |      |      |
|-----------|-------------------|------|------|-------------------|------|------|
|           | G                 | P    | F    | G                 | P    | F    |
| W.Y.1     | 0,50              | 0,32 | 0,25 | 1,17              | 0,26 | 0,20 |
| W.Y.2     | 0,34              | 0,25 | 0,32 | 0,35              | 0,30 | 0,28 |
| W.Y.3     | 0,22              | 0,11 | 0,06 | 0,72              | 0,32 | 0,18 |
| W.Y.4     | 0,36              | 0,22 | 0,19 | 0,71              | 0,26 | 0,20 |
| W.Y.5     | 0,32              | 0,21 | 0,17 | 1,07              | 0,24 | 0,21 |
| W.Y.6     | 1,59              | 0,33 | 0,26 | 1,01              | 0,41 | 0,21 |
| W.Y.7     | 0,18              | 0,12 | 0,09 | 1,30              | 0,26 | 0,20 |
| W.Y.8     | 0,39              | 0,23 | 0,22 | 1,34              | 0,52 | 0,20 |
| W.Y.9     | 0,39              | 0,18 | 0,17 | 1,70              | 0,22 | 0,15 |
| W.Y.10    | 0,10              | 0,19 | 0,14 | 1,66              | 0,16 | 0,16 |
| W.Y.11    | 0,48              | 0,16 | 0,12 | 1,31              | 0,23 | 0,15 |
| W.Y.12    | 0,82              | 0,16 | 0,11 | 1,04              | 0,20 | 0,09 |

Upon examining the bending rigidity results, a decreasing trend in rigidity values was observed in both cellulosic- and polyester-based fabrics after printing and particularly after finishing treatments. This behaviour is attributed to the increased flexibility of the fabric structure resulting from the finishing process. Among the cellulosic-based samples, sample W.Y.3 exhibited the lowest bending rigidity values after processing, indicating a more flexible structure. In the case of polyester-based samples, W.Y.11 and W.Y.12 demonstrated low and closely similar rigidity values in both the weft and warp directions. This indicates a more balanced and homogeneous bending behaviour in these samples.

The color measurement results of the woven fabric samples, after the completion of printing and finishing processes, are presented in Table 5. Color measurements were carried out under D65 illumination and 10° standard observer conditions.

Upon evaluating the color measurement results, a general increasing trend in L\* values was observed in both groups after the finishing process. Among the cellulosic-based samples, this increase was found to be more pronounced particularly in samples W.Y.2 and W.Y.3, indicating a lightening of color in these samples. When the a\* and b\* values of the cellulosic samples were examined, a general decreasing trend was observed, indicating a reduction in redness and yellowness. This change is attributed to the effect of the finishing process on color saturation. In contrast, for the polyester-based samples, the changes in L\*, a\*, and b\* values were found to be more limited. Particularly in sample W.Y.12, very minimal variations in L\*, a\*, and b\* values were observed, which can be explained by its high color stability.

**Table 5.** Color Measurement Results

| Yarn Code | L*    |       |       | a*    | b*    |       |   |
|-----------|-------|-------|-------|-------|-------|-------|---|
|           | G     | P     | F     |       | G     | P     | F |
| W.Y.1     | 53,08 | 53,18 | 27,10 | 27,03 | 12,82 | 12,35 |   |
| W.Y.2     | 64,21 | 82,04 | 20,35 | 8,06  | 11,17 | 8,91  |   |
| W.Y.3     | 65,67 | 79,94 | 19,05 | 7,64  | 10,81 | 7,93  |   |
| W.Y.4     | 55,55 | 61,76 | 27,14 | 21,31 | 11,58 | 10,12 |   |
| W.Y.5     | 56,58 | 72,01 | 23,42 | 14,35 | 11,92 | 9,54  |   |
| W.Y.6     | 63,20 | 58,90 | 20,90 | 23,47 | 11,32 | 12,21 |   |
| W.Y.7     | 66,22 | 67,46 | 17,94 | 16,89 | 9,39  | 10,26 |   |
| W.Y.8     | 60,64 | 56,20 | 22,81 | 25,67 | 10,08 | 10,96 |   |
| W.Y.9     | 50,62 | 59,32 | 29,99 | 25,63 | 12,42 | 11,38 |   |
| W.Y.10    | 55,76 | 51,08 | 31,06 | 35,87 | 13,41 | 15,75 |   |
| W.Y.11    | 58,33 | 68,65 | 24,05 | 17,63 | 10,49 | 9,46  |   |
| W.Y.12    | 55,88 | 55,75 | 0,88  | 0,89  | 3,79  | 3,65  |   |

The color fastness properties of the woven fabric samples, after the completion of printing and finishing processes, were evaluated as follows: color fastness to water according to TS EN ISO 105-E01, acidic and alkaline perspiration fastness according to TS EN ISO 105-E04, and dry and wet rubbing fastness according to TS EN ISO 105-X12. The results are presented in Table 6.

**Table 6.** Color Fastness Test Results

| Yarn Code | Acidic Perspiration Fastness |   | Alkaline Perspiration Fastness |   | Water Fastness |   | Dry Rubbing Fastness |     | Wet Rubbing Fastness |     |
|-----------|------------------------------|---|--------------------------------|---|----------------|---|----------------------|-----|----------------------|-----|
|           | B                            | A | B                              | A | B              | A | B                    | A   | B                    | A   |
| W.Y.1     | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4   | 3/4                  | 3/4 |
| W.Y.2     | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4   | 3                    | 3   |
| W.Y.3     | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4   | 4                    | 3   |
| W.Y.4     | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4/5 | 3                    | 3/4 |
| W.Y.5     | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4/5 | 3                    | 3   |
| W.Y.6     | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4/5 | 3                    | 3/4 |
| W.Y.7     | 5                            | 5 | 5                              | 5 | 5              | 5 | 5                    | 4/5 | 4                    | 3/4 |
| W.Y.8     | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4/5 | 4                    | 4   |
| W.Y.9     | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4/5 | 4                    | 4   |
| W.Y.10    | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4   | 3/4                  | 3   |
| W.Y.11    | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4/5 | 4                    | 4   |
| W.Y.12    | 5                            | 5 | 5                              | 5 | 5              | 5 | 4/5                  | 4/5 | 4/5                  | 4/5 |

When the color fastness test results were evaluated separately for cellulosic and polyester-based samples, it was determined that all samples exhibited a rating of 5 for acidic and alkaline perspiration fastness as well as water fastness. This indicates the effectiveness of the applied dyeing and finishing processes and the strong affinity of the colorants to the fiber structure [9].

For the cellulosic-based samples, dry rubbing fastness values were generally found to be in the range of 4–5 to 4, while wet rubbing fastness values were observed between 3 and 3–4. In the case of polyester-based samples, dry rubbing fastness values were similarly in the range of 4–5 to 4–5, whereas wet rubbing fastness values were generally between 3–4 and 4. This behaviour is attributed to the easier removal and transfer of colorants from the fiber surface in the presence of water [10].

The improvement observed in rubbing fastness after the finishing process is considered to be associated with the enhanced fixation of dye/pigment on the fabric surface. Moreover, the higher fastness values obtained in polyester-based samples, particularly in sample W.Y.12, highlight the influence of fiber structure and the applied coloration method on fastness performance [11].

#### 4. CONCLUSION

In this study, the performance properties of bedroom textiles produced using different cellulosic and polyester based yarns were comparatively investigated. The findings revealed that both fiber type and the applied finishing processes have a decisive effect on fabric performance. According to the results obtained, polyester-based yarns provided higher tensile strength, abrasion resistance, and pilling resistance. In contrast, although fabrics containing cellulosic and regenerated fibers exhibited lower strength values, they were found to maintain acceptable performance. Evaluation of bending rigidity results indicated that fabric stiffness is directly related to fiber type and fabric weight, and that fabrics gained a softer structure after the finishing process. In particular, modified polyester yarns were found to improve the drape properties of the fabrics. When the color and fastness results were assessed, it was determined that the applied printing and finishing processes were effective for all samples and provided high fastness values. In addition, yarn type and surface structure were found to be decisive factors influencing the color coordinates of the fabrics. As a result, the combined use of sustainable cellulosic fibers and functional polyester fibers enables the development of bedroom textiles with optimized performance properties. This study contributes to the literature by revealing the effects of different fiber types on fabric performance.

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## DEVELOPMENT OF GREEN COMPOSITES REINFORCED WITH BAST FIBER FOR ACOUSTIC APPLICATIONS

Akande Çelebi<sup>1\*</sup>, Abdulkadir Pars<sup>1</sup>, Fatma Zehra Engin Sağırılı<sup>1</sup>, Ali Beyit<sup>1</sup>

<sup>1</sup>Department of Textile Engineering, Faculty of Technology, Marmara University, Istanbul, Türkiye

### ABSTRACT

Natural fibers, defined as bio-based materials derived from plant or animal sources, have become critical in materials science for their potential to replace synthetic counterparts. Among these, bast fibers obtained from plant stems offer specific advantages such as low density, high specific strength, and biodegradability. Noise has become a major worldwide issue due to population growth, increased demand for goods and services, and industrial expansion. These fibers can effectively rival synthetic fibers in terms of acoustic qualities. As the demand for sustainable materials grows, the focus has shifted toward optimizing the polymer matrix to fully leverage these fiber properties without compromising environmental compliance. The present research work aims to evaluate the acoustic and mechanical performance of biodegradable PLA-based green composites reinforced with jute fabric. Different combinations of PLA/ Jute and bicomponent-PLA/Jute green composites were fabricated by varying the fabric layer and weight fraction. The matrix phase was engineered using a blend of staple Polylactic Acid (PLA) and staple bicomponent PLA fibers. The inclusion of bicomponent PLA was significant; its sheath-core structure functions as a thermal bonding agent, facilitating superior matrix consolidation and structural integrity during processing without the need for chemical adhesives.

These polymer fibers were first processed into uniform nonwoven webs using a conventional carding machine. To fabricate the bio-composite structures, jute fabric layers were intercalated with the carded matrix webs. The experimental design focused on the effect of reinforcement volume by producing laminates with single-, double-, and triple-layer jute fabrics. These stratified assemblies were subsequently consolidated under controlled heat and pressure in a hot press machine to ensure effective impregnation. Acoustic and mechanical properties were evaluated in accordance with ISO standards to characterize both sound transmission loss capabilities and the structural strength of the materials. The findings established the viability of jute-reinforced PLA-based green composites as high-performance, eco-friendly materials suitable for a broad spectrum of general industrial applications.

**Keywords:** Natural fibers, green composites, PLA, Bicomponent PLA, Jute.

### INTRODUCTION

Green composites are advanced engineering materials developed in line with sustainability principles, typically composed of natural fibers such as jute, flax, or hemp combined with biodegradable or bio-based polymer matrices like polylactic acid (PLA). These materials offer significant advantages over conventional synthetic composites due to their low density, renewability, and reduced environmental impact at the end of their life cycle. The mechanical performance of green composites is strongly influenced by factors such as fiber-matrix interfacial adhesion, fiber orientation, fabric architecture, and processing techniques. Recent studies have demonstrated that surface treatments and hybridization strategies can significantly enhance the mechanical and thermal properties of these materials, making them increasingly suitable for applications in automotive, construction, and textile industries (Faruk et al., 2012; Koronis et al., 2013).

Polylactic acid (PLA) and bicomponent PLA have gained considerable attention as matrix materials in green composites due to their bio-based origin, biodegradability, and favorable processing characteristics. PLA exhibits relatively high stiffness and strength compared to many other biodegradable polymers; however, its inherent brittleness and low impact resistance can limit its performance in certain applications.

In this context, bicomponent PLA fibers—typically consisting of a core–sheath structure with differing thermal or mechanical properties—offer significant advantages by enhancing interfacial bonding, improving toughness, and facilitating better processing through lower melting sheath components. The use of bicomponent PLA as a matrix or binding phase can promote more efficient stress transfer between reinforcement and matrix, particularly in natural fiber–reinforced systems such as jute or flax fabrics. Additionally, the tunable thermal behavior and crystallization characteristics of bicomponent PLA enable improved consolidation and reduced processing temperatures, which is critical for preserving the integrity of temperature-sensitive natural fibers. Therefore, combining PLA and bicomponent PLA in composite systems provides a promising strategy to balance stiffness, ductility, and sustainability requirements in advanced green composite applications (Auras et al., 2010; Lim et al., 2008; Faruk et al., 2012).

This study investigates the acoustic and mechanical performance of biodegradable PLA-based green composites reinforced with jute fabrics. Composites were produced using different configurations of PLA/jute and bicomponent PLA/jute systems, with variations in fabric layer number and weight fraction. The matrix was composed of staple PLA and bicomponent PLA fibers, where the sheath–core structure of bicomponent PLA acted as a thermal bonding agent, enabling effective consolidation without chemical adhesives. Initially, polymer fibers were converted into nonwoven webs via carding, and these webs were then combined with jute fabric layers in single-, double-, and triple-layer configurations. The layered structures were consolidated using hot pressing under controlled temperature and pressure conditions. Acoustic and mechanical properties were evaluated according to relevant ISO standards, demonstrating that jute-reinforced PLA-based green composites offer a promising combination of structural performance and sound insulation, making them suitable for various eco-friendly industrial applications.

## **MATERIALS AND METHODS**

### ***Materials***

Two different types of bio-fibres, PLA and bicomponent PLA fibres, were used as the matrix materials. The matrix phase for these composites was engineered using a blend of staple Polylactic Acid (PLA) and staple bicomponent PLA fibers. Jute is a natural, bio-based bast fiber derived primarily from the stems of plants. A jute fabric with a 2/1 warp rib weave was used as reinforcement. The fabric exhibited an areal density of 600 g/m<sup>2</sup>. The linear densities of the yarns were 1000 tex in the weft direction and 500 tex in the warp direction. The fabric sett was 3 picks/cm (weft) and 7 ends/cm (warp). The selection of a 2/1 warp rib jute fabric provides a balanced distribution of yarns, which influences the impregnation quality during the hot-pressing process.

### ***Method***

#### ***Carding machine***

Polymer fibers were first processed into uniform nonwoven webs using a Mesdan laboratory-type carding machine. To fabricate the bio-composite structures, jute fabric layers were intercalated with the carded matrix webs. The experimental design focused on the effect of reinforcement volume by producing laminates with single-, double-, and triple-layer jute fabrics. These stratified assemblies were subsequently consolidated under controlled heat and pressure in a hot press machine to ensure effective impregnation.

#### ***Hydraulic hot press machine***

A hydraulic hot press machine (Hürsan Pres, Konya, Türkiye) was utilized for the fabrication of the green composites under controlled temperature and pressure conditions. Owing to the heating conditions utilized in the press, the thermoplastic biofibres melted at the specified temperature and time conditions and were contained inside the mould. The composites were further set in the mould with the help of the cooling system present in the press to obtain the final samples.

### ***Testing***

#### ***Mechanical***

Tensile properties of the produced biocomposite materials were evaluated using a universal testing machine (Zwick/Roell Z4100). All tests were conducted in accordance with the ASTM D638 standard at a crosshead speed of 50 mm/min. For each sample group, five specimens were tested, and the reported results represent the average values to ensure statistical reliability.

### Acoustic

The acoustic properties of the green composites were measured using the two-microphone transfer-function method in accordance with ISO 10534–2 and ASTM E1050–98 standards. Measurements were carried out using a Brüel & Kjær Type 4206 impedance tube system with a 29 mm diameter tube over a frequency range of 400–6400 Hz. The system was integrated with the Brüel & Kjær PULSE™ platform for data acquisition and analysis.

## RESULTS AND DISCUSSIONS

The mechanical performance of jute fabric–reinforced green composites is significantly influenced by both the reinforcement structure and the matrix type (Zhang et al., 2025; Kumar and Singh, 2026). In the *A*-series composites, produced with 100% PLA, tensile strength increases markedly with the number of jute fabric layers, rising from 415 MPa (A1) to 560 MPa (A3). This trend reflects the enhanced load transfer efficiency and improved stress distribution enabled by the multilayer reinforcement structure (Lee et al., 2025). Moreover, A3 shows the highest strain value of 0.81%, suggesting that adding more layers not only enhances strength but also increases the material’s energy absorption capacity. This enhanced performance is due to stronger fiber–matrix interactions and greater interfacial friction, which help to delay crack initiation and propagation during tensile loading (Kumar and Singh, 2026). In contrast, the *B*-series composites, fabricated using bicomponent PLA, exhibit comparatively lower tensile strength values (234–286 MPa) despite following a similar increasing trend with layer number. This reduction may be associated with the relatively lower stiffness of the bicomponent matrix and differences in interfacial load transfer efficiency. However, the strain behavior of the *B*-series suggests improved ductility, particularly for B3 (0.62%), which indicates enhanced deformability and energy dissipation capacity. The sheath–core structure of bicomponent fibers likely promotes more effective stress redistribution and accommodates higher deformation before failure (Wang et al., 2025). Overall, while 100% PLA matrices favor strength-dominated performance, bicomponent PLA systems contribute to a more ductile response, highlighting the importance of matrix selection in tailoring the mechanical performance of sustainable biocomposites (Zhang et al., 2025).

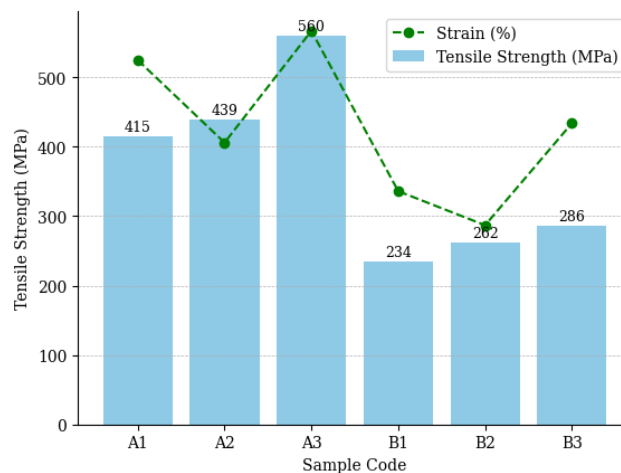


**Figure 1.** Mechanical Properties of the green composites.

The acoustic performance of the developed jute fabric–reinforced green composites is influenced by both the structural configuration and the matrix system. Increasing the number of jute fabric layers from single-layer to three-layer architectures consistently improved sound transmission loss (STL) across the entire frequency range. This behavior can be attributed to the increase in areal density and overall thickness, which enhances acoustic impedance mismatch and promotes more effective attenuation of incident sound waves (Chen et al., 2026).

A clear distinction is observed between the two composite series in terms of matrix type. The *B*-series composites, produced using bicomponent PLA, exhibit superior STL performance compared to the *A*-series samples fabricated with 100% PLA. This difference is particularly evident in the three-layer configuration, where B3 demonstrates the highest acoustic attenuation. The enhanced performance of the bicomponent PLA system can be associated with its improved thermal bonding behavior, which promotes stronger interfacial adhesion between the jute fibers and the polymer matrix. Additionally, the sheath–core structure

of bicomponent fibers likely contributes to more efficient consolidation during hot pressing, resulting in reduced interfacial voids and improved structural integrity (Lee et al., 2025).

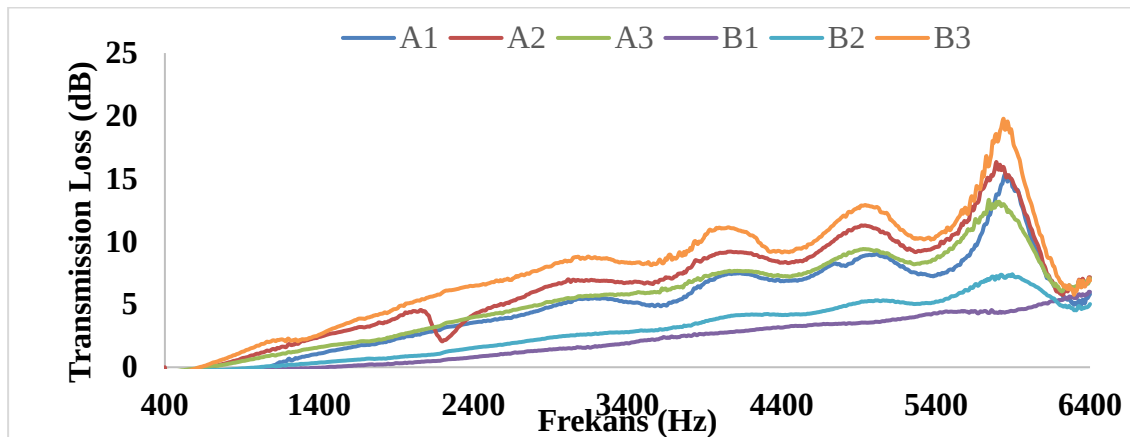


Figure 2. Sound transmission loss of green composites.

## CONCLUSION

The present study indicates that both the acoustic and mechanical performances of jute fabric–reinforced green composites are strongly controlled by reinforcement architecture and matrix type. Increasing the number of jute fabric layers significantly enhances sound transmission loss (STL) as well as tensile strength, primarily due to increased areal density, improved stress transfer, and more effective internal damping mechanisms within the multilayered structure. Among all samples, three-layer configurations provide the most favorable performance, with B3 exhibiting superior acoustic insulation, while A3 achieves the highest tensile strength and elongation. The use of bicomponent PLA matrix further improves the acoustic response by promoting enhanced interfacial bonding and energy dissipation, whereas melt PLA leads to a relatively stiffer structure that favors strength-dominated behavior. These findings highlight that the balance between stiffness and damping in green composites can be effectively tailored through the appropriate selection of matrix systems and reinforcement layering. Overall, the developed jute-based multilayer green composites offer a promising and sustainable alternative for applications requiring a combination of mechanical robustness and efficient sound insulation.

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# DIGITAL CRAFTSMANSHIP IN FASHION DESIGN: HYBRIDIZING TRADITIONAL TECHNIQUES AND EMERGING TECHNOLOGIES

Arzu Vuruskan<sup>1\*</sup>, Ender Bulgun<sup>1</sup>, Ahmet Belen<sup>1</sup>, Melis Ozen<sup>1</sup>

<sup>1</sup> Izmir University of Economics, Department of Textile and Fashion Design, Izmir, Turkiye

\*ender.bulgun@ieu.edu.tr

## ABSTRACT

Craftsmanship practices, including traditional textile techniques such as weaving, embroidery, and patchwork, are a significant element of cultural identity. However, the continuity of these craftsmanship practices is threatened to disappear by the digitalization of industry and the decline of apprenticeship-based knowledge transfer. In this context, digitalisation presents both challenges and opportunities, raising critical questions about how emerging technologies can support rather than replace craftsmanship.

This study aims to explore the relationship between emerging technologies and craftsmanship in contemporary fashion design, with a focus on their role in preserving cultural heritage. Patchwork is selected as a case study due to its strong connections to material reuse, cultural expression, and modular design logic. The research adopts a mixed-method approach, combining qualitative and quantitative data. Semi-structured interviews were conducted with fashion industry professionals to examine their perspectives on digitalisation and craftsmanship. Also, a survey was carried out with fashion and textile design students to assess emerging thoughts toward digital tools and craftsmanship practices.

The results imply that digitalization and craftsmanship are mostly perceived as complementary practices. While digital tools are valued for improving efficiency, visualization, and data-driven decision-making, participants emphasized that they cannot replace the cultural, emotional, and creative value of craftsmanship. Concerns regarding authenticity, particularly in relation to AI-generated outputs, were frequently highlighted. At the same time, craftsmanship practices were identified as effective strategies for sustainability through material reuse and extended product lifecycles. The results also reveal gaps in fashion education, particularly in the integration of digital literacy, business competencies, and practical industry experience.

**Keywords:** *Digital Craftsmanship, Intangible Cultural Heritage (ICH), Sustainable Fashion Design, Patchwork*

## 1. INTRODUCTION

Cultural heritage is not limited to monuments or physical artifacts but also includes the practices, skills, expressions, and knowledge that communities transmit over time [1]. Intangible Cultural Heritage (ICH) includes traditional textile techniques such as embroidery, weaving methods, dyeing methods and patchwork that is rooted within cultural memory. These techniques are not just for decoration or aesthetic purposes; they reflect regional identities, culture and social relationships. Moreover, these techniques reflect ways of sustainable living, producing and using.

Industrial standardization that results in shrinking artisan communities, and the loss of apprenticeship systems are threatening the continuity of knowledge that is learned through experience. As a result, technological progress becomes both a challenge and an opportunity. If applied without care, digitalization will continue damaging artisan communities and reduce handmade practices. The question should not be whether technology should replace craft, but how they can coexist and improve each other. Digital fabrication tools and 3D printing, for instance, can act as extensions of the artisan's hand, expanding creative capacity and precision without discarding the essential tactile qualities of the craft [2]. Rather than replacing

the craftsmanship, digital systems can help its reach by preserving and sharing skills. By approaching technology as a collaborator rather than a competitor, fashion can move towards a future where innovation supports cultural continuity.

Within this progressing environment, digital cultural heritage (DCH) frameworks have emerged as important arrangements for preservation and education. Digital heritage includes resources that are either born digital or converted into digital form, emphasizing the growing importance of digital literacy and technological competencies in heritage-related disciplines [3]. However, while DCH initiatives often focus on archives, museums, and archaeological documentation, fashion and textile crafts remain under-theorized within these frameworks. This gap reveals the need for a fashion-specific digital heritage approach capable of translating embodied craft knowledge into sustainable digital ecosystems.

The integration of digital tools does not necessarily contradict these values. Rather, when approached critically, technology can strengthen them. The dialogue between craftsmanship and technology should be understood as complementary rather than oppositional [4]. Within this framework, digital systems such as algorithmic modeling, digital archiving, and parametric design can document and systematize traditional techniques while preserving their cultural meaning. This enables designers to scale sustainable craft principles without reducing them to superficial aesthetic references.

### **Digitalisation of Patchwork**

Due to its strong relationship with cultural heritage, sustainability, and personalisation, patchwork is selected as a case study for analysing digital craftsmanship. It emerged from limited material resources [5]; however, over time, these functional objects shifted, and patchwork has transformed from a domestic textile practice into a distinct design identity within the fashion industry, creating a bridge between heritage and contemporary reinterpretations of traditional handicrafts. Furthermore, in contemporary fashion, patchwork is increasingly recognized as a sustainable tool and a key component of slow fashion, valued by consumers for both its ecological benefits and its cultural significance [6].

From a production perspective, patchwork also offers a structural system that is particularly suitable for digital reinterpretation. It operates through modular logic, repetition, and pattern variation. These compositional principles can be easily translated into digital systems such as algorithmic design methods and parametric modeling processes [7].

Although patchwork is deeply rooted in handcraft, it contains both material and compositional structures that can be scanned, recorded, archived, and reinterpreted within digital environments. This dual nature makes it an appropriate case for combining digital craftsmanship with traditional practice, contributing to the preservation of Intangible Cultural Heritage while allowing reinterpretation rather than replacement.

## **2. METHODOLOGY**

This research adopts a mixed-method approach by combining qualitative and quantitative methods, which allows for a broader understanding of the relationship between traditional craft practices and digital technologies in contemporary fashion design. The study focuses on digital craftsmanship, the preservation of Intangible Cultural Heritage (ICH), and the role of digital tools in sustaining traditional textile knowledge within modern fashion systems.

The qualitative part of the research consists of interviews with 6 fashion industry professionals. The interviews are conducted online and semi-structured; participants are selected based on their engagement with craft-based textile techniques and digital design processes. The aim is to gain insight into how professionals in the fashion industry approach the integration of traditional craftsmanship and emerging digital technologies within contemporary design and production processes. To support this objective, the qualitative data are analyzed using MAXQDA software to support thematic interpretation.

In addition, the research consists of a survey conducted with 35 students from the Izmir University of Economics between the ages of 18 and 25, from the Textile and Fashion Design Department, as potential

fashion designers. Their responses help reveal how younger generations perceive the relevance of traditional craftsmanship within contemporary fashion practice. The survey asks participants about their perceptions of digital technologies in fashion, the importance of cultural heritage in design and production, and their attitudes toward the digital preservation of traditional textile knowledge. It also explores whether participants believe digital tools can support the continuity of craft practices in the future.

The interview data were examined through thematic analysis in order to identify recurring themes related to digitalisation and craft integration, sustainability and cultural heritage, and business and future industry transformation.

The survey data were analyzed quantitatively using a five-point Likert scale, and the results were analyzed using statistical methods. This process allowed the identification of general tendencies and attitudes toward the hybridizing of traditional techniques and emerging technologies.

### **3. RESULTS and DISCUSSION**

#### **3.1. Survey Results**

The findings from the survey are evaluated under three items:

Firstly, participants reveal the value of blended skills in education. A major proportion (82.8%) confirmed that future fashion professionals will be required to combine traditional practices with emerging digital technologies, and similarly, 77.1% agreed that educational approaches should remain balanced in order to achieve this without excluding either digitalisation or traditional craftsmanship.

Secondly, the findings demonstrate that there are concerns about digitalisation and authenticity. More than half of the participants (57.2%) stated that the authenticity of traditional crafts may be threatened by digitalisation, while 37.1% maintained a neutral position. This data may suggest some hesitation, possibly linked to limited familiarity with AI technologies and how they may relate to craft practices.

Another point is that respondents strongly support the digital preservation of traditional practices, and 85.7% agreed that it is necessary to use digital archiving for sustaining cultural textile heritage and recognised the essential role of digital tools in safeguarding conventional practices.

These findings reveal that students, as future designers, acknowledge the potential of digital tools in fashion design while highlighting the significance of a balanced approach between digital technologies and traditional craftsmanship in future institutional education.

#### **3.2. Interview Results**

The interview results show that participants recognize digitalization and AI as increasingly integrated into the industry. They believe it can improve efficiency, speed up workflows, and support idea generation, particularly in visual content production. For this reason, they think it should be adopted more widely. At the same time, they do not view it as a substitute for craftsmanship in the design process. Craft is still considered essential because of its cultural significance and emotional value. Participants generally described the relationship between traditional craft practices and digital technologies as complementary rather than conflicting. However, they also raised concerns about the authenticity of AI-generated outputs, noting that such results can appear overly perfect and lack a human touch. Overall, digitalization is not rejected but approached cautiously and integrated selectively.

Participants pointed to a gap between fashion education and industry expectations, explaining that although creative skills are developed well, practical experience and business knowledge are often underdeveloped. Competencies such as marketing, brand development, and digital literacy were identified as essential, but participants noted that these should be more fully integrated into the curriculum.

Participants emphasized that transforming leftover materials into new products reduces waste while enhancing creativity and product value. Beyond production methods, sustainability was also associated with better planning and reduced overproduction. Traditional craft practices were therefore seen as inherently sustainable, promoting durability, uniqueness, and longer product lifecycles.

Participants also stressed that while digital technologies offer significant opportunities for archiving and publishing cultural knowledge, digitalization is insufficient for preserving craft heritage because craftsmanship is deeply involved in master-apprentice relationships. Digital archiving that typically consists of photographs, videos, and documentation has a risk of superficial representation if the cultural context, narratives, and historical significance of crafts are not adequately expressed.

These results suggest that participants are more comfortable using digital tools in business-related processes rather than in the design stage. While digital tools are seen as helpful for managing production, communication, and marketing, there is still a clear preference for keeping the design process more hands-on and personal. The findings also highlight a need for fashion education to better balance creative training with practical and digital skills. In terms of cultural heritage, although digital tools make it easier to document and share information, participants felt that they are not always enough to fully represent the deeper meaning and background of craft practices. This suggests that digitalization can support preservation, but it needs to be used more carefully to also include cultural context, not just visual or technical information.

#### **4. CONCLUSION and FUTURE WORK**

Both the interview data and survey results point to a strong hybrid perspective, in which participants position themselves between digital and craft-based practices rather than fully identifying with one side. Digital tools are widely valued for their contributions to efficiency, visualization, documentation, and business-related processes. However, they are less readily accepted in the design phase itself, where creativity, individuality, emotional expression, and the human touch continue to be strongly associated with handmade practices. In this respect, craft remains central not only as a production method but also as a cultural and creative value.

At the same time, concerns about authenticity, particularly regarding digital- and AI-generated outputs, show that participants remain sensitive to the preservation of the human dimension of design. While digitalisation is generally seen as useful for supporting sustainability, accessibility, and the preservation of cultural heritage, the findings also suggest that its current applications may be limited in communicating deeper cultural meaning. This indicates that digital preservation should go beyond technical recording and include narrative, context, and interpretation.

Overall, the findings suggest that the future of fashion design may lie in a balanced and complementary relationship between digital technologies and craftsmanship, where digital tools support and extend craft practices without reducing their cultural, emotional, and creative significance.

For future work, the number of participants in both the survey and interview phases can be increased in order to develop a broader and more representative understanding of these issues. In addition, the inclusion of perspectives from the ready-to-wear industry could provide further insight into how these dynamics are understood in mass production contexts.

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## ELECTRICAL RESISTANCE OF EMBROIDERED CONDUCTIVE STRUCTURES FOR SMART TEXTILE ANTENNAS

Inga Breitmozere<sup>1,\*</sup>, Guste Lastauskaite<sup>1</sup>, Jurgita Domskiene<sup>1</sup>

<sup>1</sup> Kaunas University of Technology, Faculty of Mechanical Engineering and Design, Kaunas, Lithuania

\* [inga.breitmozere@ktu.edu](mailto:inga.breitmozere@ktu.edu)

### ABSTRACT

Conductive embroidered structures are increasingly used in smart textiles for the integration of antennas in NFC and RFID systems, where controlled electrical resistance and well-defined conductive geometry are essential. The performance of such systems is controlled by a combination of material properties and structural design. While increasing the conductive loop can enhance electromagnetic functionality, it simultaneously introduces additional resistance losses. These effects are further influenced by stitch pattern, stitch density, and the intrinsic electrical properties of conductive yarns, making the optimisation of embroidered conductive tracks a multi-parameter design problem.

This study investigates the influence of geometric parameters on the electrical resistance of embroidered conductive structures, with a focus on stitch pattern and density effects across different conductive yarns. Rectangular conductive tracks with a fixed length of 100 mm and 5 mm width were fabricated using four stitch patterns and three density levels. Multiple commercially available conductive threads with different linear resistances were used to evaluate material structure interactions under controlled fabrication conditions. Electrical resistance was measured using a four-wire Kelvin method specified in standard EN 16812 to ensure high accuracy and repeatability.

The results show that electrical resistance is strongly dependent on both stitch pattern and density, with significant variations observed across different configurations. The findings confirm that the electrical behaviour of embroidered conductive structures cannot be described solely by material properties therefore must also account for geometric design parameters. This highlights the importance of integrated material–geometry optimisation for the development of reliable embroidered antennas in textile-based electronic systems.

**Keywords:** *stitching, geometry, NFC, RFID, pattern, density*

### 1. INTRODUCTION

The development of e-textiles represents a fundamental shift in wearable technology, enabling integration of wireless communication capabilities directly into textile products [1,2]. Conductive embroidered structures have emerged as a key solution for implementing wearable antennas using standard textile manufacturing processes [3,4]. Embroidered antennas operate based on the same electromagnetic principles as conventional ones. However, their implementation on textile backgrounds introduces specific design limitations related to material properties and structural configuration [5,6].

The electrical performance of embroidered conductive tracks depends on both the linear resistance of conductive threads and the geometric parameters of stitch pattern and density [7,8]. These factors influence the effective conductive track length and continuity, which determine resistance and antenna performance. Therefore, optimisation of embroidered structures requires balancing conductive track geometry with minimal electrical resistance to ensure stable and efficient operation [6,9,10].

Embroidered antennas face inherent limitations compared to metallic antennas. Conductive threads exhibit significantly higher resistivity, and parasitic effects may arise during embroidery [11,12]. Common conductive materials include twisted metal wires, silver- or copper-coated yarns, stainless-steel fibres, as

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well as polymer-based conductive coatings such as PEDOT:PSS, PANI [12,13]. Each material exhibits distinct electrical behaviour, making material selection a critical factor in design [6,14].

Previous studies have demonstrated that stitch pattern, type and density significantly affect electrical properties by altering the internal structure of conductive tracks [15-18]. However, existing research is generally limited either to a restricted number of conductive threads or to a narrow range of stitch patterns. As a result, combined effects of multiple conductive threads and diverse stitch configurations, particularly regarding variability and stability of electrical resistance, remain insufficiently characterised

In this context, the present study investigates the electrical resistance of embroidered conductive tracks using multiple conductive threads and stitch configurations, with particular emphasis on the influence of stitch pattern and stitch density on electrical performance.

## 2. EXPERIMENTAL STUDY

As the base fabric, a white 100% cotton twill weave fabric with a thickness of 0.53 mm and 270 g/m<sup>2</sup> density was selected. It is characterized by sufficient mechanical stability and stiffness, ensuring that the conductive track geometry defined during embroidery is not altered by deformation of the fabric structure.

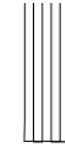
To assess how electrical resistance varies, six different electrically conductive threads were selected (Table 1). Five of the selected threads are metallized using silver coatings and one is made of stainless-steel filaments. Considering the capabilities of the equipment used, threads S1, S2, M1, and M2 were used as upper threads, while a standard 100% PES, 8.33 tex thread was used as the bobbin thread, forming an embroidered conductive track system. For threads B1 and S3, this configuration was reversed, with the conductive threads used as bobbin threads.

**Table 1.** Conductive threads specification.

| Code | PRODUCT                                  | COMPOSITION                                           | LINEAR DENSITY, TEX | RESISTANCE $R_{TH}$ , $\Omega/m$ |
|------|------------------------------------------|-------------------------------------------------------|---------------------|----------------------------------|
| S1   | Shieldex 117/17 2-ply HC + B             | 99.9% PA 6.6, Silver plated<br>Nitrile rubber coating | 29.6                | <300                             |
| S2   | Shieldex 235/36 2-ply HC + B             | 99.9% PA 6.6, Silver plated<br>Nitrile rubber coating | 59.6                | 80±30                            |
| S3   | Shieldex 235/36 4-ply HC + B             | 99.9% PA 6.6, Silver plated<br>Nitrile rubber coating | 121                 | 40±10                            |
| M1   | Madeira HC 40                            | 100% PA, Silver plated                                | 29.0                | <300                             |
| M2   | Madeira HC 12                            | 100% PA, Silver plated                                | 61.0                | <100                             |
| B1   | Bekaert Bekinox<br>VN 12/1x275/100Z/316L | Stainless steel filament yarn                         | 235                 | 30                               |

To ensure that the results could be compared under identical conditions, conductive tracks of 100 mm in length and 5 mm in width were embroidered using a Brother Innov-is M380D embroidery machine. The geometry and fill patterns of these tracks were designed using the open-source vector graphics editor Inkscape, with the InkStitch plugin specifically developed for creating embroidery patterns. This plugin not only offers a wide selection of embroidery stitches and their parameters but is also compatible with the software of the Brother embroidery machine in use. A total of four different stitch patterns were selected (Zigzag, Running stitch, Legacy and Tripple Zigzag), and three densities were defined for each conductive track, resulting in 12 different geometric configurations (Table 2). Each of designed conductive track was embroidered with six different threads, resulting in a total of 72 samples for electrical resistance measurements.

**Table 2.** Conductive track patterns specification.

| Code    | Z1                                                                                | Z2                                                                                | Z3                                                                                | R1                                                                                | R2                                                                                | R3                                                                                | L1                                                                                | L2                                                                                | L3                                                                                  | TZ1                                                                                 | TZ2                                                                                 | TZ3                                                                                 |
|---------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| SCHEME  |  |  |  |  |  |  |  |  |  |  |  |  |
| TYPE*   | Z                                                                                 | Z                                                                                 | Z                                                                                 | R                                                                                 | R                                                                                 | R                                                                                 | L                                                                                 | L                                                                                 | L                                                                                   | TZ                                                                                  | TZ                                                                                  | TZ                                                                                  |
| SPEC.** | S 0.5                                                                             | S 1.0                                                                             | S 1.5                                                                             | PL 7                                                                              | PL 5                                                                              | PL 3                                                                              | S 0.5                                                                             | S 1.0                                                                             | S 1.5                                                                               | S 0.5                                                                               | S 1.0                                                                               | S 1.5                                                                               |

\*Abbreviations: Z – zigzag; R – Running stitch; L – Legacy; TZ – Triple zig-zag;

\*\*Abbreviations: S – spacing between peaks, mm; PL – number of parallel lines;

Electrical resistance was measured using a four wire Kelvin method as specified in EN 16812:2016 [19], with a Keithley 2614B SourceMeter®. The electrodes were attached to the embroidered conductive tracks using special clamps, to ensure stable electrical contact during measurement. The samples were measured using an automatic 30-cycle measurement sequence, yielding average electrical resistance values with an accuracy of 0.01 Ω.

To enable comparison of electrical performance across different conductive tracks, a normalised resistance factor K was calculated (Eq.1).

$$K = \frac{R_{emb}}{R_{th}} \quad \text{Eq. 1}$$

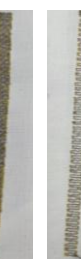
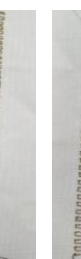
where:  $R_{emb}$  – measured linear resistance of embroidered track, Ω/m;  $R_{th}$  – linear resistance of the conductive thread, Ω/m;

A statistical evaluation of the experimental results was carried out using ANOVA to assess the significance of conductive thread type, embroidery pattern, and density level on the measured linear resistance values.

### 3. RESULTS

Table 3 presents embroidered conductive track structures fabricated using the S1 conductive thread. The images show the actual realised stitch patterns and density configurations as implemented in the embroidery process.

**Table 3.** Embroidered Conductive track examples using S1 thread

| Code                          | Z1                                                                                  | Z2                                                                                  | Z3                                                                                  | R1                                                                                  | R2                                                                                  | R3                                                                                  | L1                                                                                  | L2                                                                                   | L3                                                                                    | TZ1                                                                                   | TZ2                                                                                   | TZ3                                                                                   |
|-------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| S1<br>(SHIELD<br>EX<br>117x2) |  |  |  |  |  |  |  |  |  |  |  |  |

ANOVA revealed statistically significant effects of conductive thread type ( $p < 0.001$ ) and embroidery pattern ( $p = 0.002$ ) on the linear resistance values. Density level did not demonstrate a statistically significant effect ( $p = 0.730$ ). Nevertheless, its influence may depend on the specific embroidery pattern, suggesting interaction effects between variables.

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The analysis of linear resistance of embroidered conductive track (Table 4) confirms the prediction, that higher thread linear resistance results in higher resistance values, regardless of stitch density and selected pattern. The lowest values were obtained for threads with declared linear resistance of 30-40  $\Omega/m$  (B1 and S3). Intermediate values, although relatively close to the minimum, were obtained for threads S2 and M2 with 80-100  $\Omega/m$  linear resistance. The highest resistance values were observed for threads S1 and M1 with declared  $<300 \Omega/m$  linear resistance. The M1 thread exhibits the most pronounced resistance changes while S3 shows the most stability. Differences observed within groups of identical linear resistance further indicate that electrical performance is not determined by material properties alone but is also influenced by structural factors such as stitch pattern and density.

The analysis of the normalised resistance factor K across thread types (Fig. 1) shows clear differences in both median values and data spread. The lowest median K values are observed for S2 and M2 (1.83 and 1.38), while highest values are found for M1 and B1 (5.39 and 4.95). The widest range is observed for M1 (1.66–15.18 with outlier value 26.09), S1 (0.44–15.80) and B1 (0.88-16.81), where extended whiskers and outlier value indicate non-uniform electrical response across different stitch configurations applied to the same thread type. In contrast, S3 demonstrates a relatively narrow range (0.38–4.99) with a median of 3.05 reflecting more stable electrical behaviour. Overall, these results indicate that different threads exhibit varying degrees of variability in K, reflecting differences in how consistently they perform across stitch patterns.

**Table 4.** Linear resistance of conductive track.

| Thread Code | Z1     | Z2     | Z3       | R1    | R2    | R3     | L1     | L2     | L3     | TZ1    | TZ2    | TZ3   |
|-------------|--------|--------|----------|-------|-------|--------|--------|--------|--------|--------|--------|-------|
| <b>S1</b>   | 559.5  | 2823.1 | 1873.1   | 130.8 | 275.2 | 230.8  | 4739.2 | 3126.7 | 1993.3 | 837.3  | 732.1  | 473.7 |
| <b>S2</b>   | 128.1  | 719.3  | 555.7    | 34.40 | 42.6  | 62.9   | 689.2  | 874.3  | 604.6  | 134.7  | 157.0  | 135.4 |
| <b>M1</b>   | 1335.1 | 3736.1 | 1266.3.6 | 865.5 | 882.0 | 1155.9 | 7826.8 | 4554.8 | 3541.1 | 1190.6 | 1897.5 | 498.3 |
| <b>M2</b>   | 140.5  | 694.0  | 515.0    | 50.4  | 55.9  | 68.0   | 819.6  | 926.5  | 650.0  | 119.4  | 134.9  | 124.5 |
| <b>B1</b>   | 504.3  | 267.0  | 172.6    | 26.3  | 62.7  | 34.0   | 329.5  | 202.1  | 148.2  | 117.8  | 148.7  | 107.8 |
| <b>S3</b>   | 155.9  | 183.9  | 157.1    | 15.1  | 35.4  | 27.0   | 41.9   | 199.7  | 129.6  | 75.3   | 124.0  | 120.0 |

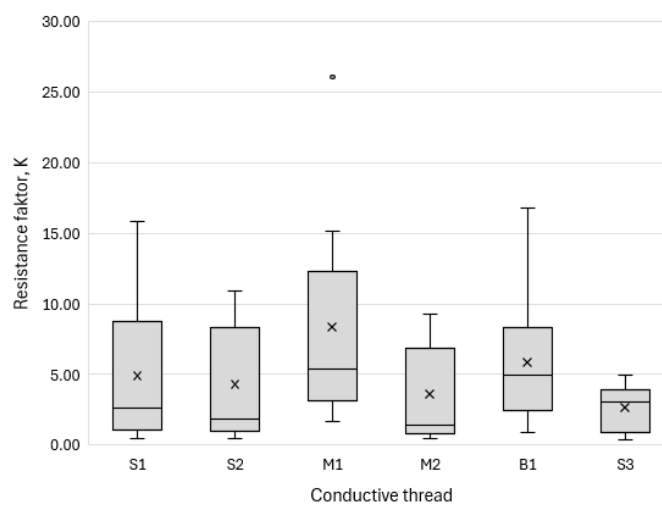


**Figure 1.** Normalised resistance factor K by conductive thread type.

The analysis of K across stitch patterns (Fig. 2) demonstrates that stitch pattern has a strong influence on both magnitude and distribution of electrical response. Running stitch patterns show the lowest median K values (0.42-0.78) and the narrowest spread, despite few outlier values (R1 – 2.89, R3 – 3.85), indicating the most stable and efficient conductive behaviour. Legacy stitch patterns exhibit the highest median values (6.57-9.80) and the widest distributions, with values for L1 from 1.05 reaching up to 26.09, confirming strong resistance amplification due to elongated conductive tracks. Zigzag patterns show intermediate

medians (2.88-6.00) with considerable variability, while Triple Zigzag patterns demonstrate lower medians (1.68-2.34) and reduced dispersion compared to Zigzag structures.

While stitch pattern determines the overall level and distribution of K, the analysis of density impact on the K factor (Fig. 2) shows no clear overall correlation, suggesting that pattern type dominates over density effects. The Zigzag pattern exhibits an inverted U-shaped response, with K values increasing from Z1 to Z2 and decreasing at Z3 (5.00 – 8.55 – 6.15). The Triple Zigzag pattern shows a similar trend, with a peak at intermediate density (2.53 – 3.36 – 2.13 for TZ1–TZ3, respectively). The Legacy stitch demonstrates a positive relationship between stitch density and electrical resistance, with higher density corresponding to higher K values, as K decreases consistently from L1 to L3 (11.79 → 9.59 → 6.78). The Running stitch pattern shows a weak and partially saturating trend, with K values increasing from R1 to R2 and remaining stable at higher densities (0.92 – 1.32 – 1.32).

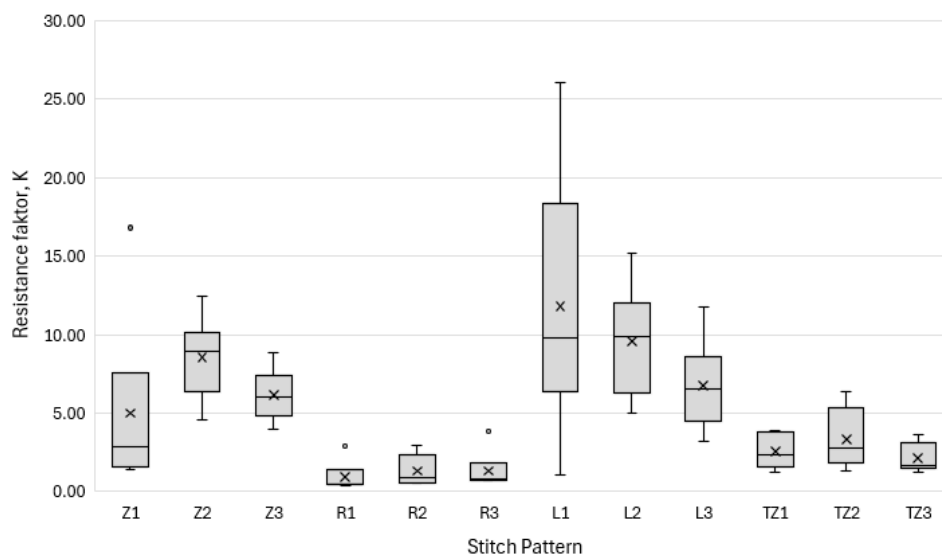


**Figure 2.** Normalised resistance factor K by stitch pattern.

#### 4. CONCLUSION

The results show that the electrical performance of embroidered conductive paths is determined by the combined influence of thread properties and stitch pattern, while stitch density demonstrates a secondary, pattern-dependent effect. Absolute resistance values reveal a wide dynamic range (up to  $\approx 518$  times), confirming strong interactions between thread properties and conductive track geometry.

The normalised resistance factor K highlights structural effects independent of thread linear resistance. Threads Madeira HC 40 (M1) and Shieldex 117/17 2-ply HC + B (S1) exhibit the highest variability (up to  $\approx 26$  and  $\approx 16$ ), whereas Shieldex 235/36 4-ply HC + B (S3) shows more stable behaviour ( $\approx 0.38$ – $4.99$ ), indicating more consistent performance across stitch patterns.

Stitch pattern is identified as the dominant factor affecting electrical behaviour. Running stitch provides the lowest and most stable performance, whereas Legacy patterns exhibit the highest resistance amplification. Zigzag-based patterns show non-linear, pattern-dependent behaviour with no consistent relationship with stitch density.

For optimal conductivity, the Shieldex 235/36 4-ply HC + B (S3) thread combined with a Running stitch pattern, seven parallel lines configuration, is recommended. Zigzag patterns should be avoided in applications requiring predictable electrical performance due to their non-linear response to stitch density, highlighting that both material selection and stitch design must be considered when developing embroidered conductive structures.

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## ELECTROLESS COPPER PLATING OF PET–POPLAR HYBRID NONWOVENS FOR WEARABLE HEATING SYSTEMS

Erdem Serin\*, Pelin Altay, Selin Hanife Eryürük, Özgür Atalay, Alper Gürarslan, Aybeniz Seyhan,  
Canan Usta

Istanbul Technical University, Faculty of Textile Technologies and Design, Textile Engineering Department  
İstanbul, Türkiye

\* [serine23@itu.edu.tr](mailto:serine23@itu.edu.tr)

### ABSTRACT

This study focuses on the development and optimisation of electroless copper plating processes to achieve stable and uniform metal deposition on PET–poplar hybrid nonwoven fabrics. The nonwoven structure consists of approximately 67% polyethylene terephthalate (PET) fibres and 33% poplar fibres. Key parameters influencing metallisation behaviour and conductivity were studied to enhance coating quality and electrical performance. Although low initial resistance values ( $\sim 3\text{--}4\ \Omega/\text{sq}$ ) were achieved, a significant increase to the  $\text{k}\Omega\text{--}\text{M}\Omega$  range was observed after post-treatment and conditioning, indicating limited coating stability and highlighting a key challenge in achieving stable conductive performance in practical wearable heating applications.

**Keywords:** *Conductive textiles, Electroless copper plating, Lignocellulosic biomass, PET fibres, Poplar fibres*

### INTRODUCTION

Nowadays, the growing demand for smart and wearable electronic systems attracted significant interest in development of conductive textiles [1–3]. Numerous studies have explored the integration of electronic functionalities into textile-based applications, including sensing, energy management, and thermal regulation [2,3]. Among various fabrication techniques, due to its ability to deposit metallic layers on complex and non-conductive surfaces without the need for external electrical current, electroless copper plating is widely recognised as a cost-effective and scalable method for imparting electrical conductivity to textile substrates [4,5]. The process is autocatalytic, typically involving surface preparation, catalytic activation, and subsequent metal deposition from a chemical bath [5].

Conventional electroless copper plating generally involves surface preparation, sensitisation, activation and copper deposition, commonly using  $\text{SnCl}_2/\text{Pd}$  activation and formaldehyde as the reducing agent [6]. However, formaldehyde raises significant health and environmental concerns [7], while Pd-based activation increases process cost [8]. Accordingly, alternative approaches have been explored, including the use of glyoxylic acid as a formaldehyde-free reducing agent [9,10] and Ag- or Cu-based activation routes as substitutes for conventional Pd/Sn systems [8], as well as optimisation of bath parameters such as reducing agents, complexing agents and operating conditions to improve process efficiency and environmental compatibility [7]. However, achieving both high conductivity and long-term stability remains a recognised challenge. This is particularly evident for heterogeneous textile surfaces, where coating adhesion and durability are strongly influenced by surface characteristics and processing conditions [4].

In this study, a PET–poplar hybrid nonwoven fabric incorporating poplar fibres derived from lignocellulosic biomass residues was investigated. This work aims to identify the key process parameters governing the electroless copper deposition on this hybrid structure and evaluates the influence of key process parameters on coating quality and conductive performance, particularly in relation to coating stability and conductivity.

## **EXPERIMENTAL STUDY**

### **1.1 Materials**

A PET–poplar hybrid nonwoven fabric consisting of approximately 67% polyethylene terephthalate (PET) and 33% poplar fibres was used as the substrate. Prior to metallisation, the fabric was cut into specimens of  $2 \times 2$  cm, each with a mass of approximately 0.15 g. Sodium carbonate, citric acid monohydrate, hydrochloric acid, tin (II) chloride, silver nitrate, ammonia solution, copper (II) sulfate pentahydrate, ethylenediaminetetraacetic acid (EDTA), sodium hydroxide, 2,2'-bipyridine and glyoxylic acid monohydrate were respectively used for the cleaning, etching, sensitisation, activation and electroless copper plating processes.

### **1.2 Methodology**

A sequential experimental approach was adopted to investigate the influence of etching temperature, sensitisation and post-activation treatment on electroless copper plating performance.

Experimental Set 1 (ES1) compared etching at 90 °C and room temperature. Subsequently Experimental Set 2 (ES2) evaluated the effect of omitting sensitisation, and eventually Experimental Set 3 (ES3) examined different post-activation treatments.

#### **1.2.1 Pre-treatment**

The samples were cleaned using an aqueous solution containing sodium carbonate ( $\text{Na}_2\text{CO}_3$ , 3 g/L) and a 2% wetting agent at 80 °C for 1 h and then rinsed with distilled water at 80 °C. Etching was performed using a citric acid solution (20 g/L) for 2 h under two conditions: 90 °C and room temperature. After etching, both samples were rinsed thoroughly with distilled water and dried at 70 °C for 1.5 h.

#### **1.2.2 Sensitisation & Activation**

For conventional processing, samples were immersed in a sensitisation solution containing  $\text{SnCl}_2$  (5 g/L) and HCl (5 mL/L) at 25 °C for 20 min, then rinsed thoroughly with distilled water. In selected experimental sets (ES2), sensitisation was omitted to evaluate a simplified processing route. Activation was carried out using a silver-based solution containing  $\text{AgNO}_3$  (10 g/L) and  $\text{NH}_3$  (10 mL/L) at 25 °C for 1 h, followed by rinsing with distilled water. Activated samples were either air-dried under dark conditions for 24 h, thermally treated at 50 °C, or transferred directly to the plating bath without any intermediate drying, depending on the experimental set.

#### **1.2.3 Plating**

Electroless copper plating was carried out using an alkaline glyoxylic acid-based bath containing copper(II) sulfate pentahydrate ( $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ , 8 g/L), ethylenediaminetetraacetic acid (EDTA, 70 g/L), glyoxylic acid monohydrate (16 g/L), and 2,2'-bipyridyl as stabiliser. The bath pH was adjusted to  $\geq 11.8$  using 10 M NaOH, and plating was performed at  $45 \pm 1.5$  °C for 30 min under continuous stirring at 200 rpm. Samples were suspended in the bath using a thin nylon thread to maintain positional stability during deposition. Immediately after plating, electrical resistance was measured without rinsing to capture the initial plated conductive state.

#### 1.2.4 Post-treatment

After the initial resistance measurement, the samples were rinsed thoroughly with distilled water and dried at 60 °C for 1 h in the oven. A second resistance measurement was then performed, followed by conditioning for 24 h at 20 ± 1 °C and 60% relative humidity before subsequent measurement.

**Table 1. Summary of subsequent experimental sets, initial resistance values, observations**

| Experimental set | Variable                  | Condition                                    | Initial resistance ( $\Omega/\text{sq}$ ) $\pm$ SD | Key observation / decision                                  |
|------------------|---------------------------|----------------------------------------------|----------------------------------------------------|-------------------------------------------------------------|
| ES1-RT           | Etching temperature       | RT + sensitisation                           | $3.39 \pm 0.44$                                    | Lowest resistance; RT selected                              |
| ES1-90           | Etching temperature       | 90 °C + sensitisation                        | $172.6 \pm 5.8$                                    | Increased hydrophilicity but poorer conductivity            |
| ES2 / ES3-1      | Sensitisation reference   | RT + without sensitisation + 24 h air drying | $8.74 \pm 1.31$                                    | Conductive without sensitisation; simplified route selected |
| ES3-2            | Post-activation treatment | RT + without sensitisation + 50 °C treatment | $181.5 \pm 17.5$                                   | Thermal treatment increased resistance                      |
| ES3-3            | Post-activation treatment | RT + without sensitisation + wet transfer    | $9355 \pm 12181$                                   | Highly variable and unstable coating                        |

**Note:** Initial resistance values were measured immediately after plating, before rinsing and drying.

## RESULTS & DISCUSSION

In Experimental Set 1 (ES1), despite the increased hydrophilicity observed after high temperature etching, samples treated at room temperature showed considerably lower resistance ( $3.39 \pm 0.44 \Omega/\text{sq}$ ) than the one etched at 90 °C. Thus, suggesting the improvement in wettability during pre-treatment stage does not necessarily mean better conductive performance after plating. Based on these findings, the RT etching condition was selected for further experimentation. In subsequent Experimental Set 2 (ES2), sensitised samples exhibited lower resistance values ( $3.39 \pm 0.44 \Omega/\text{sq}$ ) compared to non-sensitised samples ( $8.74 \pm 1.31 \Omega/\text{sq}$ ). Although sensitisation improved initial conductive performance, the non-sensitised samples also exhibited conductive behaviour within the same order of magnitude. Considering the reduced process complexity and elimination of additional chemical steps, the non-sensitised route was selected for the following experiments. Experimental Set 3 (ES3) revealed that post-activation treatment had a strong influence on conductive performance. Samples subjected to thermal treatment at 50 °C (ES3-2) exhibited a substantial increase in resistance to  $181.5 \pm 17.5 \Omega/\text{sq}$ . In contrast, samples transferred directly to plating without drying (ES3-3) showed extremely higher resistance values ( $9355 \pm 12181 \Omega/\text{sq}$ ), accompanied by very large variability. The resistance values in this condition spanned several orders of magnitude, indicating highly non-uniform conductive behaviour.

These results suggest that post-activation conditions are critical for the stability and uniformity of the conductive coating. This implies the integrity of the conductive pathways formed during plating is highly sensitive to these conditions, particularly drying and thermal effects. Furthermore, large standard deviations observed in ES3, particularly in the wet condition, and a high degree of instability in the conductive coating

may be attributed to the disruption of highly sensitive conductive pathways during post-activation treatment.

Additionally, in all cases, an immediate increase in resistance was observed after plating and subsequent drying. A further rise in electrical resistance was recorded over time under ambient conditions. Even in some cases, resistance values increased to the  $k\Omega$  and even  $M\Omega$  range following extended exposure. These results indicate that the conductive coating is not only sensitive to post-activation, plating and drying processes but also undergoes progressive time-dependent degradation. The results further suggest that initial low resistance values obtained immediately after plating do not necessarily reflect stable conductive performance.

The observed deterioration in conductive performance after post-treatment processes is consistent with previous studies, which report that conductive coatings on textile substrates exhibit poor adhesion and limited durability [4]. The heterogeneous nature of textile structures also contributes to non-uniform coating behaviour and instability in conductive pathways [11]. In this study, this effect is manifested as variability and a significant increase in resistance. Furthermore, the results show a two-stage degradation behaviour, with an initial increase in resistance after post-treatment followed by further degradation over time. The observed increase in resistance may be associated to degradation of conductive pathways under both post-treatment and ambient conditions. This behaviour may also be associated with oxidation of the deposited copper layer, which can lead to the formation of less conductive oxide phases, as reported in the literature [4,12].

While low resistance values can be achieved immediately after plating, maintaining stable conductive performance remains a challenge for textile-based metallisation systems. These findings highlight that initial conductivity does not necessarily reflect long-term performance. Therefore, this emphasises the importance of improving coating adhesion and stability for reliable application in wearable textile systems.

## CONCLUSION

This study investigated electroless copper plating on PET–poplar hybrid nonwoven fabrics using a sequential experimental approach. While low resistance values can be achieved immediately after plating, conductive performance is highly sensitive to processing conditions.

Although higher etching temperatures improved hydrophilicity, they resulted in poorer electrical performance. Sensitisation reduced resistance; however, acceptable conductivity was also achieved without sensitisation, allowing for a simplified process.

The most significant finding is the strong influence of post-treatment conditions on coating stability. Resistance increased substantially after drying and continued to rise over time, reaching the  $k\Omega$ – $M\Omega$  range. This behaviour indicates a progressive degradation of conductive pathways, driven by both drying and environmental exposure over time.

Overall, these findings indicate that initial conductivity does not represent long-term performance. Improving coating adhesion, structural uniformity and resistance to degradation remains a key challenge for conductive textile systems.

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## ENHANCED MOISTURE MANAGEMENT AND BARRIER FUNCTION: DEVELOPMENT OF BIOFUNCTIONAL KNITTED FABRIC FOR ATOPIC AND SENSITIVE SKIN

Bilge Koyuncu<sup>1,2,\*</sup>, Banu Nergis Uygun<sup>1</sup>, Cevza Candan<sup>1</sup>, Murphy M. Peksen<sup>3</sup>

<sup>1</sup> Istanbul Technical University, Textile Engineering and Design Faculty, Istanbul, Turkey

<sup>2</sup> DeepTech Engineering Ltd. Co, Izmir, Turkey

<sup>3</sup> Technische Universität München, School of Engineering and Design, Chair of Thermodynamics and Heat Transfer,  
Boltzmannstraße 15, 85748 Garching b. München, Germany

\* [koyuncubil@itu.edu.tr](mailto:koyuncubil@itu.edu.tr)

### ABSTRACT

This study addresses the challenge of designing functional and comfortable knitted fabrics for individuals with sensitive skin, focusing on comfort, functionality, and sustainability. The focus lies in the utilization of Umorefil® viscose fiber, a biofunctional material enriched with marine collagen peptides, selected for its superior skin compatibility, moisture-regulating properties, and reduced irritation potential. To maintain elasticity without compromising dermatological safety, the fabric incorporates core-spun yarns where elastane is fully encapsulated by the Umorefil® viscose sheath, thus preventing direct skin contact with synthetic materials. A total of six fabric variants were initially produced using three standard knitted structures — namely Plain jersey, 1×1 Rib, and Interlock — manufactured with two yarn feeding configurations (full core-spun and hybrid). Initial evaluations led to the exclusion of hybrid fabrics due to noticeable dimensional instability and high spirality. The remaining full core-spun fabrics were subjected to moisture comfort related performance assessments in accordance with textile standards, in addition to their mechanical as well as dimensional properties such as bursting strength and dimensional stability. The results demonstrated that the full core-spun plain jersey structure exhibited the most favorable overall performance. In particular, it achieved a high Overall Moisture Management Capacity (OMMC, ~0.82), higher water vapor permeability (67%), and adequate mechanical durability. These findings indicated that the Plain jersey structure is the optimal design for dermatologically preferable, namely breathable, textile solutions addressing to people with sensitive skin.

**Keywords:** *Sensitive Skin, Knitted Fabric, Umorefil® Viscose, Core-Spun, Moisture Management*

### 1. INTRODUCTION

Sensitive skin is a prevalent dermatological condition characterized by subjective symptoms such as burning, stinging, itching, and tightness, frequently occurring without visible clinical lesions [1, 2]. Epidemiological data indicate that atopic dermatitis (AD), the most common manifestation of sensitive skin, affects approximately 15–20% of children and 1–3% of adults globally, representing a significant public health burden [1]. The pathophysiology of sensitive skin involves a compromised epidermal barrier, heightened neurosensory reactivity, and increased transepidermal water loss (TEWL), all of which render the skin more susceptible to external irritants, including textile materials in direct contact with the body [2].

The interaction between textiles and human skin is a critical yet often underappreciated factor in dermatological health. Fiber composition, yarn structure, fabric construction, surface roughness, and moisture transport properties collectively determine the comfort and biocompatibility of a textile product [3, 4, 11]. For individuals with sensitive or atopic skin, inappropriate textile choices can exacerbate symptoms by increasing friction, trapping moisture against the skin, and creating a microclimate conducive to irritation and microbial proliferation [10, 12]. Conversely, thoughtfully engineered textiles can serve as a therapeutic interface, actively managing moisture, reducing mechanical irritation, and supporting the skin's natural barrier function [3, 4].

A growing body of literature has explored functional textiles designed specifically for sensitive and atopic skin. DermaSilk®, an antimicrobial silk fabric with sericin removed, has been shown to reduce

SCORAD (Scoring Atopic Dermatitis) scores in clinical trials, attributed to its smooth surface and inherent biocompatibility [5]. Similarly, studies on superfine Merino wool fibers with diameters of 17.5  $\mu\text{m}$  or less demonstrated improvements in EASI (Eczema Area and Severity Index) scores, challenging the conventional assumption that wool is universally irritating to sensitive skin [6]. Chitosan-coated cotton textiles have been reported to reduce SCORAD scores by 43.8%, leveraging the antimicrobial and moisture-absorbing properties of chitosan [7]. Furthermore, linen fabrics functionalized with plant-derived microcapsules have shown measurable improvements in skin hydration parameters [8]. These studies collectively underscore the potential of material-level innovation in textile engineering to address dermatological needs [12, 17].

Despite these advances, a notable gap persists in the literature concerning the application of collagen-peptide-enriched regenerated cellulose fibers for sensitive skin textiles. Umorefil® viscose is a biofunctional fiber produced through the incorporation of marine collagen peptides into the viscose spinning dope, resulting in a fiber that inherently possesses pH-buffering capacity, enhanced moisture regulation, and superior skin compatibility compared to conventional viscose [9]. The collagen peptides embedded within the fiber matrix are gradually released during wear, providing a sustained skin-conditioning effect. These properties make Umorefil® viscose a promising candidate for next-generation sensitive skin textiles, yet systematic studies evaluating its performance in knitted fabric structures remain scarce.

In addition to fiber selection, yarn architecture plays a crucial role in dermatological suitability. Core-spun yarn technology, in which an elastane filament is fully encapsulated by a staple fiber sheath, provides stretch and recovery while preventing direct contact between the synthetic elastane core and the skin surface [10, 13]. This is particularly relevant for sensitive skin applications where minimizing synthetic exposure is a fundamental design criterion.

The choice of knitted fabric structure further influences functional performance. Single jersey structures are lightweight and breathable, suited for base-layer garments [13, 14]. Rib structures (1×1 rib) offer enhanced elasticity and stretch recovery, while interlock structures provide superior dimensional stability and a denser fabric surface [13, 15, 16]. Each structure presents distinct trade-offs with respect to moisture management, air permeability, mechanical durability, and dimensional stability [18, 19].

The present study aims to identify the optimal knitted fabric structure for sensitive skin applications by evaluating three knitting constructions — Single Jersey, 1×1 Rib, and Interlock — produced using Umorefil® viscose core-spun yarns. Six fabric variants were produced with two feeding configurations: full core-spun and hybrid. Following preliminary assessments revealing dimensional instability in hybrid constructions, the study focused on full core-spun variants. Comprehensive characterization encompassing physical, mechanical, and moisture management properties was performed before and after five laundering cycles, aiming to establish an evidence-based recommendation for sensitive and atopic skin textile design [14, 20].

## 2. EXPERIMENTAL STUDY

### 2.1. Materials

Two types of yarns were utilized in this study: a conventional ring-spun Umorefil® viscose yarn and a core-spun Umorefil® viscose yarn. The conventional yarn was produced at a linear density of Ne 40/1 with a twist level of 1000 T/m and contained no elastane component. The core-spun yarn was similarly produced at Ne 40/1 with a twist level of 920 T/m, incorporating a 22 dtex elastane filament as the core material, resulting in an elastane content of 3% by weight. In the core-spun configuration, the Umorefil® viscose fibers form a complete sheath around the elastane core, ensuring that no synthetic material comes into direct contact with the skin surface. The yarn specifications are summarized in Table 1.

**Table 1.** Yarn specifications used in fabric production.

| Yarn Type    | Count (Ne) | Structure | Core Material      | Cover Material    | Elastane (%) | Twist (T/m) |
|--------------|------------|-----------|--------------------|-------------------|--------------|-------------|
| Conventional | 40/1       | Ring-spun | —                  | Umorefil® Viscose | 0            | 1000        |
| Core-spun    | 40/1       | Core-spun | Elastane (22 dtex) | Umorefil® Viscose | 3            | 920         |

Yarn tensile properties were evaluated in accordance with ISO 2062. The conventional yarn exhibited a breaking force of  $167 \pm 22.5$  cN, an elongation at break of  $17 \pm 8.2\%$ , and a tenacity of  $11.5 \pm 1.6$  cN/tex. The core-spun yarn demonstrated a substantially higher breaking force of  $2141 \pm 195$  cN with an elongation at break of  $11.71 \pm 0.93\%$  and a tenacity of approximately 13.0 cN/tex. The markedly higher breaking force of the core-spun yarn is attributed to the reinforcing contribution of the elastane core filament, while its lower elongation at break reflects the restraining effect of the elastane under tensile loading.

## 2.2. Fabric Production

A total of six fabric variants were produced by combining three standard knitted structures with two yarn feeding configurations. The three knitted structures — Single Jersey, 1×1 Rib, and Interlock — were selected to represent a range of structural characteristics relevant to base-layer garment applications. For each structure, two feeding configurations were employed: a full core-spun configuration (100% core-spun yarn at all feeders) and a hybrid configuration (alternating core-spun and conventional yarns). The knitting machine specifications for each structure are presented in Table 2.

**Table 2.** Knitting machine specifications for each fabric structure.

| Structure     | Gauge (GG) | Feeders | Needle Systems |
|---------------|------------|---------|----------------|
| Single Jersey | 28         | 26      | 78             |
| 1×1 Rib       | 20         | 30      | 60             |
| Interlock     | 28         | 30      | 94             |

## 2.3. Test Methods

All produced fabrics were characterized using a comprehensive set of standardized test methods to evaluate their physical, mechanical, and moisture management properties. Basis weight was determined according to ISO 3801, and fabric thickness was measured under a standard pressure of 1 kPa in accordance with ISO 5084. Dimensional stability and spirality were assessed following five domestic washing cycles at 40°C as per ISO 5077, with washing conditions specified by ISO 6330.

Air permeability was measured using the pressure-drop method at 125 Pa in accordance with ASTM D737. Fabric porosity was calculated using the bulk density method, applying the formula  $P(\%) = [1 - (\text{bulk density} / \text{fiber density})] \times 100$ . Vertical wicking behavior was evaluated according to DIN 53924-2020 to characterize capillary liquid transport. Moisture management properties, including wetting time, absorption rate, spreading speed, and overall moisture management capacity (OMMC), were measured using the SDL Atlas Moisture Management Tester in accordance with AATCC 195. Water vapor permeability was determined using the Permetest instrument following TS EN ISO 11092. All tests were performed on both unwashed specimens and specimens subjected to five domestic washing cycles to assess the durability of functional properties.

## 3. RESULTS AND DISCUSSION

### 3.1. Pre-wash Fabric Properties

The physical and mechanical properties of the six fabric variants in their unwashed state are presented in Table 3. Across all three structures, the full core-spun variants consistently exhibited higher basis weights and greater fabric thicknesses compared to their hybrid counterparts. This is attributable to the higher linear density contribution of the elastane core present in every course of the full core-spun fabrics, resulting in a more compact and heavier fabric structure.

**Table 3.** Physical and mechanical properties of unwashed fabric variants.

| Fabric Type            | Weight (g/m <sup>2</sup> ) | Thickness (mm) | Stitch Density | Air Perm. (cm <sup>3</sup> /cm <sup>2</sup> /s) | Porosity (%) | Bursting Str. (kg/cm <sup>2</sup> ) | Pilling Grade |
|------------------------|----------------------------|----------------|----------------|-------------------------------------------------|--------------|-------------------------------------|---------------|
| Single Jersey (Full)   | 157.35                     | 0.490          | 17×30          | 24.80                                           | 78.44        | 9.12                                | 3–4           |
| Single Jersey (Hybrid) | 137.56                     | 0.464          | 16×27          | 43.98                                           | 80.17        | 9.76                                | 3             |

|                    |        |       |           |       |       |       |   |
|--------------------|--------|-------|-----------|-------|-------|-------|---|
| Rib (Full)         | 219.68 | 0.680 | 13×2×25   | 15.42 | 78.31 | 9.33  | 3 |
| Rib (Hybrid)       | 170.41 | 0.642 | 11.5×2×24 | 57.40 | 82.24 | 8.43  | 3 |
| Interlock (Full)   | 307.55 | 0.796 | 17×28     | 3.90  | 74.06 | 13.48 | 3 |
| Interlock (Hybrid) | 259.79 | 0.756 | 17×26     | 13.26 | 77.01 | 12.91 | 3 |

The interlock structure exhibited the highest basis weight (307.55 g/m<sup>2</sup>) and thickness (0.796 mm), consistent with its double-faced construction. The single jersey was the lightest (157.35 g/m<sup>2</sup>) and thinnest (0.490 mm). Air permeability followed an inverse relationship with fabric density: single jersey exhibited the highest value (24.80 cm<sup>3</sup>/cm<sup>2</sup>/s) among full core-spun fabrics, while interlock showed the lowest (3.90 cm<sup>3</sup>/cm<sup>2</sup>/s). Hybrid variants demonstrated higher air permeability than their full core-spun counterparts due to reduced elastane content and looser structure.

Initial evaluation of dimensional stability and spirality revealed that the hybrid fabric variants exhibited noticeable dimensional instability and elevated spirality values compared to the full core-spun variants. This behavior is attributed to the inconsistent tension distribution resulting from alternating yarns with different elastic properties at successive feeders. The asymmetric elastic recovery in hybrid fabrics induces differential shrinkage and torque, leading to fabric distortion. Based on these findings, the hybrid variants were excluded from further testing, and all subsequent analyses were conducted exclusively on the full core-spun fabric variants.

Moisture management properties of the unwashed fabrics were assessed using the AATCC 195 standard. The single jersey structure exhibited an OMMC value of approximately 0.65, while the rib structure achieved a slightly higher OMMC of approximately 0.70. The rib (hybrid) variant showed the highest cumulative one-way transport capacity (COTC) among all pre-wash variants, attributed to its relatively open structure facilitating capillary liquid transport. Water vapor permeability measurements indicated that the single jersey structure performed best at approximately 68%, followed by rib and interlock structures, with the interlock recording the lowest value at approximately 51%. These pre-wash results established a baseline for evaluating the effects of laundering on functional performance.

### 3.2. Post-wash Fabric Properties

A critical aspect of evaluating biofunctional textiles for chronic dermatological conditions is their long-term functional durability under repeated maintenance cycles. While conventional functional textiles often rely on topical surface coatings or microcapsules that progressively leach during laundering, the Umorfil® viscose fiber utilized in this study intrinsically features marine collagen peptides. This chemical and structural integration ensures that the biofunctional properties are not merely transient surface phenomena but are sustained throughout the textile's lifecycle.

Following five domestic washing cycles, the three full core-spun fabric variants were re-evaluated. The physical and mechanical properties of the washed fabrics are presented in Table 4. All three structures exhibited increases in basis weight and thickness after washing, consistent with the expected relaxation shrinkage behavior of knitted fabrics containing elastane.

**Table 4.** Physical and mechanical properties of washed full core-spun fabrics.

| Fabric Type   | Weight (g/m <sup>2</sup> ) | Thickness (mm) | Stitch Density | Air Perm. (cm <sup>3</sup> /cm <sup>2</sup> /s) | Porosity (%) | Bursting Str. (kg/cm <sup>2</sup> ) | Pilling Grade |
|---------------|----------------------------|----------------|----------------|-------------------------------------------------|--------------|-------------------------------------|---------------|
| Single Jersey | 212.80                     | 0.562          | 16×26          | 15.92                                           | 74.58        | 8.13                                | 3             |
| Rib           | 266.05                     | 0.724          | 13×2×26        | 8.96                                            | 75.33        | 7.97                                | 4             |
| Interlock     | 385.90                     | 0.926          | 20×31          | 2.68                                            | 72.02        | 11.65                               | 3             |

Dimensional stability analysis revealed structure-dependent shrinkage patterns. The single jersey fabric exhibited shrinkage of 8.2% in the length direction and 13.9% in the width direction, with a spirality of 2.2%. The rib structure showed shrinkage of 13.0% in length and 2.9% in width, with a spirality of 3.8%. The interlock structure demonstrated shrinkage of 9.7% in length and 9.1% in width, with the highest



spirality at 4.0%. The notably lower spirality of the single jersey structure is a significant advantage for garment applications, as spirality causes seam displacement and visual distortion that can increase mechanical irritation on sensitive skin.

Post-wash moisture management testing revealed substantial improvements, particularly in the single jersey structure. The single jersey fabric achieved the highest OMMC of approximately 0.82, a significant enhancement from its pre-wash value of 0.65, attributed to fabric densification enhancing capillary action. The COTC of single jersey reached approximately 410%, indicating excellent unidirectional moisture transfer. The rib structure exhibited the highest absolute COTC but a lower OMMC, suggesting less balanced moisture management. The interlock recorded the lowest values in both metrics, consistent with its dense construction.

Water vapor permeability of the washed single jersey fabric was measured at approximately 63%, remaining the highest among all three structures despite a modest decrease from the pre-wash value of 68%. This slight reduction is consistent with the increase in fabric density following relaxation shrinkage. The combination of high OMMC, high COTC, and superior water vapor permeability positions the single jersey structure as the optimal choice for sensitive skin applications, where effective moisture management is essential to maintain a dry and comfortable skin microclimate [14, 18, 19].

Considering all evidence, the full core-spun single jersey fabric demonstrates the most favorable balance of properties for sensitive skin garments. Its lightweight construction (212.80 g/m<sup>2</sup>), low spirality (2.2%), highest OMMC (0.82), best vapor permeability (63%), and adequate bursting strength (8.13 kg/cm<sup>2</sup>) collectively establish it as the recommended structure. The core-spun yarn design ensures no elastane contacts the skin, while Umorefil® viscose provides collagen-peptide conditioning and moisture regulation [9, 20].

From a clinical perspective, the translation of laboratory-measured moisture management metrics into dermatological benefits is of paramount importance for patients suffering from atopic dermatitis (AD) and sensitive skin. The underlying disease mechanism of AD is fundamentally rooted in a epidermal barrier, which triggers an elevated transepidermal water loss (TEWL) and reactivity to tactile stimuli. The post-wash single jersey fabric's high Overall Moisture Management Capacity (OMMC of ~0.82) and high water vapor permeability (63%) directly address this disturbance. By rapidly transporting liquid sweat away from the skin and allowing efficient vapor dissipation, this specific structure prevents the formation of a humid, occlusive microclimate. Minimizing moisture entrapment is crucial to prevent the itch-scratch cycle that routinely exacerbates AD lesions.

Furthermore, the core-spun yarn structure, which entirely shields the skin from synthetic elastane contact, effectively mitigates mechanical friction. The biological synergy of the collagen peptides, combined with the lowest post-wash spirality (2.2%) of the single jersey construction, minimizes localized shear stress and seam displacement against inflamed epidermal sites.

#### **4. CONCLUSION**

This study systematically evaluated six knitted fabric variants produced using Umorefil® viscose — a marine collagen-peptide-enriched biofunctional fiber — to identify the optimal fabric construction for individuals with sensitive and atopic skin. The investigation encompassed three knitted structures (Single Jersey, 1×1 Rib, and Interlock) manufactured with two yarn feeding configurations (full core-spun and hybrid), followed by comprehensive characterization of physical, mechanical, and moisture management properties before and after five domestic laundering cycles.

The hybrid fabric variants were eliminated from further evaluation due to their pronounced dimensional instability and elevated spirality, attributed to asymmetric elastic behavior arising from alternating yarn types. Among the three full core-spun variants, the single jersey structure demonstrated the most favorable overall performance profile. Specifically, it achieved an OMMC of approximately 0.82, a water vapor permeability of approximately 63%, and the lowest spirality of 2.2% after washing, while maintaining adequate mechanical durability with a bursting strength of 8.13 kg/cm<sup>2</sup>.

The core-spun yarn architecture successfully prevented direct elastane-skin contact, preserving the dermatological safety of the fabric while providing the necessary stretch and recovery for comfortable garment fit. The Umorefil® viscose fiber contributed inherent biofunctional properties, including collagen-

peptide release, pH-buffering capacity, and enhanced moisture regulation, all of which are beneficial for compromised skin barriers.

Based on these findings, the full core-spun single jersey construction with Umorefil® viscose is recommended as the optimal fabric design for sensitive skin base-layer garments. Future work should explore the integration of antimicrobial finishing treatments, seamless knitting technologies to further minimize mechanical irritation, and clinical trials involving patients with diagnosed atopic dermatitis to validate the in-vivo performance of the developed fabric.

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## EVALUATION OF HIGH-TENACITY POLYESTER YARNS ON THE ABRASION RESISTANCE OF AUTOMOTIVE SEAT FABRICS

Emir Baltacıoğlu<sup>1</sup>, Semih Oylar<sup>2</sup>, Benamir Fidancı<sup>3</sup>, Selenay Elif İşler<sup>4</sup>, Nur Ceyda Uyanıktır<sup>5</sup>

Martur Fompak International, R&D, Bursa / TÜRKİYE

[emir.baltacioglu@marturfompak.com](mailto:emir.baltacioglu@marturfompak.com)

### ABSTRACT

Automotive seat fabrics are required to exhibit high mechanical strength and durability due to the intensive service conditions encountered throughout the vehicle's lifecycle. Among textile materials, polyester yarns are extensively preferred in automotive applications owing to their optimum mechanical properties and dimensional stability under demanding conditions. Furthermore, Original Equipment Manufacturers (OEMs) are increasingly demanding enhanced abrasion resistance to ensure long-term performance across various vehicle segments, such as public transportation and logistics vehicles. Although the utilization of High Tenacity Polyester (HT PES) yarns has historically been limited by over-spec performance and cost-benefit considerations, their technical suitability for the specific production volumes of these segments has recently gained significant importance among OEMs.

This study investigates the usability of high tenacity polyester (PES) yarns in automotive seat fabrics by focusing on the effect of yarn structure and combinations on abrasion performance. Within the scope of the study, woven fabrics were produced using different yarn types and configurations. High tenacity polyester yarns were used in two different forms: flat and air-textured (ATY). In addition, virgin polyester yarns were also included in the study to provide a comparative evaluation. Various combinations of these yarn types were applied in both warp and weft directions during the weaving process in order to observe their influence on fabric performance.

Following the weaving process, the same finishing processes were applied to all produced fabrics. After finishing, the fabrics were subjected to automotive-related abrasion tests to observe their durability and resistance to wear. The obtained test results were analyzed and compared in order to evaluate the performance differences between yarn structures and combinations.

The findings of this study provide an evaluation of the suitability of high tenacity polyester yarn structures for automotive seat fabrics and contribute to a better understanding of their performance limits in terms of abrasion resistance and durability in automotive textile applications.

**Keywords:** *Automotive textiles, High tenacity polyester, Abrasion resistance, Air textured yarn (ATY), Flat Yarn*

### 1. INTRODUCTION

Automotive seat fabrics are required to maintain their structural integrity and aesthetic properties under prolonged mechanical and environmental stresses throughout the vehicle lifecycle, which typically exceeds ten years. Therefore, high abrasion resistance, tensile strength, dimensional stability, and resistance to environmental factors such as ultraviolet (UV) radiation are considered critical performance criteria for these materials [1]. Among these requirements, abrasion resistance is one of the most decisive parameters,

as it directly affects the durability and service life of seat upholstery under repetitive loading and friction conditions [2].

The performance of automotive textiles depends on several factors, including fiber type, yarn structure, and fabric construction. Among these, the selection of fiber and yarn type plays a dominant role in determining the resistance of fabrics to wear and mechanical degradation. Polyester fibers have been extensively used in automotive applications due to their balanced mechanical properties, cost efficiency, and suitability for large-scale production. Their high strength, good abrasion resistance, and low moisture absorption make them the most widely preferred fiber type in automotive seat fabrics [3].

However, increasing performance expectations from Original Equipment Manufacturers (OEMs), particularly in high-usage applications such as public transportation and commercial vehicles, have led to the need for materials with enhanced durability. Conventional (virgin) polyester yarns, while adequate for standard applications, may not always provide sufficient long-term abrasion resistance under intensive service conditions defined by automotive standards [4]. In this context, high tenacity polyester (HT PES) yarns, which exhibit higher molecular orientation and improved mechanical strength, have gained attention as a potential alternative for high-performance automotive textiles [5].

In addition to fiber properties, yarn structure significantly influences fabric surface characteristics and abrasion behavior. Different yarn forms, such as flat yarns and air-textured yarns (ATY), can alter the frictional interaction and wear mechanisms of woven fabrics, thereby affecting their overall performance [6]. Despite this, comparative studies focusing on the effect of high tenacity yarn structures on abrasion resistance in automotive seat fabrics remain limited.

In this study, the abrasion performance of automotive seat fabrics was evaluated by comparing different polyester yarn types and structures. Three different woven fabric constructions with the same pattern were produced, all having virgin polyester yarns in the warp direction. The weft yarns were varied as follows: virgin polyester yarn, high tenacity flat polyester yarn and high tenacity air-textured polyester yarn (ATY). The produced fabrics were subjected to Martindale and Velcro abrasion tests in order to assess their performance under automotive usage conditions.

## 2. EXPERIMENTAL STUDY

This study investigates the effect of different polyester yarn types on the abrasion performance of automotive seat fabrics. Three different woven fabric samples were produced by varying the weft yarn type while keeping the warp yarn constant as virgin polyester.

All fabrics were produced under identical weaving and finishing conditions to ensure comparability. The abrasion performance of the fabrics was evaluated using Martindale and Velcro abrasion test methods.

### 2.1 Materials and Preparation Techniques

Fabric production was carried out using a conventional weaving process. Three different fabric samples were produced in order to evaluate the effect of yarn type on abrasion performance. In all fabric constructions, virgin polyester yarn was used in the warp direction, while the weft yarns were varied

The yarn compositions of the fabrics are given in Table 1.

**Table 1.** Yarn Composition

|                 | Warp       | Weft                           |
|-----------------|------------|--------------------------------|
| <b>Sample 1</b> | Virgin PES | Virgin PES                     |
| <b>Sample 2</b> | Virgin PES | High Tenacity Flat PES         |
| <b>Sample 3</b> | Virgin PES | High Tenacity Air-Textured PES |



The high tenacity polyester flat yarn used in the study was an untextured filament yarn with a yarn count of 300 denier/96 filaments and a twist level of 350 turns/m. Both the virgin polyester yarn and the high tenacity polyester air-textured yarn (ATY) were textured filament yarns with a yarn count of 300 denier/96 filaments.

After weaving, all fabrics were subjected to identical finishing processes. The fabrics were washed in open-width form at 90 °C to ensure cleanliness and dimensional stability. Following the washing process, flame lamination was applied by bonding the fabric surface with polyurethane foam and backing fabric. This lamination process was carried out to simulate the actual automotive seat fabric structure and end-use conditions.

All fabric samples were produced using a 2/2 twill weave structure, which is widely preferred in automotive seat fabrics due to its balanced mechanical performance, durability, and abrasion resistance. The weaving process was carried out on air-jet weaving machines under the same production parameters. The warp density was kept constant at 32 ends/cm for all samples, while the weft density was set to 30 picks/cm. These parameters were selected to ensure structural consistency and to reflect typical automotive fabric constructions.

The fabric weights were also measured to ensure comparability between the samples. The areal densities of the fabrics were determined as 282 g/m<sup>2</sup> for the 100% virgin polyester fabric, 259 g/m<sup>2</sup> for the fabric containing high tenacity flat yarn in the weft, and 257 g/m<sup>2</sup> for the fabric containing high tenacity air-textured yarn in the weft.

All production and finishing steps were completed under controlled conditions to ensure consistency between the samples prior to testing.

## **2.2 Characterization of Materials**

### **2.2.1. Martindale Abrasion Test Method**

Martindale abrasion tests are conducted in accordance with automotive standards under controlled laboratory conditions. Prior to testing, all specimens are conditioned at a temperature of  $23 \pm 2$  °C and a relative humidity of  $50 \pm 5\%$  for at least 24 hours.

From each fabric sample, circular specimens with a diameter of  $38 \pm 1$  mm are prepared. The specimens are cut at least 50 mm away from the fabric edges to avoid edge effects. If required, a polyurethane foam backing with a thickness of approximately 3 mm is applied to the backside of the specimens.

The test is performed using a Martindale abrasion tester. Standard wool felt is placed on the lower platform, and a standard abrasive fabric is mounted on top of the felt. The specimens are fixed in the upper holders and brought into contact with the abrasive surface under a pressure of 12 kPa.

The abrasion process is carried out in cyclic motions, and the specimens are evaluated at defined intervals. During the test, the abrasive fabric is replaced periodically to ensure consistent test conditions. At the end of the test, the samples are visually assessed for surface degradation, including yarn breakage, surface appearance degradation, pattern loss, and hole formation.

### **2.2.2. Velcro Abrasion Test Method**

Velcro abrasion tests are conducted according to automotive test procedures under controlled environmental conditions. Prior to testing, the samples are conditioned at  $20 \pm 2$  °C and  $65 \pm 5\%$  relative humidity for 24 hours.

Fabric specimens with dimensions of 70 × 300 mm are prepared in the required directions. Each specimen is mounted onto the cylinders of the abrasion device with the face side exposed. A polyurethane foam layer is placed beneath the fabric to simulate end-use conditions.

The abrasive element used in the test is the hook (hard) side of a Velcro strip, cut into standard dimensions and mounted onto the abrasion head. The abrasion head is applied to the fabric surface under a load of approximately 9.8 N.

The test is conducted at a speed of 60 ± 10 cycles per minute, and the abrasion is applied to the central region of the specimen. After completion of the test cycles, the samples are visually evaluated under standardized lighting conditions. The assessment focuses on surface damage such as fiber pull-out, yarn breakage, fuzzing, and structural deformation.

The results are graded according to a standard evaluation scale, ranging from no visible change to severe surface damage.

### 3. RESULTS

The abrasion performance of the produced woven fabrics was evaluated using Martindale and Velcro abrasion test methods. The results clearly demonstrate the influence of yarn type and structure on fabric durability.

**Table 2.** Martindale Test Results

|                 | Warp       | Weft                           | Results                           |
|-----------------|------------|--------------------------------|-----------------------------------|
| <b>Sample 1</b> | Virgin PES | Virgin PES                     | Grade 4<br>(After 50,000 cycles)  |
| <b>Sample 2</b> | Virgin PES | High Tenacity Flat PES         | Grade 4<br>(After 500,000 cycles) |
| <b>Sample 3</b> | Virgin PES | High Tenacity Air-Textured PES | Grade 4<br>(After 500,000 cycles) |

According to the Martindale abrasion test results, the fabric produced entirely with virgin polyester yarns achieved grade 4 according to the gray scale evaluation after 50,000 cycles. Beyond this level, surface degradation such as yarn breakage and loss of surface appearance due to fiber protrusion became more evident. In contrast, fabrics incorporating high tenacity polyester yarns in the weft direction demonstrated significantly improved abrasion resistance, maintaining grade 4 gray scale performance up to 500,000 cycles. This indicates that the use of high tenacity yarns leads to a substantial increase in durability under cyclic abrasion conditions.

**Table 3.** Velcro Test Results

|                 | Warp       | Weft                           | Results |
|-----------------|------------|--------------------------------|---------|
| <b>Sample 1</b> | Virgin PES | Virgin PES                     | 3       |
| <b>Sample 2</b> | Virgin PES | High Tenacity Flat PES         | 5       |
| <b>Sample 3</b> | Virgin PES | High Tenacity Air-Textured PES | 5       |

The Velcro abrasion test results further highlight the effect of yarn type on surface performance. The minimum acceptable grade for automotive applications is defined as 3. The fabric produced with 100% virgin polyester yarn achieved a grade of 3, which represents the threshold value. On the other hand, both

hybrid fabric structures containing high tenacity polyester yarns, namely flat and air-textured, achieved a grade of 5, which is the maximum possible rating in the evaluation scale.

These results indicate that the use of high tenacity polyester yarns improves the resistance of fabrics to severe abrasion conditions, particularly against surface damage and fiber pull-out caused by Velcro abrasion.

Overall, both Martindale and Velcro test results consistently demonstrate that replacing conventional polyester yarns with high tenacity polyester yarns in the weft direction leads to a remarkable improvement in abrasion resistance and surface durability. This improvement is particularly significant for automotive seat fabrics exposed to intensive and long-term usage conditions.

#### **4. CONCLUSION**

The objective of this study was to investigate the effect of high tenacity polyester yarns on the abrasion performance of automotive seat fabrics. For this purpose, three different woven fabric structures were produced by varying the weft yarn type while keeping the warp yarn constant as virgin polyester.

The findings of the study clearly indicate that the use of high tenacity polyester yarns leads to a significant improvement in abrasion performance. Fabrics containing high tenacity yarns in the weft direction exhibited substantially higher resistance under both Martindale and Velcro abrasion tests compared to the fabric produced entirely from virgin polyester. In particular, the increase from 50,000 to 500,000 Martindale cycles and the improvement from grade 3 to grade 5 in Velcro testing demonstrate the effectiveness of high tenacity yarns under both standard and severe abrasion conditions.

The originality of this study lies in the direct comparison of high tenacity flat and air-textured polyester yarns within automotive seat fabric constructions under identical conditions. The results contribute to the existing literature by providing practical insight into how yarn type and structure influence abrasion resistance in woven automotive textiles.

Based on the findings, it is recommended that high tenacity polyester yarns be preferred in the weft direction for automotive seat fabrics, particularly in applications requiring high durability and extended service life. Future studies may focus on optimizing fabric constructions and evaluating additional performance properties such as comfort and cost efficiency in order to achieve a balanced material design.

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## EVALUATION OF THE UV-PROTECTION PERFORMANCE OF FABRICS FINISHED WITH POMEGRANATE PEEL POWDER

Sinem Öztürk<sup>1,\*</sup>, Bekir Boyacı<sup>1</sup>, Elif Pınar Yozgath<sup>1</sup>

<sup>1</sup> Sun Tekstil Sanayi ve Ticaret A.Ş., Ar-Ge Merkezi, İzmir, Türkiye

\* sinem.ozturk@suntekstil.com.tr

### ABSTRACT

In recent years, the textile industry has increasingly focused on the development of sustainable and environmentally friendly finishing processes. Agricultural wastes represent a promising source of natural functional materials that can be utilised in textile applications. Among these wastes, pomegranate peel has attracted particular attention due to its high content of polyphenolic compounds and its reported antioxidant, antibacterial and UV protective properties. In this study, pomegranate peel powder was utilised as a biobased functional material to enhance the UV protection properties of woven fabrics. The investigation focused on fabrics with various substrate chemistries, including 100% cotton (cellulosic), 100% polyamide, and 100% polyester (synthetic). By incorporating these diverse textile matrices, the research identifies how the chemical affinity of pomegranate peel polyphenols varies across different fiber surfaces, ultimately influencing the durability and effectiveness of the functional finish. Initially, the UV protection performance of the untreated fabrics was evaluated. Subsequently, a coating paste containing pomegranate peel powder was prepared and applied to the fabrics using a knife coating technique. After the coating process, the UV protection performance of the treated fabrics was evaluated and compared with the untreated fabrics using Ultraviolet Protection Factor (UPF) measurements. The results indicated that the application of pomegranate peel-based coatings markedly improved the UV protection properties of the fabrics. The findings demonstrate that pomegranate peel powder can be effectively utilised as a sustainable and natural alternative for improving UV protective properties of textile fabrics. Furthermore, the antioxidant and antibacterial properties of pomegranate peel suggest its potential as a biobased material for multifunctional textile finishing applications. The study highlights the potential of agricultural waste valorisation as a sustainable strategy for developing eco-friendly functional textile finishes.

**Keywords:** *Pomegranate peel, UV protection, biobased coating, sustainable finishing, agricultural waste*

### 1. INTRODUCTION

The development of sustainable and environmentally friendly finishing processes has become a significant area of research in the textile industry. Conventional textile finishing treatments frequently utilise synthetic chemicals, which have the potential to contribute to environmental pollution and pose health risks. Consequently, there has been an increased focus on the utilisation of renewable and biobased resources as alternative functional materials for textile applications. In this context, agricultural waste materials have emerged as promising candidates due to their abundance, low cost, and rich content of bioactive compounds. The valorisation of agricultural by-products in the context of textile processing offers a sustainable approach that contributes to the reduction of waste, as well as to the development of value-added functional textile materials (Hussain et al., 2024).

Agricultural residues generated during food processing frequently contain significant amounts of natural compounds such as polyphenols, flavonoids, and tannins. These compounds are known for their antioxidant, antimicrobial, and ultraviolet (UV) absorbing properties. Consequently, plant-based extracts derived from agricultural wastes have increasingly been investigated as natural alternatives to synthetic chemicals in textile finishing processes (Hussain et al., 2024).

Ultraviolet radiation is one of the most important environmental factors affecting both human health and textile materials. Solar ultraviolet radiation mainly consists of three regions: UVA (315–400 nm), UVB (280–315 nm), and UVC (100–280 nm). While most UVC radiation is absorbed by the ozone layer, UVA and UVB radiation reach the Earth’s surface and may cause harmful biological effects such as skin ageing, sunburn, and an increased risk of skin cancer. Consequently, the development of textiles capable of protecting the human body against UV radiation has gained increasing importance, particularly for protective clothing and outdoor textile applications. Textile materials can reduce UV exposure by absorbing, reflecting, or scattering ultraviolet radiation. The UV protective performance of textile materials is commonly evaluated using the Ultraviolet Protection Factor (UPF), which represents the ability of a fabric to prevent the transmission of UV radiation through the material (Lu et al., 2022; AATCC 2023).

The UV protection behaviour of textiles depends on several parameters, including fiber type, fabric construction, fabric density, thickness, color, and finishing treatments applied to the fabric surface. In many cases, conventional textile fabrics do not provide sufficient protection against UV radiation. Therefore, the development of effective and environmentally friendly finishing treatments to enhance the UV protection properties of textile materials has become an important research topic. Among these approaches, coating techniques offer an effective method for incorporating functional materials onto textile surfaces (Santiago et al., 2025; Pachiyappan et al., 2025).

Natural plant-based compounds have attracted increasing interest as functional materials for textile finishing due to their ability to enhance UV protection while providing additional properties such as antioxidant and antimicrobial activity. Among various plant-derived materials, pomegranate peel (*Punica granatum*) has received considerable attention because of its high content of polyphenolic compounds such as tannins, flavonoids, and ellagic acid. These compounds exhibit strong antioxidant properties and contribute to improved UV protection performance, making pomegranate peel a promising biobased material for functional textile applications (Pachiyappan et al., 2025).

Previous studies have demonstrated that pomegranate peel extracts can significantly improve the functional properties of textile materials. For example, cotton fabrics treated with pomegranate peel extract have shown enhanced antibacterial activity and improved UV protection performance compared with untreated fabrics (Pachiyappan et al., 2025). In another study, pomegranate peel was successfully utilised as a natural bio-mordant in combination with plant-based dyes, improving dye fixation and color fastness properties on silk and cotton fabrics (Hussain et al., 2024). Furthermore, the incorporation of pomegranate peel extract together with zinc oxide nanoparticles has been reported to enhance the photoprotective performance of textile materials through the combined UV-absorbing effect of polyphenolic compounds and the UV-reflecting properties of inorganic particles (Otaviano et al., 2023).

Similarly, Rahman, Koh, and Hong (2024) investigated the sustainable single-bath dyeing and functionalisation process of cotton fabrics using pomegranate peel and onion peel extracts with chitosan biomordant; they reported that the application had positive effects on color intensity, wash fastness, UV protection, and antimicrobial performance.

Previous studies have investigated the use of pomegranate peel in textile applications, particularly in dyeing processes applied to cotton fabrics. In the present study, pomegranate peel powder was applied to woven fabrics using a coating technique. In addition, fabrics composed of different fiber types were investigated to evaluate the influence of fiber chemistry on the performance of the pomegranate peel-based coating.

Therefore, the aim of this study is to investigate the potential use of pomegranate peel powder as a biobased functional material for enhancing the UV protection properties of textile fabrics. In this study, woven fabrics composed of different fiber types, namely cotton, polyamide, and polyester, were treated with a coating formulation containing pomegranate peel powder using a knife coating technique. The UV protection performance of treated and untreated fabrics was evaluated by measuring the Ultraviolet Protection Factor (UPF) in order to assess the effectiveness of pomegranate peel-based coatings as sustainable UV protective textile finishes.



## 2. EXPERIMENTAL STUDY

### 2.1 Materials

In this study, three different woven fabrics were used with 100% cotton, 100% polyamide and 100% polyester fabrics. Cotton fabric had a Panama (2/2) woven structure, while the polyamide and polyester fabrics had plain woven structures.

100% polyamide fabric is a plain weave fabric with a weight of approximately 200 g/m<sup>2</sup>. Fabric thickness is 0,56 mm and it is produced from 600 denier multifilament yarns. 100% polyester fabric is a plain weave fabric with a weight of approximately 305 g/m<sup>2</sup>. Fabric thickness is 0,50 mm and it is produced from 900 denier multifilament yarns. 100% cotton fabric is a 2x2 panama weave fabric with a weight of approximately 285 g/m<sup>2</sup>. Fabric thickness is 0,77 mm and it is produced from Ne 16/1 and Ne 8/1 staple cotton yarns. Table 2 shows the technical details regarding the fabrics used in the study.

These materials are widely used in applications including workwear, outdoor equipment, tents and awnings due to their high mechanical strength, durability, and resistance to environmental conditions. Woven constructions were preferred because they provide dimensional stability and a uniform surface structure, which facilitates controlled application of coatings and impregnation treatments while also representing typical substrates used in industrial finishing processes and end products.

These fabrics were selected in order to investigate the effect of fiber chemistry on the performance of the pomegranate peel-based coating.

Pomegranate peel powder (*punica granatum*) was used as a natural functional material in the coating formulation. The powder was obtained from Oxypome brand products in dried and ground form.

After the coating process, the fabrics were dried and cured under defined conditions to remove moisture and to stabilize the coating layer.

Pomegranate peel powder samples with three different encapsulation agent contents were used in this study. Table 1 shows the encapsulation agent contents of the pomegranate peel powder samples.

**Table 1.** Pomegranate peel powder samples

| Sample Code | Encapsulation Agent Content (%) |
|-------------|---------------------------------|
| 2405        | 5                               |
| 2410        | 10                              |
| 2415        | 15                              |

### 2.2 Methods

Knife coating is a widely used application and finishing method in the textile industry for applying large quantities of polymer based coatings onto fabric surfaces to get functional properties such as water repellency, barrier performance, durability, and protective performances. In this process, a coating formulation is spread onto the textile substrate (fabric) and evenly distributed using a knife (doctor blade) positioned at a controlled distance from the fabric surface. The gap between the knife and the substrate determines the thickness of the applied coating layer, allowing precise control over the coating weight and uniformity. The coated fabric is then subjected to drying and heat curing processes to remove the water present in the formulation and to ensure that the coating forms a homogeneous film suitable for the textile structure that bonds to the fabric. Knife coating is particularly suitable for technical textiles used in applications such as protective clothing, outdoor equipment, tents, and industrial fabrics, where enhanced surface protection and barrier properties are required. Within the work, knife coating was used as an application method to evaluate the performance and surface coverage of the developed formulations and to investigate their suitability for continuous industrial coating processes. The coated fabrics were subjected to a drying process at 140°C for a duration of two minutes, followed by a heat curing step at 160°C for three minutes. This procedure was implemented to ensure the effective adhesion of the coating to the textile substrate. The pomegranate peel-based formulations consisted of a PU coating base and pomegranate peel powder. In addition, an acrylic-based coating was evaluated as a reference formulation.

**Table 2.** Fabric details

| Material / Fabric | Denier        | Weight(g/m <sup>2</sup> ) | Fabric thickness (mm) | Weft density (ends/cm) | Warp density (ends/cm) |
|-------------------|---------------|---------------------------|-----------------------|------------------------|------------------------|
| <b>POLYESTER</b>  | 900           | 305                       | 0,50                  | 13                     | 15                     |
| <b>POLYAMIDE</b>  | 600           | 200                       | 0,56                  | 13                     | 12                     |
| <b>COTTON</b>     | Ne 16/1 - 8/1 | 285                       | 0,77                  | 18                     | 42                     |

The UV protection performance of the fabric samples was determined based on the Ultraviolet Protection Factor (UPF). UPF measurements were carried out in the wavelength range of 290–400 nm using a UV–Vis spectrophotometer, in accordance with the AS/NZS 4399 standard. During the measurements, the spectral UV transmittance (%T) values of the fabrics were obtained, and UPF values were calculated according to the standard method described in the literature.

### 3. RESULTS

The UV protection performance of the fabric samples was significantly influenced by both fiber type and coating formulation. The untreated fabrics, which were used without any dyeing or finishing process, exhibited very low UPF values, confirming that the inherent UV protection of the fabrics was insufficient. The initial UPF values were measured as 0.84 for cotton, 1.47 for polyamide, and 2.22 for polyester fabrics.

Following the application of pomegranate peel-based coatings, a substantial improvement in UV protection performance was observed across all fabric types. In particular, UPF values increased up to approximately tenfold compared to the untreated fabrics, clearly demonstrating the effectiveness of the biobased coating system.

For cotton fabrics, the UPF value increased from 0.84 (untreated) to a maximum of 10.47 with the Oxpome-2410 formulation. This indicates that a moderate encapsulation agent content provided the most effective UV shielding performance. Lower (2405) and higher (2415) encapsulation levels resulted in comparatively lower UPF values, suggesting the presence of an optimal formulation.

Polyamide fabrics exhibited a similar but slightly different trend. The highest UPF value (10.04) was obtained with the Oxpome-2405 formulation.

In polyester fabrics, UPF values also increased after coating, reaching a maximum of 8.32 with the Oxpome-2405 formulation. However, the overall UV protection performance remained lower compared to cotton and polyamide.

The acrylic-based coating showed only limited improvement in UPF values compared to the pomegranate peel-based formulations.

Overall, as shown in Table 3, the results demonstrate that pomegranate peel-based coatings can significantly enhance the UV protection properties of textile fabrics, particularly in untreated materials lacking any prior finishing. The performance strongly depends on fiber type, coating formulation, and application method. The findings confirm the potential of agricultural waste-derived functional materials as sustainable and effective alternatives for UV-protective textile finishing applications.

**Table 3.** Test results of fabrics

| TEST RESULTS | Fabric Type | Sample Contents | Formulation | Weight (g/m <sup>2</sup> ) | Thickness mm | Add-On (g/m <sup>2</sup> ) | UPF          |
|--------------|-------------|-----------------|-------------|----------------------------|--------------|----------------------------|--------------|
|              | Woven       | 100% Cotton     | Untreated   | 281,9                      | 0,71         | X                          | 0,84         |
|              | Woven       | 100% Cotton     | 2405        | 325,9                      | 0,74         | 15,62                      | <b>9,68</b>  |
|              | Woven       | 100% Cotton     | 2410        | 334,7                      | 0,76         | 18,75                      | <b>10,47</b> |
|              | Woven       | 100% Cotton     | 2415        | 325,9                      | 0,72         | 15,62                      | 5,87         |

|  |       |             |                       |       |      |       |              |
|--|-------|-------------|-----------------------|-------|------|-------|--------------|
|  | Woven | 100% PA     | Untreated             | 202,6 | 0,56 | X     | 1,47         |
|  | Woven | 100% PA     | 2405                  | 264,3 | 0,62 | 30,43 | <b>10,04</b> |
|  | Woven | 100% PA     | 2410                  | 264,3 | 0,64 | 30,43 | <b>9,79</b>  |
|  | Woven | 100% PA     | 2415                  | 264,3 | 0,64 | 30,43 | <b>9,58</b>  |
|  | Woven | 100% PES    | Untreated             | 299,5 | 0,5  | X     | 2,22         |
|  | Woven | 100% PES    | 2405                  | 361,2 | 0,54 | 20,58 | <b>8,32</b>  |
|  | Woven | 100% PES    | 2410                  | 352,4 | 0,53 | 17,64 | 6,38         |
|  | Woven | 100% PES    | 2415                  | 352,4 | 0,53 | 17,64 | 6,76         |
|  | Woven | 100% Cotton | Acrylic-based coating | 318   |      | 12,8  | 1,64         |
|  | Woven | 100% PA     | Acrylic-based coating | 256   |      | 26,35 | 3,08         |
|  | Woven | 100% PES    | Acrylic-based coating | 348   |      | 16,19 | 3,68         |

#### 4. CONCLUSION

This study demonstrated the potential of pomegranate peel powder as a bio-based functional coating material for improving the UV protection performance of textile fabrics. The application of pomegranate peel-based coatings significantly enhanced UPF values compared with untreated fabrics, with improvements of up to approximately ten times depending on the fibre type and formulation. Compared with the acrylic-based reference coating, the developed bio-based formulations exhibited superior UV-protective performance, highlighting the potential of agricultural waste-derived materials as sustainable alternatives for textile finishing.

In addition, the inherent antioxidant and antibacterial potential of pomegranate peel further supports its applicability as a multifunctional biobased finishing material. Overall, this study provides a novel and sustainable approach for improving UV protection in textiles using agricultural waste. Future research should focus on color applications to also control the effect of color on UV protection, improve coating durability, wash resistance and industrial applicability, and explore additional functional properties.

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## FASHION DESIGN STUDENTS’ SUSTAINABILITY ATTITUDES, DESIGN PRACTICES, AND AWARENESS OF REBOUND EFFECTS

Meral İŞLER<sup>1,\*</sup>, Selma DOLANBAY DOĞAN<sup>1</sup>

<sup>1</sup> Selcuk University, Faculty of Architecture and Design, Fashion Design, Konya, Türkiye

\* meralisler@selcuk.edu.tr

### ABSTRACT

The fashion industry occupies a significant position in the global economy; however, it is confronted with serious sustainability challenges such as environmental pollution, resource depletion, and social inequality. In this context, designers play a critical role in the realization of sustainability goals due to their capacity to influence material selection, production processes, and consumption patterns. The aim of this study is to examine fashion design students’ attitudes toward sustainability across environmental, social, and economic dimensions in clothing and to analyze the relationship between these attitudes and their awareness of the rebound effect and design practice. It also evaluates the impact of participation in sustainability-focused education and activities on their awareness of rebound effect and design practices. The study was conducted using a quantitative research approach based on a survey design. The sample consisted of third- and fourth-year undergraduate students enrolled in a fashion design program. Data were collected through a questionnaire structured on a five-point Likert scale and comprising five dimensions, including attitudes of environmental, social, and economic sustainability, as well as awareness of the rebound effect and design practice. The collected data were analyzed using SPSS 21. The findings indicate that students’ attitudes toward all three dimensions of sustainability are at a high level. However, it was determined that the reflection of these attitudes in design practice is relatively limited, and awareness of the rebound effect remains at a lower level compared to the other dimensions.

**Keywords:** *Fashion Design, Sustainability, Design Practice, Rebound Effect Awareness*

### 1. INTRODUCTION

Due to its structure—shaped by mass production, globalized supply chains, and the dynamics of fast fashion—the fashion industry ranks among the sectors with the highest environmental impacts and social costs [1, 2]. Consequently, sustainable fashion is a complex field that extends beyond the utilization of eco-friendly materials. In this framework, design decisions must be integrated with considerations of product longevity, frequency of use, reparability, and circular service models [3–5]. Beyond ecological attributes, the field fundamentally encompasses social dimensions, including human rights, ethical production, and responsible consumption [2, 5]. Therefore, design is not merely an aesthetic intervention that comes into play at the final stage of sustainability; rather, it is a tool that shapes the impacts of a product throughout its production, use, and circulation [3, 6]. This tool makes design education one of the key areas of the sustainability transition. The literature on design education demonstrates that sustainability can only be made sustainable through interdisciplinary, problem-based, and practice-oriented approaches [7]. Studies focused on fashion design education similarly emphasize that sustainability competence can be developed not only through technical knowledge but also through an educational approach that integrates craftsmanship, creative thinking, a systems perspective, and an understanding of industry realities [8–10]. Therefore, the aim of design education is not merely to guide students toward producing “more eco-friendly” products, but also to ensure they can anticipate the long-term consequences of their decisions by understanding the product–user–system interaction. However, a significant conceptual challenge lies ahead regarding sustainability and education: not every sustainability-focused design intervention automatically



produces the expected positive outcomes. At this point, the concept of the rebound effect plays a crucial role in evaluating these contradictions and potential unintended consequences.

The rebound effect is defined as the partial or complete erosion of the expected environmental or social benefits of an efficiency or sustainability-oriented improvement, due to behavioral, economic, or system-level reactions [11–13]. While traditional approaches primarily explain the rebound effect through increased consumption driven by cost reductions, recent studies demonstrate that this phenomenon is also shaped by behavioral and social practices [11, 12, 14]. From this perspective, the rebound effect serves as a reminder that sustainability must be addressed not merely by designing 'better products,' but through a systems-level logic that interrogates the overall impact. In the fashion sector, the rebound effect refers to the partial offsetting of the expected environmental gains when the environmental impact of a product or production process is reduced per unit, but this improvement is counterbalanced by increased consumption, more frequent replacement, or new market demand [11–14]. In this respect, the issue is not only to reduce the carbon, water, or waste footprint of a single garment, but also to question, at the system level, how many new garments are produced, how many garments are actually displaced, and how much the use phase is extended [3, 15–17]. The significance of the rebound effect for sustainability stems from its ability to manifest in direct, indirect, and structural forms. A design intervention may encourage greater consumption within the same usage context, trigger consumption in disparate contexts, or, over time, generate unexpected demand patterns by altering user preferences, norms, and daily practices [12, 14, 18]. From a behavioral standpoint, mechanisms such as cost perception, moral licensing, diffusion of responsibility, convenience, and information asymmetry can exacerbate this process [18, 19]. Furthermore, research indicating that enhanced knowledge can indirectly mitigate the rebound effect demonstrates that sustainable consumption decisions are dictated not only by technological innovation but also by knowledge and awareness [18]. This underscores that the rebound effect is an indispensable concept within sustainability education. Sector-specific studies in fashion and textiles reveal that the rebound effect manifests in concrete and diverse forms. Sustainability labels, particularly those emphasizing production and distribution efficiency, may inadvertently encourage consumers to purchase more products, thereby offsetting anticipated environmental gains [2]. Similarly, while secondhand clothing consumption is regarded as a hallmark of the circular economy, it can catalyze additional consumption through price effects and moral licensing [20]. Innovative production models, such as digital textile microfactories, appear promising regarding localization, small-batch production, and on-demand manufacturing; however, they carry the inherent risk of increasing purchase frequency through personalization, speed, and ease of access [1]. These examples highlight that solutions developed in the field of fashion design must be evaluated not merely for their technical merits, but for their broader behavioral and systemic impacts. At this point, the role of design transcends the mere identification of problem-generating mechanisms; it entails developing proactive strategies to prevent the rebound effect. The 'reboundless design' approach proposed in contemporary literature argues that design must evolve beyond efficiency-centric solutions to generate interventions that foster self-sufficiency, systemic resilience, and resistance to deleterious behavioral outcomes [21]. This perspective emphasizes that design decisions inherently possess the potential to steer user behavior and normalize specific consumption patterns [19]. Consequently, cultivating awareness of the rebound effect in fashion design education necessitates that students interrogate not only material selection, waste mitigation, or life-cycle assessment, but also variables such as accessibility, the impulse to purchase, usage frequency, perceived product value, and the socio-cultural normalization of consumption. While existing research indicates a growing sustainability awareness in fashion and design education, the vast majority of these studies address sustainability attitudes, design practice, and the rebound effect as disparate entities. However, while a concurrent evaluation of these three dimensions is vital for grasping the genuine impact of sustainability education, there is a limited number of research that holistically examines fashion design students' attitudes toward sustainability, their proficiency in translating these attitudes into design practice, and their awareness of the rebound effect. This gap is particularly pronounced in fashion design a domain characterized by the intensive production of symbolic value and the volatile dynamics of rapid consumption. This is because students may adopt sustainable design interventions such as eco-friendly material selection, life-cycle thinking, and waste mitigation yet fail to perceive the indirect consequences of these solutions on consumption volume, usage frequency, or market expansion with equivalent clarity. Therefore, to rigorously assess the efficacy of sustainability education, it is imperative to consider not only environmental awareness but also students' capacity for practical integration and their nuanced understanding of systemic feedback effects.

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This study aims to investigate fashion design students’ attitudes toward sustainability across environmental, social, and economic dimensions; to analyze the correlation between these attitudes, their awareness of the rebound effect and design practice; and to evaluate whether these perspectives vary based on their participation in sustainability-focused education and activities. Within this scope, the following research questions (RQs) are addressed:

**RQ1:** What are the levels of fashion design students’ attitudes toward sustainability in clothing, their awareness of the rebound effect, and their current design practices?

**RQ2:** Are there significant relationships between fashion design students’ attitudes toward sustainability in clothing, their awareness of the rebound effect, and their design practices?

**RQ3:** Do students’ awareness of the rebound effect and their levels of design practice differ significantly based on their participation in sustainability-focused education and activities?

## 2. METHOD

This research adopts a quantitative approach based on a survey methodology. The study sample consists of 218 third- and fourth-year undergraduate students enrolled in Fashion Design and Fashion and Textile Design programs across fourteen different universities, all of whom were actively engaged in design studio courses at the time of the study. Institutional ethical approval was granted by the Scientific Ethics Review Board of the Faculty of Architecture and Design at Selçuk University (Decision No: 11/04, dated December 31, 2025). Detailed demographic and academic profiles of the participating students are presented in Table 1 below.

**Table 1.** Characteristics of the students participating in the study

| Variable                                             | Category                            | Frequency (n) | Percentage (%) |
|------------------------------------------------------|-------------------------------------|---------------|----------------|
| Gender                                               | Female                              | 202           | 92.7           |
|                                                      | Male                                | 16            | 7.3            |
| Age                                                  | 18-20 years                         | 24            | 11.0           |
|                                                      | 21-23 years                         | 130           | 59.6           |
|                                                      | 24-26 years                         | 64            | 29.4           |
| The university attended                              | Ege University                      | 48            | 22.02          |
|                                                      | Selcuk University                   | 45            | 20.64          |
|                                                      | Cukurova University                 | 24            | 11.01          |
|                                                      | Kahramanmaras Sutcu Imam University | 24            | 11.01          |
|                                                      | Nigde Omer Halis Demir University   | 13            | 5.96           |
|                                                      | Gaziantep University                | 12            | 5.50           |
|                                                      | Canakkale University                | 11            | 5.05           |
|                                                      | Atılım University                   | 9             | 4.13           |
|                                                      | Others                              | 32            | 14.68          |
| Participation in Sustainability Education/Activities | Yes                                 | 152           | 69.7           |
|                                                      | No                                  | 66            | 30.3           |

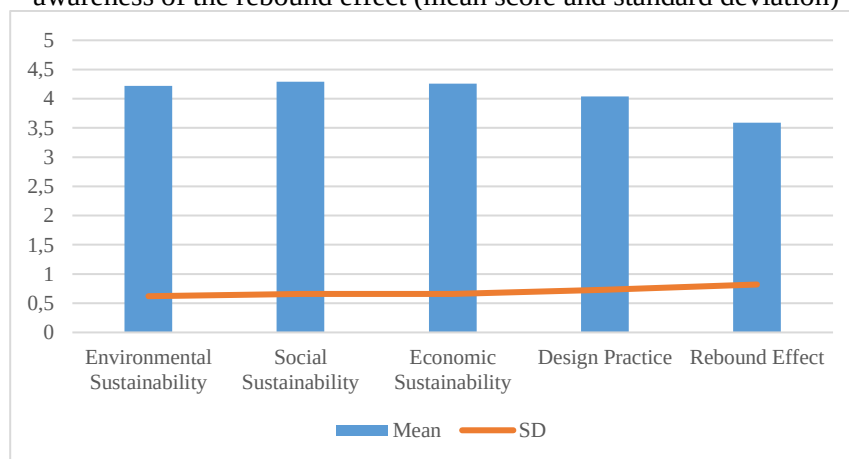
The survey form employed in this study was not directly adapted from a preexisting scale; instead, it was constructed by the researchers based on the theoretical frameworks identified in the relevant literature and previous studies. The instrument was specifically tailored to align with the unique objectives and scope of this research, ensuring that all items accurately reflected the conceptual dimensions of sustainability and the rebound effect within the context of fashion design. Data for this study were collected via a structured survey instrument consisting of four distinct sections: general information; attitudes toward environmental, social, and economic sustainability [22, 23]; awareness of the rebound effect [24-29]; and design practice [3, 9, 30-35]. The general information section sought data on age, gender, institutional affiliation, and participation in sustainability-focused education or activities. The sustainability attitude section comprised 15 items: environmental (6 items), social (4 items), and economic (5 items), evaluated on a 5-point Likert scale (1- Strongly Disagree to 5- Strongly Agree). To ascertain the construct validity, an Exploratory Factor Analysis (EFA) was performed. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was

0.901, and Bartlett's Test of Sphericity yielded significant results ( $\chi^2 = 2156.335$ ;  $p < 0.001$ ). The total variance explained by the factor structure was 68.601%. Internal consistency was confirmed with Cronbach's alpha coefficients of 0.883 for the economic dimension, 0.889 for the social dimension, and 0.872 for the environmental dimension. The design practice section included 6 items measuring students' capacity to integrate sustainability into their creative process, utilizing a 5-point Likert scale with a Cronbach's alpha value of 0.854. The rebound effect awareness section comprises five items assessing students' cognizance of this phenomenon, measured on a 5-point Likert scale with a Cronbach's alpha of 0.861. Descriptive statistics, specifically mean and standard deviation, were calculated for all dimensions. Data analysis was conducted using SPSS 21 software. Exploratory Factor Analysis (EFA) was utilized to delineate the factor structure of sustainability attitudes, while Cronbach's alpha coefficients were employed to verify internal reliability. To examine the interrelationships between sustainability attitudes (environmental, social, and economic), design practice, and awareness of the rebound effect, a correlation analysis was performed using the Pearson correlation coefficient. Additionally, an Independent-Samples T-Test was executed to determine whether students' awareness of the rebound effect and their design practices differed significantly based on their participation in sustainability-oriented activities or training. A  $p$ -value of  $< 0.05$  was established as the threshold for statistical significance.

### 3. RESULTS and DISCUSSION

Within the scope of the study, fashion design students' attitudes toward environmental, economic, and social sustainability in clothing, their awareness of the rebound effect, and their design practices were evaluated. The relationships between sustainability attitudes (environmental, social, and economic), awareness of the rebound effect, and design practice were statistically analyzed. Additionally, the study assessed whether participation in sustainability-focused activities and educational programs resulted in significant differences in environmental, economic, and social sustainability attitudes, awareness of the rebound effect, and design practices.

**Figure 1.** Fashion design students' attitudes toward sustainability in clothing, design practices, and awareness of the rebound effect (mean score and standard deviation)



The mean values regarding fashion design students' attitudes toward environmental, social, and economic sustainability in clothing are presented in Figure 1. Upon examining the mean values, it is observed that students generally demonstrate a high level of agreement with statements regarding the environmental, social, and economic dimensions of sustainability. The highest average score was obtained in the social sustainability dimension ( $M = 4.29$ ). This dimension is followed by economic sustainability ( $M = 4.26$ ) and environmental sustainability ( $M = 4.22$ ). These findings indicate that students' attitudes toward environmental, economic, and social sustainability are at a high level. The mean value for sustainable design practices ( $M = 4.04$ ) is lower than that of sustainability attitudes. The rebound effect is defined as systemic reactions to sustainability-focused interventions that partially or completely negate the expected positive effects of these interventions [36]. The lowest mean score was observed in the rebound effect awareness dimension ( $M = 3.59$ ). This indicates that students possess a moderate-to-high level of rebound effect awareness. When the findings are evaluated overall, they indicate that while students' attitudes toward the core dimensions of sustainability are strong, the translation of these attitudes into practice and

their awareness of the rebound effect are relatively more limited. Standard deviation values range from 0.62 to 0.82. The lowest standard deviation is for the environmental sustainability variable (0.62), while the highest standard deviation is for the rebound effect variable (0.82). The standard deviation values for the other variables are similar and indicate a moderate level of dispersion.

**Table 2.** Correlations among sustainability attitudes, design practice, and awareness of the rebound effect (Pearson correlation)

|                                 | Environmental Sustainability | Social Sustainability | Economic Sustainability | Design Practice | Awareness of the Rebound Effect |
|---------------------------------|------------------------------|-----------------------|-------------------------|-----------------|---------------------------------|
| Environmental Sustainability    | 1                            |                       |                         |                 |                                 |
| Social Sustainability           | .660**                       | 1                     |                         |                 |                                 |
| Economic Sustainability         | .580**                       | .604**                | 1                       |                 |                                 |
| Design Practice                 | .647**                       | .571**                | .491**                  | 1               |                                 |
| Awareness of the Rebound Effect | .266**                       | .349**                | .222**                  | .365**          | 1                               |

$p < .01$

The results of the correlation analysis conducted to examine the relationships between sustainability attitudes, design practice, and awareness of the rebound effect are presented in Table 2. The findings reveal that environmental, social, and economic sustainability attitudes are positively and significantly correlated with each other ( $r = .580-.660$ ,  $p < .01$ ). This indicates that the different dimensions of sustainability are perceived by students as interrelated. When examining the relationships between sustainability attitudes and design practice, it is observed that all dimensions of sustainability—environmental ( $r = .647$ ,  $p < .01$ ), social ( $r = .571$ ,  $p < .01$ ), and economic ( $r = .491$ ,  $p < .01$ )—exhibit positive and significant relationships with design practice. This finding indicates that an increase in sustainability attitudes is associated with the extent to which students incorporate sustainability into their design processes. When evaluated in terms of awareness of the rebound effect, positive and significant but relatively weaker relationships were found with environmental ( $r = .266$ ,  $p < .01$ ), social ( $r = .349$ ,  $p < .01$ ), and economic ( $r = .222$ ,  $p < .01$ ) sustainability attitudes. This suggests that, although students' general attitudes toward sustainability are high, these attitudes are only weakly associated with awareness of more complex, system-level outcomes such as the rebound effect. Indeed, Adigüzel et al. (2020) state that sustainability labels can increase consumption, particularly when they emphasise production and distribution efficiency, which can lead to rebound effects [2]. This result suggests that students' general attitudes towards sustainability and their understanding of the potential indirect consequences of sustainability interventions do not develop at the same rate. Furthermore, a positive and meaningful relationship was observed between design practice and awareness of the rebound effect ( $r = .365$ ,  $p < .01$ ). This finding suggests that students who integrate sustainability into their design processes may be more aware of the potential indirect effects of sustainability interventions.

**Table 3.** The effect of participation in sustainability-focused education/activities on students' sustainability attitudes, rebound effect awareness, and design practices (Independent samples t-test)

| Variable                            | Participation in Sustainability Education/Activities<br>n:152 |     | Non-participants in Sustainability Education/ Activities<br>n:66 |     |       |     |             |
|-------------------------------------|---------------------------------------------------------------|-----|------------------------------------------------------------------|-----|-------|-----|-------------|
|                                     | Mean                                                          | SD  | Mean                                                             | SD  | t     | df  | p           |
| <b>Economic Sustainability</b>      | 4.33                                                          | .63 | 4.12                                                             | .70 | 2.217 | 216 | <b>.028</b> |
| <b>Social Sustainability</b>        | 4.37                                                          | .60 | 4.09                                                             | .74 | 2.962 | 216 | <b>.003</b> |
| <b>Environmental Sustainability</b> | 4.31                                                          | .60 | 4.02                                                             | .63 | 3.293 | 216 | <b>.001</b> |
| <b>Design Practice</b>              | 4.12                                                          | .69 | 3.87                                                             | .81 | 2.161 | 216 | <b>.022</b> |

|                                        |      |     |      |     |      |     |      |
|----------------------------------------|------|-----|------|-----|------|-----|------|
| <b>Awareness of the Rebound Effect</b> | 3.61 | .84 | 3.54 | .79 | .572 | 216 | .576 |
|----------------------------------------|------|-----|------|-----|------|-----|------|

The differences in the design practice and rebound effect awareness scores of students who participated in sustainability-focused education/activities were statistically analysed. T-test results are presented in Table 3. The findings show that students who participated in sustainability-focused had higher social ( $M = 4.37$ ), economic ( $M = 4.33$ ) and environmental ( $M = 4.31$ ) sustainability attitudes than those who did not participate in these educations/activities. These differences were found to be statistically significant in all dimensions ( $p < 0.05$ ). Similarly, it was found that students who participated in sustainability-focused activities demonstrated higher levels of translation into design practice compared to those who did not ( $M = 4.12$ ;  $M = 3.87$ ), and this difference is statistically significant ( $p < 0.05$ ). This finding is consistent with Liao's (2024) study, which demonstrates a positive relationship between sustainability education factors and sustainable consumption behaviors [37]. Furthermore, it is noted that sustainability-focused pedagogical tools have a positive impact on students' understanding of sustainable design practices and the relationship between these practices and the industry [38]. Furthermore, it is emphasized that sustainability-based teaching approaches in fashion and textile education play a significant role in developing students' sustainability knowledge and skills, and that such educational models are both feasible and effective [39]. However, no statistically significant difference was found between the two groups in terms of awareness of the rebound effect ( $p > 0.05$ ). This finding is consistent with a study that highlights the lack of sufficient attention to behavioral dimensions in the literature on the rebound effect [40].

#### 4. CONCLUSION

This study aims to examine fashion design students' attitudes toward environmental, economic, and social sustainability in clothing and to evaluate these attitudes in the context of their awareness of rebound effect and design practice. The findings indicate that students' attitudes toward all three dimensions of sustainability are at a high level. However, it was determined that the reflection of these attitudes in design practice is relatively limited, and awareness of the rebound effect remains at a lower level compared to the other dimensions. The results of the correlation analysis reveal that attitudes toward environmental, social, and economic sustainability are positively and significantly correlated with design practice. This suggests that students with strong sustainability attitudes incorporate sustainability principles into their design processes to a greater extent. In contrast, the relationship between sustainability attitudes and awareness of the rebound effect appears to be weaker. This finding suggests that general sustainability awareness does not always develop in parallel with an understanding of the indirect and systemic-level outcomes of sustainability-focused interventions. Furthermore, it was determined that participation in sustainability-focused education and activities was associated with significant differences in students' sustainability attitudes and levels of design practice but did not result in a significant difference in terms of awareness of the rebound effect. This finding suggests that current approaches to sustainability education are effective in developing students' sustainability-focused thinking and application skills; however, they may not provide sufficient support for understanding more complex and indirect outcomes, such as the rebound effect. Overall, the findings reveal a significant gap between sustainability awareness and understanding of the rebound effect. This indicates the need for a more open and holistic approach to fashion design education, incorporating systems thinking, user behaviour and the indirect effects of sustainability interventions. Future studies could focus on designing pedagogical models to develop students' ability to evaluate the wide-scale effects of sustainable design decisions. However, the findings of this study are limited to the study's sample group; it is expected to serve as a guide for future studies involving different groups.

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## FAST FASHION AND MICROPLASTIC POLLUTION: THE HIDDEN ENVIRONMENTAL COST

Semih Ozkur<sup>1,\*</sup>, Hande Sezgin<sup>1</sup>, Ipek Yalcin-Enis<sup>1</sup>

<sup>1</sup> Istanbul Technical University, Textile Engineering Department, Istanbul, Türkiye

\* [semihozkur@itu.edu.tr](mailto:semihozkur@itu.edu.tr)

### ABSTRACT

The textile industry faces a significant challenge to global sustainability due to the rise of the "fast fashion" business model, which relies on high-volume production and planned obsolescence. This study examines the multifaceted environmental impact of fast fashion, focusing on the historical transition from natural to synthetic fibers and the resulting increase in microplastic pollution. Findings indicate that the industry consumes approximately 93 billion cubic meters of water annually and is responsible for 10% of global carbon emissions. Central to this crisis is the dominance of synthetic fibers, particularly polyester, which now accounts for 59% of global fiber production. The laundering of these synthetic textiles is estimated to contribute between 16% and 35% of the primary microplastics in the world's oceans. Furthermore, this paper critiques current industry sustainability efforts, such as the transition to recycled polyester (rPET). Evidence suggests that rPET often functions as "downcycling" and may increase microfiber shedding by up to 55% compared to virgin polyester. The study concludes that current recycling-based strategies often amount to "greenwashing" and argues that a radical shift away from the overproduction-based fast fashion model is necessary to mitigate global ecological degradation.

**Keywords:** *Fast fashion, Microplastic pollution, Synthetic fibers, Recycled polyester, Sustainability*

### 1. INTRODUCTION

While the textile industry is an indispensable part of modern life, it poses a significant challenge to global sustainability goals due to its environmental impact. To understand this impact, it is crucial first to define the "fast fashion" business model that has dominated the industry since the early 2000s. Fast fashion is a strategy that aims to shorten the time cycle from design to consumption, allowing retailers to respond rapidly to emerging fashion trends through high-volume, low-cost manufacturing. This model relies on a "planned obsolescence" approach, where garments are designed to be short-lived, both physically and stylistically, thereby encouraging continuous purchasing [1].

The need for such rapid production and low-cost output has fundamentally shifted the industry's reliance on raw materials. Since natural fibers like cotton and wool are subject to seasonal and agricultural constraints, the fast-fashion sector has turned heavily to petrochemical-based synthetic fibers, particularly polyester. Petrochemical-based synthetic fibers pose a major waste management problem because they do not decompose in nature. Moreover, 30 percent of newly arrived clothes in stores are never sold [1, 2], 50 percent of those sold are discarded in some countries without being worn even once [3, 4], and, in general, an outfit is worn only 7 times on average [1, 5]. Considering this situation, the size of the problem becomes much more striking. But the problem doesn't end there, and all this change brings a hidden environmental cost beyond visible waste: microplastic pollution. During production, repeated laundering, and eventual disposal, these synthetic garments release millions of microscopic plastic fibers, smaller than 5 mm, into the environment. These microplastics have now permeated every layer of the ecosystem, creating a persistent, invisible form of pollution that links textile consumption to global ecological degradation.

This study aims to examine the multifaceted role of fast fashion in the environmental crisis, focusing specifically on the relationship between the dominance of synthetic fibers and microplastic emissions. In the following sections, the historical development of consumer culture and the transition to the fast-fashion model will be discussed. Subsequently, the environmental consequences of this model will be analyzed through the lens of microplastic pollution and the limitations of current sustainability efforts, such as the transition to recycled polyester (rPET). Finally, the necessity for a radical shift in production and consumption paradigms will be evaluated in the conclusion.

## **2. THE HISTORICAL DEVELOPMENT OF CONSUMER CULTURE AND FAST FASHION**

To understand the environmental impacts of fast fashion, it is necessary to examine the dynamics of consumer culture that sustain this production model. Consumption is not merely the fulfillment of basic needs; rather, it is a set of socially and culturally constructed practices shaped by the economic and ideological conditions of a given period [6-8].

In the contemporary world, consumption habits are largely influenced by globalization, where local practices are shaped by distant economic and political developments [9], and by capitalism as the dominant global system. From the mid-19<sup>th</sup> century onward, the ethical legitimization of labor and capital accumulation, combined with technological innovations, significantly increased production capacities [10]. This process led to what has been described as the “democratization of consumption,” allowing lower social classes to participate in consumer markets and gradually transforming consumption into a central life philosophy [11–14].

Industrial production, which escalated during the Industrial Revolution, reached the scale of mass production in the 1930s, during the era of Fordism. The transition to post-Fordism in the 1980s fragmented production processes across multiple geographies, enabling flexible production systems and access to low-cost labor. These changes reduced production costs while dramatically increasing product variety and volume, making continuous and excessive consumption a structural necessity of the system [15, 16].

With the technological advancements of the 1990s, economic and political boundaries became increasingly permeable, leading to what can be described as the global intensification of consumption practices [17]. As a result, consumption ceased to function primarily as a means of satisfying needs and instead became an end in itself [18].

This historical transformation paved the way for the emergence of the fast fashion business model in the late 20<sup>th</sup> century [19]. Within this framework, garments have shifted from durable necessities to rapidly consumed and frequently renewed social symbols, as conceptualized by Baudrillard’s notion of the consumer society [14]. Fast fashion brands such as Zara, H&M, and Shein now replace traditional seasonal collections with up to 52 micro-seasons per year, significantly shortening garment lifespans and accelerating consumption cycles [20].

Consequently, consumers are encouraged to discard clothing long before it wears out, reinforcing a throwaway culture. Research conducted in 2022 indicates that global clothing consumption increased by 60% compared to 2000, while 85% of purchased garments were discarded within a year [21]. These findings clearly demonstrate how fast fashion intensifies overconsumption and contributes to environmental degradation by normalizing disposability.

## **3. ENVIRONMENTAL IMPACT OF FAST FASHION**

Overproduction, driven by overconsumption, has environmental impacts both during the use phase and at the end of a product’s life cycle. These negative effects begin during production and are further worsened by inadequate waste management practices. As the fast fashion business model is based on high-volume and rapid production cycles, the sector consumes vast amounts of water and energy, leading to environmental problems such as severe water pollution and high carbon emissions [1]. The textile industry, which constitutes a major component of fast fashion, is among the leading sectors in global water consumption, using approximately 93 billion cubic meters of water annually [22]. This intensive water use begins at the raw material stage, particularly in the production of natural fibers such as cotton [23]. The widespread use of pesticides, agricultural chemicals, and other harmful substances during cotton cultivation causes substantial water and soil pollution, harming ecosystems. In addition, chemicals and dyes used



during textile processing, whether natural or synthetic fibers are involved, represent one of the most significant sources of industrial water pollution. Research indicates that approximately 15% of chemicals used in textile dyeing are discharged directly into waterways, where they can contain toxic substances such as lead, arsenic, and mercury, posing serious threats to aquatic ecosystems [24]. High energy consumption throughout the production process further increases carbon emissions. At this point, the impact of synthetic fibers, due to petroleum-based production mechanisms, begins at the raw material stage [25]. According to the European Environment Agency, the fashion industry is responsible for approximately 10% of total global carbon emissions [26]. These emissions are not limited to textile production alone but continue to rise during transportation, distribution, and product use stages.

Beyond the intensive use of water, energy, and chemicals, the fast fashion production cycle generates another major environmental burden: excessive textile waste and microplastic pollution. Global data show that approximately 92 million tons of textile waste are produced each year, a figure projected to reach 148 million tons by 2030 [27]. Moreover, a large part of this comes from products made with petroleum-based synthetic fibers, especially polyester, which exacerbates microplastic pollution. In many countries, a large proportion of this waste is sent directly to landfills without being recycled. Due to the high cost and complexity of textile recycling, most discarded garments end up in landfills, causing long-term environmental damage [28]. The scale of this waste problem is so vast that discarded clothing has been reported to be visible from space and, in some regions, accumulates along coastlines in the form of clothing piles reaching heights of up to 30 meters [29-32].

#### **4. THE ROLE OF FAST FASHION IN MICROPLASTIC POLLUTION**

Fast fashion products are generally of low quality due to high-speed production processes and low-cost policies. As a result, these products not only generate large amounts of macro-scale waste but also release significant amounts of microplastic fibers during use due to their poor quality [33]. Microplastics, defined as synthetic particles smaller than 5 mm, have now penetrated every layer of the ecosystem, from the deepest parts of the oceans to the human placenta. It is estimated that between 16% and 35% of primary microplastics in the oceans originate from the laundering of synthetic textiles [34, 35].

Fast fashion is fundamentally based on low cost and an extremely short time frame from design to consumer; in other words, speed. To meet these two factors, low cost and high speed, the vast majority of products are low quality, and achieving this speed has required greater reliance on synthetic fibers, which can be produced continuously and cheaply in petrochemical plants, rather than cotton or wool, which are subject to agricultural restrictions. According to a 2024 report by the Changing Markets Foundation analyzing 50 companies (including Inditex, Mango, Nike, United Colors of Benetton, and Primark) with a total value of 1 trillion dollars in the global fashion market, the fashion industry's reliance on synthetic fibers, particularly polyester, is increasing [36]. As of 2024, global fiber production has reached 132 million tons, with synthetic fibers accounting for 69% of total production. Among these, polyester alone constitutes 78% of synthetic fibers, corresponding to 59% of overall global fiber production [37]. This increasing dominance of synthetic materials exacerbates the environmental problems associated with fast fashion, as synthetic textiles are a major source of microplastic pollution during their production, use, and disposal, and the low quality of fast-fashion products further increases microfiber emissions.

#### **5. DOWNCYCLING AND THE MYTH OF CIRCULARITY**

The industry is increasingly seeking to expand the use of recycled fibers to address this problem and reduce its environmental footprint. At this point, synthetic fibers, especially polyester, which dominates the sector, come to the forefront, and the use of rPET instead of virgin polyester is rapidly increasing. However, this practice represents an example of "downcycling" rather than a genuinely circular recycling process. Instead of recycling its own waste in the form of discarded garments, the textile industry primarily relies on PET bottles and similar packaging waste from other sectors [1, 28].



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According to sector data, 98% of recycled polyester is produced from plastic bottles rather than textile waste [38]. Similarly, data from the Ellen MacArthur Foundation indicate that less than 1% of clothing is recycled into new garments [5].

Furthermore, evidence suggesting that the use of rPET increases the risk of microplastic pollution is steadily growing. A study by Özkan and Gündoğdu [39] demonstrated that rPET knitted fabrics release approximately 2.3 times more fibers compared to virgin PET fabrics. This is because the recycling process weakens polymer chains through repeated thermal and mechanical treatments, making fibers more brittle and increasing microfiber shedding during laundering. Supporting these findings, a 2024 study reported that rPET fabrics can release up to 55% more microfibers than virgin polyester [38]. These findings indicate that the industry’s so-called “sustainability” strategies fail to resolve the textile waste problem and instead transform it into another environmental burden: microplastic pollution.

In conclusion, the recycling-based solutions promoted by fast fashion brands under the banner of “sustainability” can be interpreted as a form of “greenwashing” in their current configuration, as they effectively obscure the structural root of the problem, overproduction. At this point, while working on what can or should be done to prevent or at least mitigate the negative environmental impact caused by “fast fashion,” it is crucial not to miss the root of the problem. As Sahimaa et al. [40] stated, “The only way to fix fast fashion is to end it.”

## 6. CONCLUSION

This study examined fast fashion through its historical development within consumer culture and assessed its environmental impacts across production, use, and end-of-life stages. The findings indicate that, in its current operational form, fast fashion generates both large volumes of textile waste and a continuous source of microplastic pollution. Beyond the well-documented accumulation of macro-scale waste, the widespread use of synthetic fibers and the rapid turnover of garments contribute to persistent microplastic emissions, extending the environmental footprint of the fast fashion ecosystem beyond visible waste streams.

Taken together, the available evidence demonstrates the structural unsustainability of a production model characterized by high volumes, speed, and short product lifespans. Discussions on the future of textiles, therefore, increasingly focus on the ecological debt created by a throwaway culture and on the limitations of existing recycling practices, where less than 1% of clothing is recycled into new garments. Rather than relying solely on downcycling-based solutions, ongoing debates emphasize the need to reconsider production models, material choices, and technological approaches that shape both current impacts and future environmental pressures in the fashion industry.

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## FROM ALGORITHMS TO APPAREL: ANALYZING AI INTEGRATION IN FASHION DESIGN

Melis Küçükyılmaz<sup>1,\*</sup>, Serna Uçar Hatipoğlu<sup>1</sup>

<sup>1</sup> Istanbul Technical University, Istanbul, Turkey

\* [kucukyilmazm@itu.edu.tr](mailto:kucukyilmazm@itu.edu.tr)

### ABSTRACT

The rapid advancement of Artificial Intelligence (AI), particularly Generative AI, is significantly transforming the fashion industry by reshaping design processes, production workflows, and consumer engagement strategies. This study examines the integration of AI across the fashion ecosystem, covering trend forecasting, design ideation, pattern optimization, and virtual retail applications such as Virtual Try-On (VTO) technologies. Adopting a holistic framework, the paper maps AI integration across pre-production, production, and post-production stages, with an in-depth focus on generative design and VTO systems as the most strategically impactful domains. To validate these theoretical frameworks, the study presents an applied industry-university case study conducted in collaboration between Istanbul Technical University (ITU) Fashion Design students and the ready-to-wear brand, using the AI platform Refabric. Results demonstrate that generative AI tools can streamline the entire design-to-campaign workflow by integrating concept development, flat-lay generation, photorealistic model visualization, and animated content production into a single cohesive process. The findings demonstrate that AI-augmented workflows substantially reduce time, cost, and material resources compared to conventional methods, while also offering meaningful sustainability benefits through the elimination of physical sampling and location-based production. This study contributes to the emerging body of literature by bridging the gap between theoretical AI capabilities and applied educational practice, positioning AI-integrated pedagogy as a strategic response to the growing demand for digitally literate fashion professionals.

**Keywords:** *AI in Fashion, Generative Design, Virtual Prototyping, Virtual Try-On (VTO), Industry-University Collaboration*

### 1. INTRODUCTION

Artificial intelligence (AI) research first marked the beginning of a new era in computer science in the mid-20th century, notably with Alan Turing's work in the 1950s. The intersection of the fashion industry and technology has developed in parallel with industrial revolutions. With the Third Industrial Revolution (the 1960s and beyond), digital design and computer-aided manufacturing systems, such as CAD/CAM, were integrated into the sector. This integration replaced manual processes with digital tools, as the introduction of CNC technology enabled a 'direct link between the three-dimensional (3D) CAD model and its production', thereby revolutionizing manufacturing systems through mass production and enhanced flexibility [1].

The truly disruptive impact of AI on fashion began with the Fourth Industrial Revolution (Industry 4.0). The integration of Big Data, machine learning, and 3D technologies has enabled data-driven decision-making at central stages of the design process. In recent years, the rise of Generative AI systems, such as GANs and Diffusion models, has paved the way for designers to create hyper-realistic designs within entirely digital ecosystems.

Despite these rapid technological advancements, significant gaps remain in the current literature. Most existing studies tend to focus in isolation on either the creative design phase or retail applications, rather than examining AI integration holistically across the full production cycle [2]. Furthermore, while the technical capabilities of generative AI have been extensively documented, the link between theoretical AI frameworks and applied educational practice remains underexplored [3]. In particular, there is limited empirical work investigating how these advanced AI tools perform in real-world academic and industry collaboration settings, where both human creativity and commercial viability must be balanced. To address

these gaps, this paper sets out to map AI integration comprehensively across the pre-production, production, and post-production stages of the fashion ecosystem. Within this broader context, the study focuses in depth on two high-impact areas: generative design and Virtual Try-On (VTO) technologies. Most importantly, we aim to validate these theoretical frameworks through an applied industry-university case study conducted in collaboration between Istanbul Technical University (ITU) students and the fashion brand DeFacto. By doing so, this paper combines a comprehensive literature-based framework with a qualitative, practice-oriented case study. This dual approach bridges the gap between theoretical AI capabilities and practical, educational applications, situating the empirical work firmly within contemporary academic discourse.

## **2. CLASSIFICATION OF AI IN FASHION INDUSTRY**

When the historical development and methodological transformation of AI technologies in the fashion industry are examined through a holistic lens, it is evident that AI plays a strategic role in every phase of the fashion production cycle. In contemporary practice, the integration of AI within the fashion production cycle is primarily structured into three main stages to optimize operational efficiency and predictive accuracy: pre-production, production, and post-production [4].

In the pre-production stage, AI automates market research and trend analysis through big data analytics, allowing designers to develop data-driven concepts. In the design and material selection processes, generative models facilitate rapid prototyping, reducing traditional sample preparation phases, which could take weeks, to durations measured in seconds within digital environments.

In the production phase, AI integration optimizes supply chains and manufacturing efficiency through predictive maintenance algorithms that anticipate equipment failures. Additionally, computer vision technologies within smart factories minimize defect margins by detecting textile and sewing flaws in real time.

The post-production stage is the phase where AI completes the cycle by analyzing consumer behavior. Sales forecasting and inventory management algorithms prevent overproduction by optimizing stock levels. In marketing strategies, hyper-personalized campaigns and VTO technologies enrich the customer experience and reduce return rates. AI-supported route optimizations in distribution and logistics lower operational costs, while continuous customer service provided via chatbots strengthens brand loyalty on a digital plane.

While AI transforms all production stages, this study deliberately focuses on pre-production (design) and post-production (virtual retail), bypassing physical manufacturing. Advanced generative AI creates a direct bridge between design and sales by generating hyper-realistic digital prototypes, allowing brands to present unmade concepts to consumers and initiate physical production only after confirming market demand [2]. In this context, the pre-production and post-production phases are thematically connected as two ends of the same digital fashion pipeline, which the upcoming case study demonstrates in practice.

### **2.1 Pre-production focus: Design and Design Generation**

The design stage in fashion represents a critical process where conceptual frameworks are transformed into tangible product proposals. Today, with the integration of generative AI models, the design process has evolved from traditional form-finding methods into a hybrid creative model. This technological transformation offers designers methodological advantages across a wide spectrum, from the ideation stage to final visualization. Designers can create or enhance their work using various AI tools through text-to-image and image-to-image methods, or by blending these approaches.

In text-to-image generation, when there is no visual input at the beginning of the design process, generative AI models serve as a virtual prototyping engine that rapidly visualizes initial design variations compatible with the concept using text-based commands. At this point, obtaining qualified and applicable outputs from AI depends not only on the designer's creative vision but also on their command of professional terminology such as silhouette, pattern techniques, fabric types, and detailing, because prompt engineering becomes a technical skill at this stage.





**Figure 1.** Refabric - Prompt to Design Tool [5].

The subsequent image-to-image method allows the designer to progress using existing moodboards, sketches, or reference images. This method enables the effortless generation of new variations while preserving the aesthetic codes of an existing design. Furthermore, through models trained on a brand's historical collection data, the unique design DNA of a brand or designer can be transferred to new products.

In design revision processes, specific modifications can be made to existing models without disrupting overall integrity by using regional editing techniques. These digital interventions on specific components such as collars, cuffs, pockets, or stitching details allow for updates in color, texture, and accessories without the need to recreate the entire design. This application minimizes time costs in the iterative design cycle and enhances operational efficiency.



**Figure 2.** Refabric - Prompt to Editing Tool [5].

During the visualization phase, AI functions as a digital render engine that transforms 2D linear sketches into photorealistic images. Thanks to structure-preserving architectures like ControlNet, the forms and edge lines of the designer's hand drawings remain fixed, while desired fabric textures and light interactions are applied to the model accurately [6]. This technology provides a powerful and rapid alternative to traditional 3D modeling processes by creating high-fidelity virtual prototypes in seconds without the need for complex CAD data.

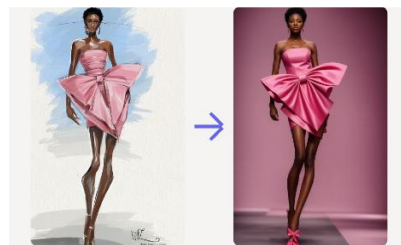


**Figure 3.** Refabric - Sketch to Design Tool [5].

To contextualize these theoretical frameworks within the contemporary fashion industry, it is essential to examine real-world applications of generative AI during the creative design phase. Currently, brands and designers are increasingly utilizing machine learning models not merely as generic visualization tools, but as customized extensions of their creative identities. By training AI systems specifically on their own historical archives, previous collections, and proprietary imagery, designers can generate novel concepts that inherently preserve their unique brand DNA and aesthetic signatures [7]. The following industry case studies illustrate how this practice of utilizing archive-trained AI is actively employed to conceptualize new collections while maintaining human creative integrity and mitigating copyright concerns.

Designer Norma Kamali has innovated her design process by collaborating with AI studio Maison Meta to train a specialized model on her extensive archive, replacing traditional hand drawing with text-based commands. Within this framework, Kamali operates as a curator who evaluates algorithmic outputs, viewing AI-generated imperfections not as errors but as unique opportunities for aesthetic development.



**Figure 4.** Norma Kamali’s AI-generated models and designs.

For its Spring/Summer 2024 collection, fashion brand Collina Strada integrated generative AI into its design process by training an algorithm on its archives to produce innovative, digital concepts. These initial algorithmic outputs were subsequently refined and adapted for physical production by the design team, demonstrating a successful hybrid model that balances technological innovation with human craftsmanship.



**Figure 5.** Selected Looks from Collina Strada’s Spring/Summer 2024 Collection [8].

## **2.2 Post-production focus: Gen AI Visualisation and VTO Systems**

Virtual Try-On (VTO) systems have evolved from simple visual aids into highly sophisticated retail standards. Recent market studies project the VTO segment to grow at a CAGR of over 36% from 2025 to 2033, driven by features that can reduce return rates for premium goods by up to 40% [9].

While the first retail implementations began in U.S. department stores during the early 2010s, these early systems often required depth sensors (such as Kinect) or 3D body scanners to estimate human shape and overlay 2D garment images [10]. In the realm of computer vision, early 2D attempts often treated VTO as a "picture analogy" problem; however, these models lacked photorealism and were often impractical for standard retail because they required product images of both the target garment and the original garment being worn [13].

While the first retail implementations in the early 2010s relied on depth sensors and 3D body scanners, VITON, introduced by Han et al. in 2018, marked a turning point by enabling realistic garment transfer using only standard 2D RGB images, making VTO practical for standard retail integration for the first time [10]. Building on this, CP-VTON introduced geometric matching via Thin-Plate Spline transformations to improve fit precision, while CVTON further enhanced realism through body-part-based matching and advanced generative algorithms [13].

The COVID-19 pandemic significantly accelerated VTO adoption globally. ASOS utilized augmented reality in 2020 to create digital twins of real models, tripling its profits between 2020 and 2021 [15]. As of February 2026, ASOS has advanced further with a hybrid shopping experience that integrates VITON technology with a personalized interface where customers can test garments on their own photos or on AI-generated avatars mirroring their physical proportions (See Figure 6).

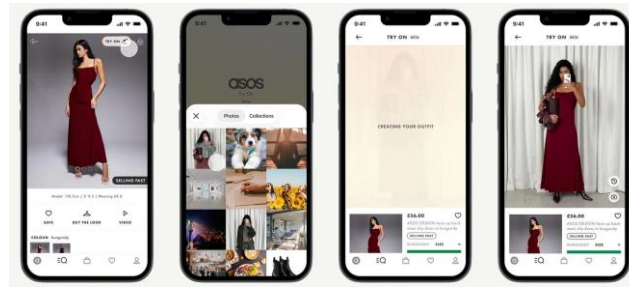


**Figure 6.** ASOS virtual try-on experience [16].

Advanced systems like CP-VTON and CVTON have enhanced virtual try-on (VTO) technology by integrating Geometric Matching Modules, Thin-Plate Spline transformations, and body-part-based matching to produce high-resolution, precise garment warps [13]. Commercial leaders such as Zara utilize these innovations to offer real-time, smartphone-based VTO visualizations. Strategically, VTO integration serves as a high-return investment that can reduce return rates by up to 40% [9], while driving engagement boosts exceeding 200% for brands like Tiffany & Co [9]. Technological efficiency has reached a critical tipping point; currently, inference times for 512x512 images are reduced to 1.5 seconds [13]. Furthermore, current systems achieve 98% accuracy in body scanning, 95% in 3D avatar generation, and 90% realism in fabric simulation [17], effectively narrowing the gap between physical and virtual fitting.

This technological accuracy directly addresses a significant industry challenge: sizing issues affect 85% of consumers and generate immense financial burdens, with return-related losses projected to decrease by 40% through AI adoption [9]. Consequently, McKinsey projections indicate that 73% of fashion executives prioritize AI investments. A key operational example is the McArthur Glen Group, which implemented a hybrid phygital marketing model for its SS26 campaigns by placing real models within high-resolution, AI-generated environments (See Figure 7). This approach optimizes logistics and aligns with environmental sustainability by reducing physical sampling and location scouting costs by up to 50% [17], while significantly lowering the industry's carbon footprint [15].



**Figure 7.** McArthur Glen AI-driven photoshootings-SS26 Campaign [18].

Ultimately, these methods demonstrate that design can be structured as an optimizable, data-driven process, specifically within the time-intensive design generation and visualization phases. The following case study tests these integration models within an applied educational framework to substantiate the sectoral potential of AI.

### 3. CASE STUDY: AI AUGMENTED DESIGN WORKSHOP

This section outlines the methodology and execution of the joint case study between Istanbul Technical University (ITU) Fashion Design students and the ready-to-wear retailer DeFacto, conducted within an academic framework serves as a strategic example of university-industry collaboration, modeling the opportunities provided by AI-driven technologies in the design process, as well as post-design visualization and marketing stages.

Participants organized into four groups of three, this case study aimed to evaluate the operational capacity of generative AI within professional fashion design workflows. In the initial phase, participants received

comprehensive training on the technical infrastructure and usage methodology of **Refabric**, a fashion-oriented AI platform. Following the registration and data entry processes, students gained hands-on experience by utilizing the platform’s tools.

The practical stage commenced with the distribution of differentiated design briefs to each participant group. This procedure is exemplified through the thematic guidelines assigned to the third group. Specifically, the brief for this group focused on the Men's Spring/Summer 2027 season, specific design theme about baseball, encompassed data-driven trend forecasts, aesthetic parameters, reference brands, and designated product categories, such as trucker hats. The established roadmap formed the conceptual foundation for the technical prompts that participants input into the generative AI model.

The workflow commenced with the selection of themes aligned with the provided briefs and the creation of moodboards. Subsequently, participants defined a target audience persona and developed a corresponding pen portrait board. Following the selection of color palettes and textile textures, the design phase (pre production) was executed using the Refabric platform. Initially, "flat-lay" design visuals (without human figures) were generated through a combination of prompt engineering and, where necessary, the integration of reference images. Specific design modifications were performed using the platform's internal editing tools. Representative visual outcomes generated by the students based on this brief are illustrated in the figure 8 below.



**Figure 8.** Group 3's flat lay design visuals.

Once the designs were finalized, they were digitally draped onto models described in accordance with the pre-defined personas. To generate hyper-realistic campaign imagery, the previously designed flat visuals were utilized as reference inputs; detailed descriptions of the model's physical attributes, background environment, and lighting parameters were then applied. The methodology facilitated the generation of photorealistic AI imagery, depicting digital models wearing complex design iterations.



**Figure 9.** Group 3's Photoshoot visuals.

These outputs were subsequently converted into five-second animated videos. The synthesized data was compiled into a final presentation and delivered to brand representatives. The entire cycle, from initial training to the final presentation, was completed in approximately five hours.

#### 4. CONCLUSION

This study has demonstrated that Artificial Intelligence, particularly Generative AI, is no longer a peripheral tool in fashion but a foundational component reshaping the industry across its entire value chain, from pre-



production to post-production visualization processes. Generative design and visualisation were designated as the primary focal areas of this research, as they constitute the most significant sectors of impact for AI intervention within the industry.

The applied case study conducted in collaboration with Istanbul Technical University and DeFacto further substantiates these theoretical claims in an academic setting. Organized into four teams of three participants each, the study followed a structured methodology consisting of an initial technical training session followed by a dedicated production phase. During this period, 12 participants successfully designed 20 distinct looks across four concepts, utilizing AI models to execute flat-lay designs, photorealistic campaigns, and video shoots before concluding with project presentations.

Without AI integration, the same workflow would have required substantially greater time, cost, and material resources. While traditional design iteration requires weeks for physical sampling, casting, and photography, this case study's five-hour completion time underscores the operational efficiency generative AI enables. By bypassing conventional lead times and material costs, the technology proves highly effective for fast-paced academic and industry collaborations. The transition from physical to digital design workflows significantly reduces the fashion industry's environmental footprint by eliminating material waste during prototyping and lowering travel-related carbon emissions through virtual campaigns. Consequently, AI-augmented workflows provide a scalable pathway toward leaner, more sustainable production cycles.

The study is subject to several limitations that should be acknowledged. The case study involved a group of twelve participants on a single platform, which restricts the generalizability of the findings. Furthermore, the integration of generative AI raises critical ethical concerns regarding intellectual property ownership, creative labor displacement, and algorithmic bias within VTO systems.

To address these limitations, future research should expand empirical investigations to larger, more diverse groups across multiple platforms and conduct longitudinal studies tracking the career trajectories of AI-literate graduates. Additionally, establishing standardized ethical frameworks specific to fashion education remains a critical direction for both academia and industry. Ultimately, this case study demonstrates that AI-augmented workflows are commercially viable and academically valuable, establishing AI-integrated curricula as a strategic necessity for training digitally literate fashion professionals.

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## GREEN REDUCTION OF GRAPHENE OXIDE USING TOMATO PEEL EXTRACT FOR FUNCTIONAL NONWOVEN TEXTILES

Nergis Demirel Gültekin<sup>1,\*</sup>, Efe Kuzey YILMAZ<sup>1</sup>, Gül TOPAL<sup>1</sup>, Bekir Cenkkut GÜLTEKİN<sup>1</sup>

<sup>1</sup> Department of Textile Engineering, Faculty of Technology, Marmara University, İstanbul, Türkiye

\* [ndemirel@marmara.edu.tr](mailto:ndemirel@marmara.edu.tr)

### ABSTRACT

In this study, GO is synthesized via the modified Hummers method and subsequently applied to needle-punched polyester nonwoven fabrics using the dip-coating technique. The GO-coated nonwoven fabric is then subjected to a reduction process using aqueous tomato peel extracts under controlled temperature conditions. The effectiveness of the reduction process is evaluated through comprehensive characterization techniques, including scanning electron microscopy (SEM) and FTIR spectroscopy. Additionally, the electrical surface resistivity and acoustic absorption properties of the resulting RGO-coated nonwoven fabrics are investigated. The results demonstrate that tomato peel extract can effectively reduce GO, leading to improved electrical conductivity and enhanced sound absorption performance of the textile structure.

**Keywords:** *Graphene oxide reduction, Tomato peel extract, Waste management, Polyester nonwoven fabric, Sound absorption coefficient.*

### 1. INTRODUCTION

Graphene oxide (GO) is a two-dimensional graphene derivative enriched with oxygen-containing functional groups, such as epoxide, hydroxyl, and carboxyl groups, which enhance its hydrophilicity and enable versatile chemical functionalization [1, 2]. Owing to these characteristics, GO can be easily dispersed in water and is widely used in the fabrication of nanocomposites, polymer systems, high-performance microelectronic devices, energy storage materials, and biomedical applications. However, the presence of oxygen functionalities significantly reduces the electrical conductivity, thermo-mechanical stability, and carrier mobility of carbon-based materials [3]. Fruits and vegetables are most popular due to their nutritional value worldwide and are rich sources of beneficial antioxidants, minerals, vitamins, and fiber. Many phenolic compounds have antioxidant properties [4]. In particular, tomato fruit contains high levels of vitamins C and E, minerals such as K, P, and Mg, carotenoids—mainly lycopene—and phenolic compounds including caffeic acid, ferulic acid, kaempferol, and quercetin. Tomato processing byproducts, such as seeds and peels, also retain considerable amounts of these bioactive compounds, along with fiber, fatty acids, sitosterol, isorhamnetin, and myricetin [5-7]. Recent studies showed that tomato peel extract can be utilized as a reducing and capping agent in the synthesis of silver nanoparticles [7], zinc oxide nanoparticles [8], and tin oxide [9].

Noise pollution significantly affects human comfort, creating a growing demand for soundproofing materials effective over a wide frequency range. Nonwoven textile structures have emerged as promising sound-absorbing materials due to their flexibility, strength, softness, low density, and high porosity. Their acoustic performance is strongly influenced by structural parameters such as thickness and pore structure, where increased thickness and porosity enhance energy dissipation and improve sound absorption. Additionally, textile-based absorbers offer advantages such as low production cost, ease of processing, and suitability for human-contact applications, along with environmental resistance properties, including moisture, mold, temperature, and corrosion resistance. The performance of such materials is typically evaluated using the sound absorption coefficient, defined as the ratio of absorbed to incident acoustic energy [10-12]. Carbon-based materials are widely used as fillers in porous sound-absorbing systems due to their

high specific surface area and excellent physical properties [13]. In this context, GO stands out as a promising candidate for the development of advanced acoustic materials due to its unique two-dimensional structure and tunable surface chemistry [14].

In this study, tomato peel extract is utilized as an eco-friendly reducing agent for graphene oxide applied onto needle-punched nonwoven textile surfaces. Tomato peels, as an abundant agro-industrial waste, are rich in polyphenols, flavonoids, and antioxidants with strong reducing capability. The valorization of this waste aligns with circular economy principles and supports sustainable material development. The reduction efficiency and structural properties are evaluated using scanning electron microscopy (SEM) and FTIR spectroscopy. Furthermore, the electrical surface resistivity and sound absorption performance of the resulting reduced graphene oxide (RGO)-coated nonwoven fabrics are systematically investigated.

## **2. EXPERIMENTAL STUDY**

### **2.1 Materials**

Graphite flakes were purchased from Sigma-Aldrich. Hydrogen peroxide ( $\text{H}_2\text{O}_2$ , 35%), sulfuric acid ( $\text{H}_2\text{SO}_4$ , 95%–98%), phosphoric acid ( $\text{H}_3\text{PO}_4$ ), potassium permanganate ( $\text{KMnO}_4$ ), boric acid ( $\text{H}_3\text{BO}_3$ ), and hydrochloric acid ( $\text{HCl}$ , 37%) were purchased from Merck. All chemicals were of analytical reagent grade and used without further purification. Distilled water was used throughout the experiments. Polyester needle-punched nonwoven fabric with a mass per unit area of  $150 \text{ g/m}^2$  was kindly provided by Hassan Textile, Türkiye.

### **2.2 Synthesis of Graphene Oxide and Preparation of Coating Dispersion**

Graphene oxide was synthesized using the improved Hummers' method using flake graphite. Briefly, 360:40 mL of a mixture of  $\text{H}_2\text{SO}_4$  and  $\text{H}_3\text{PO}_4$  was placed into a flask, to which 3g of graphite flakes were added. The flask was gradually filled with 18g of  $\text{KMnO}_4$ . Following the full dissolution of the  $\text{KMnO}_4$ , the reaction was placed in an oil bath, heated to  $50^\circ\text{C}$ , and stirred for 12 hours. The reaction was then poured onto 400 mL of ice after being cooled to room temperature. 6 mL of 35%  $\text{H}_2\text{O}_2$  was added to terminate the reaction. The suspension was purified using ethanol (2 $\times$ ) and 1 M  $\text{HCl}$  by centrifugation. After washing, the centrifugation process was maintained until a pH of 4-5 was reached. The resulting sample was dried at  $60^\circ\text{C}$  to obtain solid GO nanosheets.

For the dip-coating process, 2 g/L aqueous dispersion of GO was prepared using the bath sonication method for 60 min at ambient conditions, followed by magnetic stirring for about 60 min to obtain a homogeneous dispersion.

### **2.3 Ultrasonic Extraction of Tomato Peels**

Tomato peels used in the study were obtained as household food waste. The peels were first washed with distilled water and then dried in an oven at  $50^\circ\text{C}$ . The dried peels were ground using a grinder to prepare them for extraction. Ultrasonic extraction was employed as the extraction method, and distilled water was used as the extraction medium. A predetermined amount of ground tomato peels was placed in a flask with distilled water and transferred to an ultrasonic bath equipped with a reflux condenser at  $50^\circ\text{C}$  for 1 hour. Finally, the obtained liquid extract was filtered. In the study, two different concentrations were used for the reduction of graphene oxide-coated nonwoven fabrics. Aqueous extracts of tomato peel prepared at 10% and 20% (w/w) concentrations were stored in a refrigerator at  $4^\circ\text{C}$ .

### **2.4 GO Coatings of Polyester Nonwoven Fabric and Reduction with Tomato Peel Extract**

The polyester needlepunched nonwoven fabric (NW) was coated with GO with a subsequent coating and reduction process. The dip-coating process was first applied to the polyester nonwoven fabric at ambient conditions for 10 min, and then the fabric was dried in an oven at  $70^\circ\text{C}$ . The dip-coating process was repeated five times to increase the coating amount. After the dip-coating process, the GO-coated nonwoven fabric was coded as DGO-NW. The reduction of GO was performed with an aqueous extract of tomato peel as a reducing agent. The DGO-NW sample was treated with the 10 wt.% and 20 wt.% aqueous extract of tomato peel at  $95^\circ\text{C}$  for 24 hours. Then, the reduced samples were rinsed with distilled water to remove the remaining materials, followed by drying at  $90^\circ\text{C}$  in an oven for 90 min. After the reduction process, the samples were coded as D10RGO-NW and D20RGO-NW for the samples reduced with 10% and 20% of tomato peel extract, respectively.

## 2.5 Characterization

Scanning electron microscopy (SEM-EDX, JEOL JSM-7100-F) was employed to observe the morphology of uncoated and coated samples. The surfaces of the samples were coated with Au/Pd before analysis. An attenuated total reflection Fourier transform infrared spectrometer (ATR-FTIR, Perkin Elmer Spectrum Two) was used at 650 - 4000  $\text{cm}^{-1}$ . The surface and volume resistivity of the fabric samples were tested based on the ASTM D257-07 standard, using a setup consisting of a sourcemeter (Keithley 2450 Sourcemeter) and a resistivity test fixture (Keithley 8009). Each sample was measured at least five times, and the average value was calculated. Surface resistivity is measured by applying a voltage potential across the surface of the specimen, whereas volume resistivity is measured by applying a voltage across the sample. The following equations were used to calculate the surface and volume resistivities of the samples:

$$\rho_s = \frac{53.4 \times V}{I} \text{ ohm } (\Omega) \quad \text{Eq. 1}$$

$$\rho_v = \frac{22.9 \times V}{t \times I} \text{ ohm.cm } (\Omega \cdot \text{cm}) \quad \text{Eq. 2}$$

where  $\rho_s$  and  $\rho_v$  are the surface and volume resistivity of the specimen, respectively,  $V$  is the voltage,  $I$  is the current, and  $t$  is the average thickness of the specimen in cm.

The sound absorption coefficients of the samples were determined using the impedance tube method (Brüel&Kjær). The tests were performed in accordance with the BS ISO 10534-2 standard. In the impedance tube technique with two fixed microphones, measurements are made in the range required for the large or small tube. Sound waves travel as plane waves, strike the sample, and reflect back. The sound absorption coefficient ( $\alpha$ ) of the sample is determined by measuring the sound pressure as a function of frequency with microphones that are fixed and in two separate positions. Using the small tube (29 mm diameter), measurements can be conducted in the frequency range of 50–6400 Hz. In contrast, the large tube allows measurements between 50–1600 Hz and requires a sample diameter of 100 mm. The sound absorption coefficient ranges from 0 to 1 [15].

## 3. RESULTS

### 3.1 SEM Analysis

Figure 1 presents the surface morphology of polyester nonwoven fabric samples at 1000 $\times$  magnification. The pristine polyester fibers exhibit smooth, uniform, and defect-free surfaces (Figure 1a). The dip-coating process effectively enables the deposition of GO nanosheets onto the nonwoven fabric surface. The characteristic wrinkled and wavy structure of GO nanosheets can be clearly observed between and around the polyester fibers, forming a continuous coating layer (Figure 1b). After reduction with tomato peel extract, the GO-coated nonwoven fabric exhibits a more fragmented and discontinuous RGO nanosheet structure (Figure 1c). This morphological change suggests that the reduction process alters the structural integrity of GO sheets, likely due to the removal of oxygen-containing functional groups and partial restacking or agglomeration.

### 3.2 FTIR Analysis

Figure 2 shows the FTIR spectra of nonwoven fabric samples. The characteristic absorption bands of polyester nonwoven fabric appear at approximately 967, 1016, 1093, 1239, and 1712  $\text{cm}^{-1}$ , corresponding to C-O stretching of glycol, benzene in-plane vibrations, ester C=O stretching vibration, and the C=O group of aromatic ester, respectively [16].

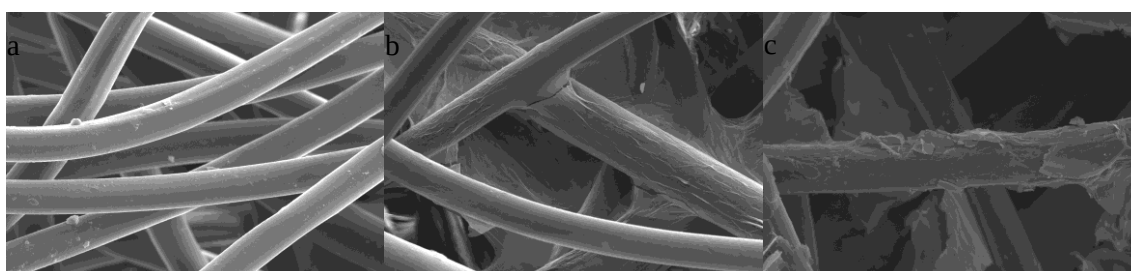


**Figure 1.** SEM images of NW(a), DGO-NW(b), D20RGO-NW(c).

The peaks observed at 1408, 1339, 722, and 871  $\text{cm}^{-1}$  are attributed to bending and wagging vibrational modes of the ethylene glycol segment [17], as well as C-H bending vibrations associated with the benzene

ring [18]. Following GO dip-coating, the FTIR spectrum shows slight changes, with the appearance of a new peak at  $1815\text{ cm}^{-1}$ , which is assigned to the stretching vibration of C=O. After reduction using tomato peel aqueous extract, the broad absorption band in the  $3600\text{--}2800\text{ cm}^{-1}$  region disappears, and the intensity of the characteristic peaks decreases. This indicates the removal of oxygen-containing groups and confirms the successful reduction of GO to RGO.

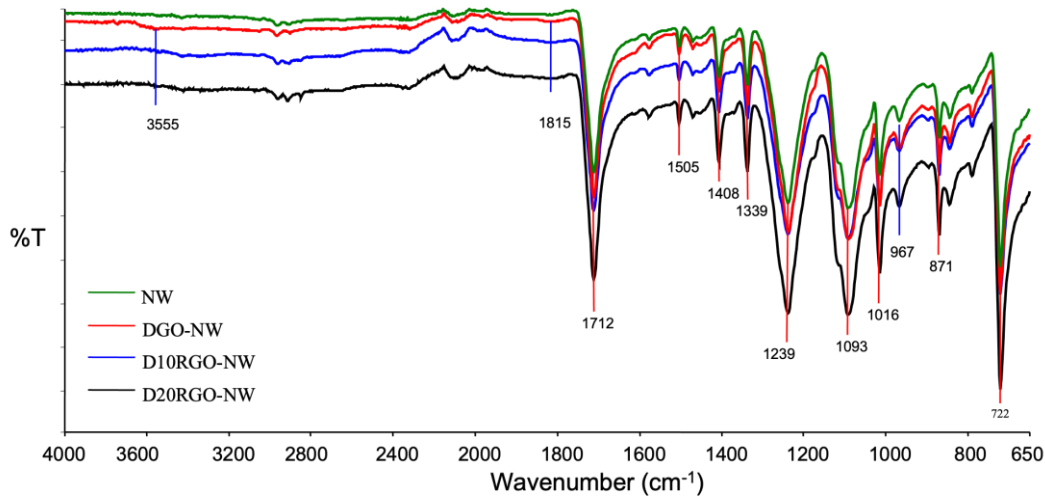


**Figure 2.** FTIR spectra of NW, DGO-NW, D10RGO-NW, and D20RGO-NW.

### 3.3 Electrical Resistivity

The electrical surface and volume resistivity values of polyester nonwoven fabric and coated samples are presented in Table 2. As expected, pristine polyester nonwoven fabric exhibits insulating behavior, with a very high surface resistivity of  $4.52 \times 10^9\text{ k}\Omega$ . Graphene oxide (GO) is also known to be electrically insulating due to the presence of oxygen-containing functional groups disrupting the  $\text{sp}^2$  carbon network [19]. Accordingly, the DGO-NW sample shows reduced but still relatively high resistivity values ( $1.08 \times 10^8\text{ k}\Omega$  surface resistivity and  $8.12 \times 10^6\text{ k}\Omega\text{cm}$  volume resistivity). A significant decrease in both surface and volume resistivity is observed after the reduction process. The D10RGO-NW and D20RGO-NW samples exhibit dramatically improved electrical conductivity, with the lowest resistivity values obtained for D20RGO-NW ( $3.93 \times 10^3\text{ k}\Omega$  surface resistivity and  $5.10 \times 10^2\text{ k}\Omega\text{cm}$  volume resistivity). This improvement can be attributed to the restoration of the conjugated  $\text{sp}^2$  carbon network during the reduction of GO, which enhances electron transport pathways within the coating layer.

### 3.4 Sound Absorption Coefficient

Figure 3(a) shows the sound absorption coefficient (SAC) of the nonwoven fabric samples, while Figure 3(b) presents their thickness values. Each measurement was conducted three times, and the average values were used for analysis. When Figures 3(a) and (b) are evaluated together, it is evident that the sound absorption performance of polyester needle-punched nonwoven fabrics is strongly influenced by both surface modification and sample thickness.

**Table 2.** Electrical resistance of samples.

|           | Electrical surface resistivity (k $\Omega$ ) | Standard Deviation | Electrical volume resistivity (k $\Omega\text{cm}$ ) | Standard Deviation |
|-----------|----------------------------------------------|--------------------|------------------------------------------------------|--------------------|
| NW        | 4.52E+09                                     | 1.96E+08           | 1.07E+09                                             | 1.27E+08           |
| DGO-NW    | 1.09E+08                                     | 5.77E+07           | 8.12E+06                                             | 3.14E+05           |
| D10RGO-NW | 4.24E+03                                     | 2.86E+02           | 5.00E+02                                             | 2.78E+01           |
| D20RGO-NW | 3.39E+03                                     | 4.24E+02           | 5.10E+02                                             | 4.44E+01           |

Compared to the NW sample, DGO-NW, D10RGO-NW, and D20RGO-NW exhibit a noticeable improvement in sound absorption coefficients, particularly in the middle and high frequency regions



( $\approx 2000$ – $6500$  Hz). This enhancement is attributed to increased surface roughness, the formation of micro/mesoporous structures, and higher internal friction losses induced by the coating and reduction processes. Although reduced graphene oxide (RGO) tends to form a more conductive and relatively compact network, the heterogeneous nature of the biomass-based reducing agent (tomato peel extract) likely results in a non-uniform coating morphology. This structure enhances the viscous dissipation of incident sound waves. The frequency-dependent behavior shows that all samples have limited sound absorption in the low-frequency region ( $<1500$  Hz), while the absorption coefficient gradually increases with increasing frequency. This trend is typical for porous fibrous materials and is associated with increased airflow resistance and enhanced frictional interactions between fibers at higher frequencies. In terms of thickness, the DGO-NW sample exhibits the highest thickness (approximately 1.08 mm), whereas the reduced samples show a slight decrease in thickness. This reduction may be due to partial densification of the fibrous structure or rearrangement of the coating layer during the reduction process. Although increased thickness is generally associated with improved sound absorption, particularly at low frequencies, the present results clearly indicate that thickness alone is not the determining factor. Despite having the highest thickness, DGO-NW does not exhibit the best acoustic performance, whereas D10RGO-NW, with a relatively lower thickness, achieves superior sound absorption.

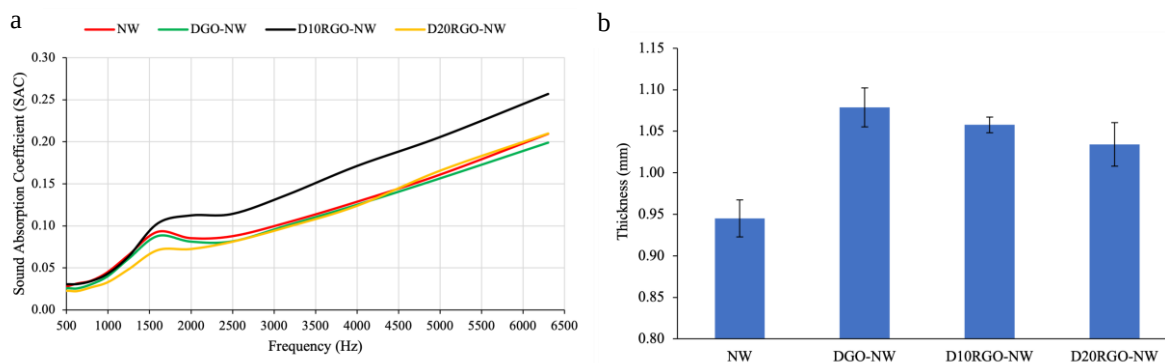


**Figure 3.** Sound absorption coefficient (a) and thickness (b) of samples.

#### 4. CONCLUSION

In this study, polyester needle-punched nonwoven fabrics were successfully modified via graphene oxide (GO) dip-coating followed by an eco-friendly reduction using tomato peel extract. SEM and FTIR analyses confirmed the successful deposition of GO and its partial reduction to RGO, accompanied by noticeable changes in surface morphology and chemical structure. Electrical measurements showed a significant decrease in both surface and volume resistivity after reduction, with the D20RGO-NW sample exhibiting the highest conductivity due to the restoration of the  $sp^2$  carbon network. Acoustic results revealed that all modified samples exhibited improved sound absorption, particularly in the middle and high frequency regions. Although DGO-NW had the highest thickness, it did not provide the best performance, indicating that thickness alone is not the dominant factor. Instead, microstructural features such as surface roughness, pore structure, and airflow resistivity play a more critical role.

Overall, tomato peel extract proved to be an effective and sustainable reducing agent, enhancing both the electrical and acoustic performance of nonwoven fabrics, making them promising for multifunctional technical textile applications.

#### ACKNOWLEDGMENT

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# HYBRID COMPOSITE DESIGN FOR SUSTAINABLE AUTOMOTIVE INTERIORS: EFFECTS OF NATURAL FIBER FABRIC POSITIONING IN BIDIRECTIONAL GLASS FIBER REINFORCED COMPOSITE STRUCTURES

Alhayat Getu Temesgen<sup>1,2\*</sup>, Jörg Kaufmann<sup>1</sup>, Holger Cebulla<sup>1</sup>

<sup>1</sup> Chemnitz University of Technology, Chemnitz, Germany

<sup>2</sup> Wollo University, Kombolcha Institute of Technology, Kombolcha, Ethiopia

\*corresponding author: alhayat@kiot.edu.et

## ABSTRACT

The integration of natural fibers into synthetic fiber composites has emerged as a promising strategy for developing sustainable materials for the automotive sector. This study examines the effects of natural fiber fabric placement in bidirectional glass fiber reinforced composites, with a focus on interior automotive component applications. Using bidirectional ( $\pm 45^\circ$ ) glass fibers and flax fabric, hybrid laminates were fabricated by a bio-based Polar Bear matrix and consolidated using a Meccatronica press system to ensure constant processing standards. For this study, three different flax fabric arrangements were examined: interleaving glass fiber layers, placing flax fabrics at the core of the laminate, and placing them at the outer layers. Physical characterization tests were performed in addition to mechanical parameters, including density, thickness swelling, void content, and moisture content. The test results revealed that the Flax-Glass hybrid composite showed a tensile modulus of 13.467 GPa, a tensile strength of 171 MPa, and a strain at break of 1.8%, with a cradle-to-gate carbon footprint of 3.70 kg CO<sub>2</sub>e/kg composite ( $\approx 0.30$  kg CO<sub>2</sub>e per GPa of modulus). These tests showed that placing flax fabrics in the core increased the composite structure's tensile strength and improved its ability to absorb energy. In contrast, interleaved arrangements performed well and maintained up to 30–40 % of the glass fiber composite's tensile performance while lowering their material density and environmental impact. On the other hand, the outer-layer flax fabrics arrangement increased eco-efficiency, it decreased surface durability and weight. These bio-resin-based hybrid composites have the potential to be practical materials for non-load-bearing and semi- structural applications where eco-efficiency and performance must be taken into account together. In general, the results show that strategic hybridization of natural fibers with synthetic fibers can optimize both mechanical performance and sustainability in automotive interiors.

**Keywords:** *Eco-efficiency, Bio-based resin, Layer positioning strategy, Mechanical performance, Sustainable materials*

## 1. INTRODUCTION

Natural fibers have recently supplanted synthetic fibers as reinforcements in polymer matrices due to their superior energy-dissipating properties. Significant advancements in green technology have already been made this century, particularly in materials science, where high-performance materials derived from natural resources have advanced for a range of structural, manufacturing, biomedical, aerospace, and automotive applications [1,2]. Researchers and manufacturers are becoming increasingly interested in natural fibers because of their biodegradability and comparable mechanical qualities [3, 4]. The advantages of natural fibers as reinforcement in composites include their high stiffness, affordability, low density, and ecological responsiveness. Future advancements in composite materials are highly promising, especially natural fiber reinforced composites [3,4]. Nowadays, glass fibers make up about 95% of all fiber-reinforced polymer composites, making them the most common type of polymer composite [5]. However, a negative carbon footprint has been caused by the high energy consumption of the production of glass and carbon fibers, as shown by numerous studies [6]. It can solve the problems caused by plastic waste and work toward a more

environmentally friendly future by refocusing attention on sustainable alternatives, such as hybrid composites with natural fibers [6]. In a hybrid composite, multiple fibers are combined in a single matrix to benefit from each fiber's unique properties. Because hybrid composites can meet the needs of a variety of industries, including aerospace, space, and biomedical applications, they have the potential to replace traditional materials [5, 6]. Because of sustainable development and environmental concerns, the use of natural fiber is steadily increasing these days [7, 8]. Hybridization offers substantial improvement in the properties of composites, which has attracted the attention of researchers for structural applications. In general, a significant weight percentage of synthetic fibers such as glass, carbon, etc., are hybridized to enhance the inherent properties of natural fiber composites for the intended applications as shown in Table 1 [9, 10].

**Table 1.** Mechanical Characteristics of the Hybrid Biocomposite made of Polymers Reinforced with Natural fibers [11-13].

| Type of Composites            | Elongation at Break (%) | Tensile Strength (MPa) | Flexural Strength (MPa) | Reference |
|-------------------------------|-------------------------|------------------------|-------------------------|-----------|
| Sisal/cotton/polyester        | 12.31                   | 65 ± 5                 | 270 ± 4                 | [11]      |
| Jute/hemp/flax/epoxy          | 5.8 ± 2.2               | 60 ± 3                 | 66 ± 4                  | [12]      |
| Palm/flax/thermoplasticstarch | 5.25                    | 31                     | 73.6                    | [13]      |
| Flax/jute/polypropylene       | 2.90 ± 0.18             | 39.48 ± 1.61           | 8.79 ± 1.73             | [14]      |
| Hemp/sisal/epoxy              | 3.2 6 ± 0.41            | 31.76 ± 0.88           | 44.47 ± 2               | [15]      |

There has been extensive work done on the mechanical characterization of the current material, according to the literature that is currently available on various aspects of developing glass fiber-epoxy composite materials. Nevertheless, there aren't many studies that examine flexural and tensile strength in epoxy composites by adjusting the positions of flax and glass fiber fabrics. Effective integration depends on the interaction between the various fiber types and the resin; successful hybridization results in improved interlocking and overall mechanical performance. While placing natural fibers at the tensile side or away from it can enhance flexural properties by influencing crack propagation, successful hybridization improves the mechanical properties of bidirectional glass fiber composites [16-20]. Fiber orientation, fiber to matrix ratio, physical bond between fiber and matrix, and other factors can all impact the composites' strength. According to Ellakwa et.al.,2001 studies, bidirectional reinforcement, as opposed to unidirectional or random Fiber orientations, typically results in higher tensile strength and resistance to impact, bending, and cracking [16-20]. Also, Bidirectional fibers are generally stronger than random or unidirectional fiber reinforcement in every direction. It is also more resilient to impact loads, bending, and cracking. Combining hemp and PALF cellulose fibres with epoxy greatly increased the mechanical properties such as tensile, flexural, impact strength, and hardness. Because fibber hybridization improves the fiber's interlocking with the matrix, it results in better mechanical qualities [16-20].

The objective of this research work is to replace petrochemical fabric reinforcing materials with natural fiber fabrics and to observe the effects of natural Fiber fabric positioning in bidirectional glass fiber reinforced composite structures. The use of natural fibres in place of glass fabrics, or to reduce the percentage of petrochemical-based fibers in hybrid composites, is explored without significantly compromising the mechanical properties. Flax fabric is selected as the natural fiber reinforcement because the mechanical properties of flax are among the best compared to other natural fibbers. By reducing the percentage of synthetic fabrics (i.e., glass fibers) and incorporating layers of flax fabrics into the composite structure, sustainable automotive interior components can be developed. This hybrid composite design is expected to be more biodegradable than pure glass fiber composites, while maintaining lightweight characteristics and adequate mechanical performance.

## 2. EXPERIMENTAL STUDY

### 2.1 Materials

**Matrix:** The properties of Polar Bear (bio-based) Epoxy resin, including its biodegradability, good stiffness, dimensional stability, corrosion and chemical resistance, and good thermal properties, make it a popular polymer matrix for advanced composites.

**Reinforcements:** Bidirectional glass fibers ( $\pm 45^\circ$  Glass Fiber Fabric) and flax fiber fabrics were selected for this study because of their high stiffness and strength. In the Polar Bear matrix composite, the most prevalent reinforcing fibers are flax fabric and glass fibers.

## 2.2. Methodology

### 2.2.1. Composite Design and Lamination

Two laminate configurations of glass- and flax-fabric-reinforced composites were fabricated: Type A, in which flax fiber fabrics were positioned in the core layers, and Type B, in which flax fiber fabrics were positioned in the outer layers, as shown in Figure 1a and 1b, respectively.



**Figure. 1.** Hybrid composite: a) Flax fiber fabrics positioned in the core layers, b) Flax fiber fabrics were positioned in the outer layers

### 2.2.2. Hybrid Composite Fabrication

Using bidirectional ( $\pm 45^\circ$ ) glass fibers and flax fabric, hybrid laminates were fabricated by Hand lay-up with bio-based Polar Bear matrix and consolidated using a Meccatronica press system to ensure constant processing standards. Laminates were cured at a temperature of  $85^\circ\text{C}$  for 15 minutes under controlled temperature and pressure conditions as shown in Figure 1.

### 2.2.3. Characterization of Hybrid Composite

**Physical and Mechanical testing:** Moisture content, thickness swelling, Tensile strength (ASTM standards).

**Morphological analysis:** High resolution optical microscopy used to evaluate fiber–matrix adhesion and position of reinforcing materials.

## 3. RESULTS

### 3.1. Density and Void formation

The densities and volume fractions of all hybrid composites were found to be comparable. Moreover, the press lamination process proved to be a reliable method for manufacturing hybrid composites within the specified tolerances. The fiber volume fraction and density of the fabricated composite panels were evaluated to ensure quality consistency across specimens prior to further testing. It was also observed that placing the flax fiber fabrics in the outer layers (Type B) of the hybrid layup reduced the likelihood of void formation or porosity while simultaneously enhancing stiffness. In contrast, positioning the flax fibers in the core layers (Type A) resulted in relatively higher void content, accompanied by reductions in weight and density due to moisture retention between the two glass fiber layers. Although void content was not quantified individually for each layup configuration, optical microscopy of two representative samples (Figure 2) revealed very low void content in the outer-layer configuration (Type B).

### 3.2. Morphological Observations

The morphological study of flax fabric layer placement in hybrid composites provides valuable insights into how layer sequencing influences microstructural characteristics such as void content, fiber waviness, porosity distribution, and resin-rich regions. Internal variations were characterized using high-resolution optical microscopy and microtomography. Positioning the flax layers in the outer regions of the laminate (Type B) markedly reduced void formation and porosity, producing a more uniform microstructure and improved stiffness. In contrast, placing the flax fibers in the core layers (Type A) resulted in higher void content and reduced density due to moisture retention between adjacent glass fiber layers. Although void content was not quantified for each configuration, optical microscopy of two representative specimens (Figure 2) confirmed very low void levels in the outer-layer arrangement. These observations underscore the critical influence of fabric placement on defect formation, microstructural integrity, and the mechanical performance of flax–glass hybrid composites, reinforcing its importance as a key design parameter for optimizing structural efficiency.



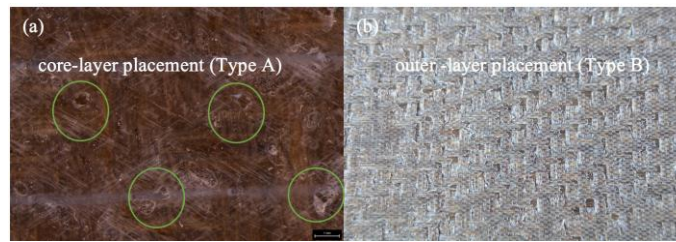


**Figure 2.** Morphological Observation of Hybrid composite due to natural fiber layer placement: a) core-layer placement (Type A), b) outer-layer placement (Type B)

### 3.3. Mechanical Properties Characterization of Hybrid Composite

Based on the test protocol following DIN EN ISO 527-4 standard, the FGFG (Glass Fiber/Flax Fiber) hybrid composite was tested on December 5, 2023, under controlled conditions of 23°C and 46% relative humidity using flat specimens Type 3. The average results from five samples showed a tensile strength of 171 MPa, tensile modulus of 13,467 MPa, and strain at maximum load of 1.8%, demonstrating excellent consistency with a low coefficient of variation of only 2.43%. Core-layer placement of flax fiber fabrics (Type A) demonstrated superior mechanical performance with the highest tensile strength of 175 MPa and tensile modulus of 14,104 MPa at 1.8% strain. Outer-layer placement of natural fibers (Type B) showed slightly lower performance with an average tensile strength of approximately 172 MPa and average tensile modulus of around 13,219 MPa.

Core-layer placement of flax fiber fabrics (Type A) provides approximately 3% higher tensile strength and 7% higher tensile modulus compared to outer-layer placement of natural fibers (Type B), confirming better load transfer efficiency when glass fibers are positioned in the outer layers. These test results show significantly higher tensile strength (171-175 MPa) compared to the reference value of 75.60 MPa, representing more than 125% improvement. This substantial difference suggests potential variations in fiber volume fractions, manufacturing process improvements, or enhanced fiber-matrix adhesion in the tested specimens. The stress-strain curve demonstrates linear elastic behavior up to approximately 1.5% strain, indicating good interfacial bonding between layers and predictable mechanical behavior.

The findings confirm that core-layer placement of flax fiber fabrics (Type A) is the superior configuration for applications requiring maximum strength while maintaining weight reduction benefits as illustrated in Table 2 and Figure 3. Outer-layer placement of natural fibers (Type B) resulted in reduced tensile strength but maintained acceptable performance levels for less demanding applications. The high tensile properties achieved make this hybrid composite suitable for lightweight structural components beyond just sustainable automotive interiors. The excellent repeatability across all specimens demonstrates reliable manufacturing quality and consistent material properties. Further investigation is recommended to understand the mechanisms behind the significant performance improvement over reference values. Overall, the hybridization strategy with appropriate layer configuration successfully balances mechanical performance with the environmental benefits of natural fiber incorporation. These findings suggest that while flax incorporation offers weight advantages, excessive core-layer placement compromises mechanical performance, limiting applicability in lightweight structural components such as sustainable automotive interiors.

**Table 2.** Tensile Strength of Hybrid Composite via Flax Fabric Layers' Placement

| Type of layer placement                                               | Tensile strength (MPa) | Modulus (GPa) | Elongation (%) |
|-----------------------------------------------------------------------|------------------------|---------------|----------------|
| Core-layer placement of flax fiber fabrics Hybrid Composite (Type A)  | 175                    | 14.10         | 1.8            |
| Outer-layer placement of flax fiber fabrics Hybrid Composite (Type B) | 172                    | 13.22         | 1.9            |

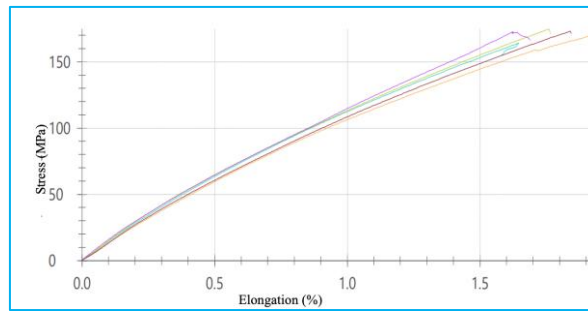


**Figure 3.** Tensile Strength Analysis of Hybrid Composite: Glass Fiber via Natural Fiber Layers' Placement

### 3.4. Environmental and Sustainability Benefits of natural fibers Hybrid composite

Positioning of flax fiber fabric–reinforced hybrid composite structures made of biodegradable, renewable materials from sustainable sources offers significant environmental benefits. The test results revealed that the flax–glass hybrid composite showed an average tensile modulus of 13.467 GPa, a tensile strength of 171 MPa, and a strain at break of 1.8%, with a cradle-to-gate carbon footprint of 3.70 kg CO<sub>2</sub>e/kg composite ( $\approx 0.30$  kg CO<sub>2</sub>e per GPa of modulus). Composites reinforced with natural fibers such as sisal, flax, and jute can be produced in ways that reduce carbon emissions and the need for non-renewable resources [22]. Natural fiber–reinforced composites are replacing traditional foldable materials in the automotive industry because they are lightweight, affordable, and environmentally friendly [23]. One of the most significant advantages of replacing automotive components made of metal and synthetic plastics with NFCs is that vehicles equipped with NFCs require less energy to operate, meaning they are not subject to high CO<sub>2</sub> emission rates [24]. Natural fibers like flax, hemp, and jute are used to reinforce biocomposites for dashboards, doors, panels, and car interiors because of their high strength-to-density ratio and durability. These materials also help reduce vibrations and noise, making cars more comfortable [25]. Hybrid composites are lighter than 100% bidirectional glass fiber–reinforced composite structures used for automotive interiors, while also providing a natural aesthetic. This weight reduction improves fuel consumption and reduces greenhouse gas emissions. Moreover, flax fiber fabric–reinforced hybrid composites can be produced with comparatively lower energy consumption, making them suitable for lightweight structural applications. Furthermore, the increased use of agricultural waste fibers and biodegradable natural fiber–reinforced composites in automotive manufacturing reflects the industry's growing emphasis on the circular economy.

## 4. CONCLUSION

This research has methodically investigated the impact of flax fiber fabric positioning on the mechanical properties, microstructure, and environmental performance of flax-glass hybrid composites made through press lamination. The results from the experiments indicate that the configuration of the layers is a significant factor in finding the right mix between mechanical properties, reduction in weight, and maintenance of the structure. Flax fiber fabrics in the core-layer position (Type A) demonstrated the highest tensile strength of 175 MPa and tensile modulus of 14.104 GPa at 1.8% strain which is almost 3% and 7% more than the tensile strength and tensile modulus of the outer-layer placement (Type B), respectively. The reason for this performance is that the glass fibers in the outer layer have the best adhesive bond with the epoxy matrix and thus, the load is transferred most efficiently. On the other hand, placing the natural fibers in the outer layer (Type B) resulted in somewhat lower tensile strength of 172 MPa and modulus of 13.219 GPa, however, it did offer the advantage of reduced voids and porosity in the microstructure. The high-resolution optical microscopy image analysis revealed that Type B configurations led to more consistent microstructures and increased stiffness properties while Type A exhibited a relatively larger void content owing to moisture being trapped in between the glass fiber layers. The press lamination process was very reliable, showing great consistency with a variation of only 2.43% for tensile strength across all specimens. The major improvement in tensile properties seen (171-175 MPa) when compared to the previously reported value (75.60 MPa) indicates that the fiber volume fraction has been optimized.

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## IMPROVING THE COMFORT PROPERTIES OF DENIM GARMENTS WITH SILICONE-BASED SOFTENERS

<sup>1</sup>Onur Balcı, <sup>1</sup>Ebru Çalışkan, <sup>2</sup>Ayrim İbiş, <sup>3</sup>Esra Tabaş Asiltürk

<sup>1</sup>Kahramanmaraş Sutcu Imam University, Textile Engineering Department, Kahramanmaraş, Turkey

<sup>2</sup>Latro Kimya, R&D Center, İstanbul, Turkey

<sup>3</sup>Baykan Denim, R&D Center, Malatya, Turkey

\* [clskn.ebruu@gmail.com](mailto:clskn.ebruu@gmail.com)

### ABSTRACT

Denim garments are preferred products not only for their durability performance but also for their aesthetic and comfort properties. Considering that denim garments are generally produced from thick 100% cotton yarns, it is inevitable to perform some additional processes, especially to improve comfort properties. For this purpose, softening is applied after base and effect washes (mechanical-chemical). Denim becomes wearable after this softening process. In this study, changes in the comfort performance of denim garments were measured by applying silicone-based softeners developed by Latro Kimya R&D Center during the washing step at Baykan Denim R&D Center. A non-silicone-based cationic softener was used as a reference. After application, samples were subjected to MMT (Moisture Management Test), thermal comfort testing with Alambeta, air permeability, and water vapor permeability tests. In addition to testing comfort properties, abrasion resistance and pilling measurements were conducted to detect possible changes on the surface. Thus, surface appearance and comfort tests were evaluated in parallel. Furthermore, the physical performance and handle (touch) of the samples were determined, and a comfort-surface-performance-handle evaluation was carried out to establish optimum results.

**Keywords:** *Comfort, washing, finishing, silicone, softness, denim, cotton*

### 1. INTRODUCTION

Denim fabric is a cotton twill fabric widely used in the textile industry due to its durability and unique surface characteristics. The result of dyeing the warp threads primarily with indigo while leaving the weft threads undyed creates blue tones on the front and lighter tones on the back. Denim fabrics have been an important garment raw material for people of different purposes and income groups for decades. This is fundamentally based on its naturalness, durability, and unique effect and color harmony. For this reason, effect processes applied to denim garments have come to the fore, and many academic studies have been implemented in this field. Most of these have focused on developing processes that are environmentally friendly and do not harm product performance [3-4]. However, in the last 10 years, expectations for denim garments have shifted from a focus on durability and appearance to a focus on comfort. This is because denim has become a garment worn regardless of summer or winter, almost never produced without elastane, highly flexible, non-restrictive of movement, and appealing to a wide audience regardless of the place of use. Denim, known as a thick and rigid fabric, has reached an expectation of being thin, flexible, and super comfortable. This has become a significant expectation, especially in the global market. Consequently, the word "comfort" is now associated with denim.

Textile comfort is defined as the condition in which the wearer remains free from physical, physiological, and psychological discomfort during garment use, while potentially experiencing a sense of well-being. Technically, this is a multidimensional performance criterion resulting from the interaction of the fabric with the human body. This criterion is evaluated in five sub-areas: thermophysiological comfort, tactile comfort, ergonomic comfort, perceptual comfort, and sensory comfort. Various review and experimental studies for textile fabrics can be found in this field [5-6-7]. Denim garments have also begun to be studied



as a fabric type in this sense. Studies focused particularly on fiber, fabric construction, and washing are encountered [8-9]. This study involves an experimental application focused on washing. A developed silicone softener was applied to a denim fabric containing elastane during washing, and its effect on comfort was examined. This was evaluated by comparing it with a commonly used cationic-based softener.

## 2. EXPERIMENTAL STUDY

### 2.1 Material

In the study, garments designed with two types of denim fabrics were used. The first is 100% cotton (Fabric 1-F1) and the other is 98% cotton-2% elastane (Fabric 2-F2). Both samples are denim fabrics woven according to a 3/1 Z twill weave report with slasher indigo-dyed warp yarns. Additionally, to measure the effect of home laundering, a "3 repetitions \* 60°C" wash was applied after softening. A softener specifically developed at the Latro Kimya R&D Center was used in the project. It has an (ab)n structure, and although it has amine content, it does not cause yellowing because the amine is not at the end of the polymer. It can be mixed directly with water and applied without the need for an emulsifier. This will be referred to as Chemical 1 (C1). A widely known cationic-based softener in the market was chosen as a reference, which will be called Chemical 2 (C2).

### 2.2 Method

Applications were carried out in drum washing machines located at the Baykan Denim R&D Center. The following preparatory washing processes were applied to the garment until the finishing wash stage. These were applied in four sub-classes: pre-treatment, base, effecting, and softening. A total of 6 steps were executed. These 6 steps are common processes for both the reference softening and the new softening process. During these 6 steps, a softening finishing process with two chemicals was applied to the two selected types of denim fabrics. In addition, untreated denim fabric, which can be called raw, was included in the study under the name Reference Fabric (RF). Table 1 shows the experiment and sample fabric numbers. Washing process details are provided in Table 1. The reference application was named Process 1 (P1), and the new process was named Process 2 (P2).

**Table 1.** Process plan and details

| The step of the Process | Name of The Process | PROCESS 1 (P1)                                                     | PROCESS 2 (P2)                                                    |
|-------------------------|---------------------|--------------------------------------------------------------------|-------------------------------------------------------------------|
| S1                      | Pre-wash            | 5 min at 55°C - 500 ml dispersant + Rinse                          | 5 min at 55°C - 250 ml C1 + Rins                                  |
| S2                      | Stone wash          | 30 min - 75 kg pumice + 150g cellulase + 500 ml dispersant + Rinse | 30 min - 75 kg pumice + 150g cellulase + 250 ml C1 + Rinse        |
| S3                      | Enzyme              | 5 min at 55°C - 150 ml dispersant + Rinse + Drying 30 min at 75°C  | 5 min at 55°C - 150 ml dispersant + Rinse + Drying 30 min at 75°C |
| S4                      | Local Spray         | Potassium permanganate                                             | Potassium permanganate                                            |
| S5                      | Neutralization      | 5 min at 50°C 300g sulfite + Rinse                                 | 5 min at 50°C 300g sulfite + Rinse                                |
| S6                      | Softening           | Softening wash with 2 liters of C2                                 | Softening wash with 1 liter of C2                                 |

In Step 1, 250 ml of C1 chemical was used instead of 500 ml of dispersant. This was followed by a rinsing process at room temperature. In Step 2, the process was applied accompanied by 250 ml of C1 softener mixture instead of 500 ml of dispersant. C1 was also used instead of dispersant in this step. In Step 6, softening was applied with 1 liter of C2 reference softener. The amount of softener was reduced by 50% compared to the reference. While a total of 2000 ml of cationic softener (C2) was used in P1, 1000 ml of C2 and 500 ml of C1 were used in P2. The main reason for using a dispersant in the recipes is to eliminate the back-staining problem. The noteworthy point in P2 is that C1 softener takes the place of dispersants. Therefore, C1 softener is expected to contribute to both softening and comfort and to prevent back-staining. The experimental plan is given in Table 2.

**Table 2.** Experimental plan

| Type of Denim Fabric | Specimen No | TYPE OF PROCESS | PRESENCE OF HOME LAUNDERING |
|----------------------|-------------|-----------------|-----------------------------|
| F1                   | N1          | - (RF)          | -                           |
| F1                   | N2          | P1              | -                           |
| F1                   | N3          | P2              | -                           |
| F2                   | N4          | - (RF)          | -                           |
| F2                   | N5          | P1              | -                           |
| F2                   | N6          | P2              | -                           |
| F1                   | N7          | P1              | 3 repetitions               |
| F1                   | N8          | P2              | 3 repetitions               |
| F2                   | N9          | P1              | 3 repetitions               |
| F2                   | N10         | P2              | 3 repetitions               |

According to Table 2, 10 samples were obtained when the trials were completed. The following tests were applied to these 10 samples:

- 1.Elasticity (%) according to ASTM D3107 and growth (%) tests according to ASTM D2594 to determine ergonomic comfort.
- 2.Circular bending strength (kgf) according to ASTM D4032, pilling according to ISO 12945-2, abrasion resistance according to ISO 12947-2-3-4, and bending stiffness (g.cm) tests according to ASTM D1388 to determine tactile comfort.
- 3.Air permeability (L/m<sup>2</sup>/sec) according to EN ISO 9237, thermal resistance (m<sup>2</sup>.K/W) and water vapor resistance (m<sup>2</sup>.Pa/W) according to ISO 11092, and Moisture Management Test (MMT) according to AATCC 195 to determine thermophysiological comfort.
- 4.Alambeta test to determine sensory comfort.
- 5.Analysis of CIELab\* values using a spectrophotometer to detect back-staining.

### 3. RESULTS

In the experimental studies, C1 chemical replaced the dispersant in the washes. Therefore, the first issue to be examined is the change in the degree of back-staining. Back-staining is a parameter monitored for aesthetic concerns, especially in denim garments. Back-staining occurs when the colorless weft yarn of the denim fabric is contaminated with the indigo dye in the warp, and it is a source of poor quality[10]. It is usually checked visually using a qualitative control method, but it can also be analyzed by measuring color with a spectrophotometer. For this purpose, the L\*, a\*, b\* values of the back side of 3 samples (N1-N2-N3) were measured and compared. When Figure 1 is examined, it is seen that back-staining is lower in sample N3, which includes C1 processes, compared to N2 samples. The biggest back-staining problem is in N1 samples where there is no washing at all. The L\* value was measured as 52.12 in sample N3 and 50.21 in sample N2. The color of the back side is lighter in sample N3. Looking at the b\* value showing yellow-blueness, it was determined that the b\* value of N3 is larger, meaning it was measured as less blue. This indicates that the back side of sample N3 retains less indigo dye. The back side of N3 is cleaner than N2. The use of C1 silicone in washing reduced back-staining. It is thought that the silicone-based material keeps the dye originating from oil in the washing solution.

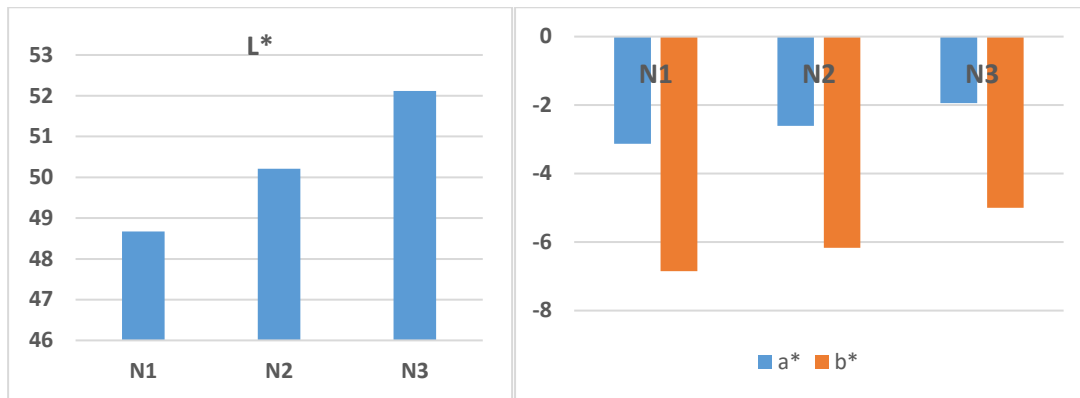


**Figure 1.** Back side L\*, a\*, b\* values and back-staining performance

After proving the success of P2 over P1 in terms of back-staining, the analysis of comfort tests began. First, elasticity (%) and permanent elongation (%) performance were compared to determine ergonomic comfort. These tests were applied to the F2 sample containing elastane, and the results for N4-N5-N6 are given in Figure 2. Elasticity is an important parameter for ergonomic comfort. High elasticity and low growth (bagging) are the expected performance criteria. After washing trials, elasticity increased from 65% to 75% for N5 and to 70% for N6. However, the growth change between N4 and N5 indicates a negative situation for the dimensional stability and wear performance of the garment. Growth worsened by increasing from 3% to 7.5%. However, in the N6 trial with C1 in the recipe, this value decreased to 2.5%. This indicates an improvement in the growth performance of N6 due to C1. Silicone in the structure of C1 succeeded in improving elasticity without harming the growth performance.

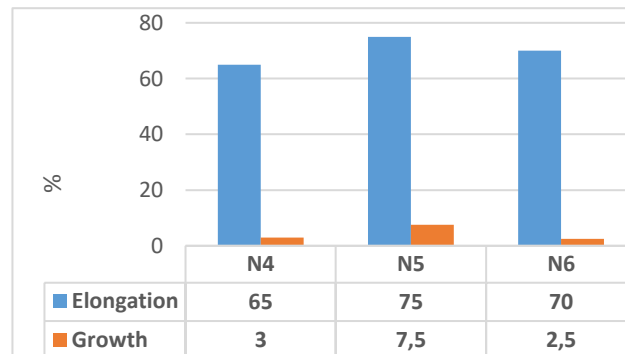


**Figure 2.** Determination of elasticity and growth performance for F2

Another important comfort performance is tactile comfort. Circular bending strength was measured first to determine this. Samples N4-N5-N6 were tested for this. The stiffness value of the untreated raw fabric was 1.46 kgf. This improved to 0.63 kgf with P1 washing where only C2 was used. In P2 applications containing both C1 and C2, this value decreased to 0.52 kgf. This shows that C1 improves the drape of the fabric and reduces its stiffness. Table 3 shows the pilling and abrasion resistance performances measured as a result of the trials. When Table 3 is examined, it can be said that there is a significant difference between F1 and F2, caused by the use of elastane. After abrasion, no difference was detected between abrasion grades. However, in terms of breakage and % mass loss, the results in P2 processes applied with C1 were lower compared to conventional applications.

**Table 3.** Change in surface properties

| Specimen No | TYPE OF PROCESS | PILLING GRADE (2000 CYCLE) | ABRASION RESISTANCE (ISO 12947-2) (CYCLE) | ABRASION RESISTANCE (ISO 12947-3) (CYCLE/%) | ABRASION RESISTANCE (ISO 12947-4) (GRADE) |
|-------------|-----------------|----------------------------|-------------------------------------------|---------------------------------------------|-------------------------------------------|
| F1-N1       | - (RF)          | 4/5                        | >25.000                                   | 25.000 - %4.79                              | 2/3                                       |
| F1-N2       | P1              | 4                          | 16.000                                    | 16.000 - %18.85                             | 1/2                                       |
| F1-N3       | P2              | 4                          | 18.000                                    | 18.000 - %19.50                             | 1/2                                       |

|        |        |     |         |                 |     |
|--------|--------|-----|---------|-----------------|-----|
| F2-N4  | - (RF) | 3/4 | >25.000 | 25.000 - %2.54  | 1/2 |
| F2-N5  | P1     | 4   | 25.000  | 25.000 - %5.65  | 1/2 |
| F2-N6  | P2     | 4   | >25.000 | 25.000 - %8.39  | 1/2 |
| F1-N7  | P1     | 4   | 22.000  | 22.000 - %13.78 | 1/2 |
| F1-N8  | P2     | 4/5 | >25.000 | 25.000 - %16.77 | 1/2 |
| F2-N9  | P1     | 4   | >25.000 | 25.000 - %10.63 | 1/2 |
| F2-N10 | P2     | 4   | >25.000 | 25.000 - %8.59  | 1/2 |

Thermophysiological comfort and Alambeta test results are shown in Table 4.

**Table 4.** Thermophysiological comfort and Alambeta test results

| Specimen<br>No<br>(Table 2) | AIR<br>PERMEABIL<br>ITY (L/M2/SN) | THERMA<br>L<br>RESISTA<br>NCE<br>(M2.K/W) | WATER<br>VAPOR<br>RESISTAN<br>CE<br>(M2.PA/W) | MMT<br>(OMMC) | $\Lambda$<br>(W/m<br>.k) | b<br>W·s <sup>1/2</sup> /<br>m <sup>2</sup> ·K | R<br>m <sup>2</sup> K/<br>W | QM<br>W/m <sup>2</sup> |
|-----------------------------|-----------------------------------|-------------------------------------------|-----------------------------------------------|---------------|--------------------------|------------------------------------------------|-----------------------------|------------------------|
| F1-N1                       | 41.14                             | 0.0041                                    | 6.5                                           | 0.1633        | 44.9                     | 405.30                                         | 14.6                        | 551.30                 |
| F1-N2                       | 13.85                             | 0.0106                                    | 5.7                                           | 0.0006        | 52.63                    | 417.87                                         | 17.40                       | 503.97                 |
| F1-N3                       | 11.70                             | 0.0066                                    | 5.3                                           | 0.0126        | 53.00                    | 439.97                                         | 17.57                       | 521.53                 |
| F2-N4                       | 54.52                             | 0.0067                                    | 5.6                                           | NA            | 52.73                    | 441.97                                         | 17.40                       | 545.27                 |
| F2-N5                       | 16.48                             | 0.0112                                    | 6.4                                           | NA            | 56.37                    | 419.83                                         | 19.37                       | 489.93                 |
| F2-N6                       | 19.01                             | 0.0094                                    | 6.1                                           | NA            | 55.13                    | 419.73                                         | 20.30                       | 479.80                 |
| F1-N7                       | 13.82                             | 0.0139                                    | 6.1                                           | NA            | 53.13                    | 453.30                                         | 18.47                       | 554.10                 |
| F1-N8                       | 13.04                             | 0.0078                                    | 5.0                                           | 0.029         | 54.13                    | 468.20                                         | 16.57                       | 554.60                 |
| F2-N9                       | 17.79                             | 0.0075                                    | 6.8                                           | NA            | 55.80                    | 436.40                                         | 19.23                       | 519.90                 |
| F2-N10                      | 18.18                             | 0.0087                                    | 5.8                                           | NA            | 56.67                    | 444.9                                          | 19.27                       | 514.60                 |

When Table 4 is examined for F1 fabric, it was determined that both chemicals significantly reduced air permeability. The performance of N3 was lower than N2. It is expected that silicone-based chemicals form a film on the fiber surface and partially close the pores. Thermal resistance increases with chemical application. While C2 applications provide the highest increase, C1 remains at a medium level. The silicone film formed by C1 prevents heat transfer to some extent, but it does not have as strong an insulation effect as C2.

All processes reduce water vapor resistance, meaning it has improved. C1 application (N3) gave the lowest value, providing the best breathability. C1 application showed a positive effect. Raw fabric has the best moisture management. Chemicals caused a serious decline. C1 is better than C2; less degradation was detected. Silicone reduced liquid transfer by giving the surface a hydrophobic character. Chemical washes increased the initial contact coolness sensation of the fabric. C1 and C2 showed similar effects. Silicone increases the contact area by increasing surface smoothness, which raises the b value. Both chemicals increased the thermal resistance of the denim garment. C1 gave similar results to C2. P2 processes applied with C1 improve comfort in terms of "thermal sensation and vapor permeability," while weakening air permeability and liquid moisture management. It is thought that the silicone in the structure of C1 causes this. Similar results were obtained in F2. In line with classic expectations, the C1 silicone-based chemical reduces liquid moisture transfer by making the fabric surface hydrophobic, but it can provide a relative improvement in water vapor transfer, which is important for the microclimate. This situation shows that C1 does not completely ruin comfort; on the contrary, it can optimize it in terms of "dry sensation and contact comfort".

#### 4. CONCLUSION

In the study, the superiority of silicone oils over fatty acid condensation products was proven. Especially the improvement in back-staining is the most striking result. C1 worked as both a softener and a dispersant. Numerical handle evaluation showed that the improvement was around 50%. Thermal comfort was tested with Alambeta and sweating guarded hot plate devices. Improvement was detected in water vapor resistance in trials made with new recipes. This improvement reached up to 15-20%. When thermal resistance values were examined, it was determined that the resistance value decreased in the silicone-based sample, meaning

the heat capacity of the garment decreased. This can be seen as an advantage for this product, which is not expected to keep warm. No significant change was detected in air permeability values. When abrasion resistance values were examined, half-point improvements were detected compared to the reference application. In general, softening caused a negative effect on abrasion resistance. When MMT values were examined, the moisture transfer capabilities of all fabrics can generally be evaluated in the poor class. However, a slight improvement was detected in this value with silicone application. For example, the OMMC value, which was 0.0006, increased to 0.0126. No change due to softening was detected in pilling values.

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## INVESTIGATION OF RING SPINNING PERFORMANCE OF KAPOK/COTTON BLENDED WEAVING YARNS

Beyzagül Payam<sup>1,\*</sup>, Erkan EVRAN<sup>2</sup>,

<sup>1</sup>Ege University, Textile Engineering Bachelor's Degree, Gaziantep, Turkey

<sup>2</sup>Gaziantep University, Department of Product Development and Design Engineering, M.Sc., Gaziantep, Turkey

\* [beyzagul.kiraz@sanko.com.tr](mailto:beyzagul.kiraz@sanko.com.tr)

### ABSTRACT

The growing demand for sustainable textile products has increased the interest in biodegradable and bio-based fiber alternatives. Kapok fiber (*Ceiba pentandra*) is a renewable natural fiber characterized by its ultra-low density, hollow structure, hydrophobic behavior, and excellent thermal insulation properties. However, its short fiber length and low cohesion create significant challenges for conventional spinning processes. This study investigates the spinnability of kapok fiber blended with cotton for the development of sustainable weaving yarns.

Kapok fibers were subjected to pre-treatment processes to improve processability and reduce fiber fly during spinning. Ring yarns (Ne 8/1) were produced from a 70% cotton / 30% kapok blend at different twist levels. Spinning performance, yarn strength, and yarn irregularity were evaluated and compared with 100% cotton yarns.

The results showed that kapok fiber cannot be spun alone under conventional short-staple spinning conditions due to its low cohesion and strength. Increasing twist levels significantly improved yarn tenacity, while yarn irregularity exhibited limited change. Although 100% cotton yarns demonstrated higher mechanical performance, the incorporation of kapok provided notable advantages such as reduced yarn weight, increased bulkiness, enhanced thermal insulation, and improved hydrophobicity.

These findings indicate that kapok fiber is more suitable as a functional blending component rather than a standalone spinning material. Cotton/kapok blended yarns present promising potential for producing lightweight, comfortable, and environmentally sustainable weaving fabrics.

**Keywords:** *Kapok fiber, Sustainable textiles, Ring spinning, Weaving yarn, Bio-based fibers*

### 1.INTRODUCTION

In recent years, increasing environmental concerns and the demand for sustainable textile production have accelerated the development of bio-based and biodegradable fiber alternatives. Natural fibers have attracted significant attention due to their renewability, low environmental impact, and compatibility with sustainable production systems [1].

Kapok fiber (*Ceiba pentandra*) has emerged as a promising natural fiber due to its unique structural and functional properties. It is characterized by an ultra-low density, hollow tubular structure, hydrophobic behaviour, and excellent thermal insulation capacity [2,3]. These properties make kapok fiber particularly suitable for lightweight and functional textile applications.

Kapok fiber, recognized as one of the lightest natural fibers, exhibits a neutral, cotton-like structure, and is hypoallergenic, non-toxic, and resistant to degradation. It is traditionally employed as a filling material in pillows, bedding, and soft toys. Due to its exceptional buoyancy, kapok fiber is widely utilized in flotation devices, such as life jackets, and serves as an effective thermal and acoustic insulator. Despite being underutilized compared to cotton and other plant-based fibers, kapok is increasingly attracting scientific attention owing to its distinctive physicochemical and functional properties. [3].

However, despite these advantages, kapok fiber presents several limitations in conventional spinning systems. Its short fiber length, smooth surface morphology, low cohesion, and weak inter-fiber friction significantly reduce its spinnability in ring spinning processes. It has been reported that kapok fibers have short length, poor cohesion, and lack flexibility, making them difficult to spin separately [4,5]. As a result, kapok fiber cannot be efficiently processed using conventional short-staple spinning technologies.

To overcome these limitations, blending kapok fiber with other fibers, particularly cotton, has been widely investigated. Cotton fibers provide higher cohesion, better flexibility, and improved processability, enabling the production of more stable yarn structures [5,6]. Previous studies have demonstrated that kapok/cotton blended yarns can be successfully produced within certain blending ratios; however, increasing kapok content generally leads to a reduction in yarn strength due to the intrinsic structural limitations of kapok fibers [6,7].

On the other hand, the incorporation of kapok fiber into yarn structures offers several functional advantages, including reduced yarn weight, increased bulkiness, improved thermal insulation, and enhanced hydrophobic properties. These characteristics make kapok particularly attractive for comfort-oriented and sustainable textile applications [2,7].

However, despite the increasing interest in kapok fiber, there is still limited research focusing on its behaviour in conventional ring spinning systems, particularly in relation to process parameters such as twist level and their influence on yarn performance. In textile engineering, yarn quality is a key factor influencing both process efficiency and end-use performance. Yarn quality is typically evaluated through parameters such as unevenness, imperfections, hairiness, and tensile strength, which are affected by both raw material properties and spinning conditions [8].

Advanced testing systems such as AFIS and Uster are widely used to analyse fiber and yarn properties, enabling detailed evaluation of structural characteristics and quality parameters [9–11]. These advanced testing systems enable a detailed understanding of the relationship between fiber properties, spinning parameters, and yarn performance. In addition, yarn strength is strongly influenced by fiber properties and twist level, which plays a critical role in determining yarn performance [12].

Therefore, this study aims to investigate the spinnability of kapok/cotton blended yarns and to evaluate the effect of twist level on key yarn properties, including tensile strength and irregularity. In addition, this study aims to provide practical insights for the utilization of kapok fiber in sustainable textile applications.

## **2. EXPERIMENTAL STUDY**

Kapok fibers used in this study were subjected to pre-treatment processes in order to enhance their spinnability by increasing fiber cohesion and mitigating the adverse effects of their hollow structure and ultra-low density. These treatments aimed to improve processability during spinning. However, despite these modifications, several challenges were observed during processing, including fiber fly generation, dust formation, and difficulties in achieving homogeneous blending with cotton fibers due to the smooth surface morphology and low inter-fiber friction of kapok fibers.

In this study, yarns were produced from a blend consisting of 70% organic cotton and 30% kapok fiber. The blend ratio was determined based on preliminary trials to ensure processability and to maintain yarn integrity during spinning. A ring spinning system was employed to produce yarns with a count of Ne 8/1. The ring spinning machine used in the production process is shown in Figure 1. To investigate the effect of spinning parameters on yarn performance, three different twist coefficients ( $\alpha_c = 3.8, 4.0, \text{ and } 4.2$ ) were applied. Twist level was considered a critical parameter influencing fiber cohesion, yarn strength, and structural stability.

All yarns were produced under controlled production conditions. In order to evaluate the effect of kapok fiber incorporation, 100% cotton yarns were also produced under identical spinning conditions and at the same twist levels for comparison.

Yarn quality parameters were evaluated using standard textile testing methods. Yarn unevenness (U% and CV%), imperfections (thin places, thick places, and neps), and hairiness were measured using Uster Tester 6, while tensile strength was determined using Uster Tensojet 4. The testing equipment used in this study is presented in Figure 2. All tests were conducted under standard atmospheric conditions ( $20 \pm 2^\circ\text{C}$  temperature and  $65 \pm 2\%$  relative humidity). Each measurement was repeated multiple times, and the average values were used for analysis to ensure the reliability and reproducibility of the results.



**Figure 1.** Ring spinning machine used for yarn production



**Figure 2.** Testing equipment used for yarn characterization

### 3.RESULTS

#### 3.1 Effect of Twist Level on Yarn Properties

The test results of 70% cotton / 30% kapok blended yarns produced at different twist levels are presented in Table 1.

An increase in the twist coefficient resulted in a clear improvement in yarn strength (RKM). This behaviour can be attributed to enhanced fiber cohesion within the yarn structure at higher twist levels, which improves fiber integration and load transfer during tensile loading.

In contrast, yarn unevenness parameters (U% and CV%) did not exhibit a significant variation with increasing twist level. Similarly, the number of imperfections, including thin places, thick places, and neps, did not follow a consistent trend, indicating that twist level had a limited influence on these properties.

Hairiness values showed a decreasing tendency with increasing twist, suggesting that higher twist levels contribute to better fiber binding and reduced fiber protrusion from the yarn surface.

**Table 1.** Test result of 70 %cotton 30 % kapok yarn at different alpha( $\alpha$ ) levels.

| PROPERTY         | 3,8 $\alpha$ e | 4 $\alpha$ e | 4,2 $\alpha$ e |
|------------------|----------------|--------------|----------------|
| YARN COUNT       | 8              | 8            | 8              |
| U %              | 10.90          | 11.32        | 10.92          |
| U CV %           | 14.57          | 15.05        | 14.60          |
| THIN PLACES -50  | 0              | 0            | 0              |
| THICK PLACES +50 | 123            | 128          | 127            |
| NEPS (+200 %)    | 133            | 128          | 146            |
| HAIRINESS        | 13.97          | 13.34        | 12.35          |
| RKM (cN/TEX)     | 15.13          | 16.39        | 17.10          |

### 3.2 Comparison Between Kapok/Cotton and 100% Cotton Yarns

A comparison between kapok/cotton blended yarns and 100% cotton yarns at the same twist levels is presented in Figure 3.

The results indicate that 100% cotton yarns demonstrated superior performance in terms of unevenness, imperfections, and hairiness. In addition, tensile strength values of 100% cotton yarns were significantly higher than those of the blended yarns

These findings can be explained by the inherent structural limitations of kapok fiber, including its low cohesion, smooth surface morphology, and short fiber length, which reduce fiber-to-fiber friction and negatively affect yarn structure formation.

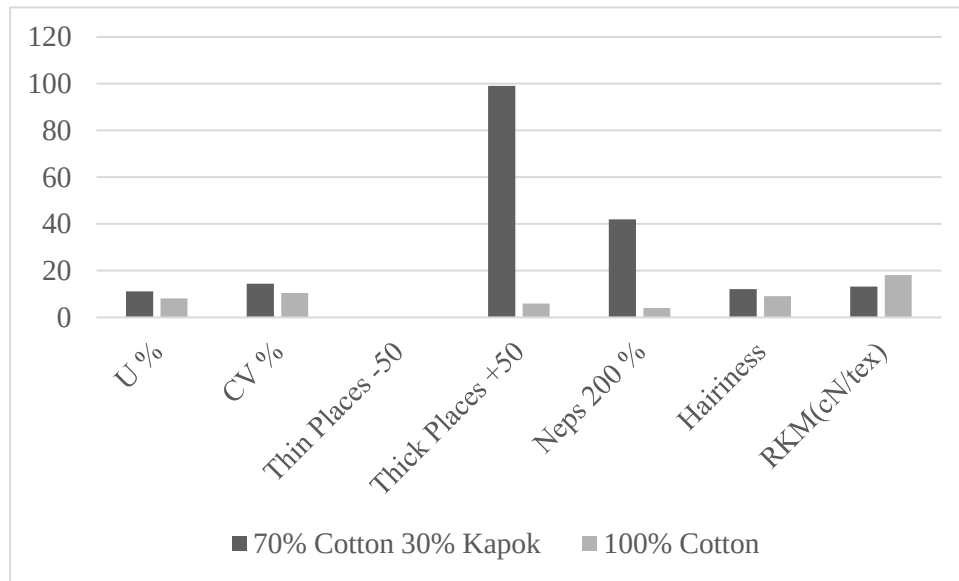


**Figure 3.** Comparison of yarn properties for 70 % Cotton 30 % kapok and 100% cotton yarns

### **3.3 Overall Evaluation of Spinning Performance**

The results clearly indicate that the inclusion of kapok fiber adversely affects yarn quality parameters, particularly tensile strength and structural regularity. However, the extent of this effect depends on the applied spinning parameters.

Although kapok fiber negatively influences mechanical performance, the results confirm that it can be incorporated into yarn structures within certain limits, particularly when appropriate twist levels are applied.

It is important to note that while mechanical properties are reduced, kapok fiber contributes to several functional advantages, such as reduced yarn weight, increased bulkiness, enhanced thermal insulation, and improved hydrophobicity. These characteristics make kapok fiber suitable for applications where comfort and functionality are prioritized over mechanical strength. The test results of the 70% cotton / 30% kapok blended yarns produced at different alpha twist levels are presented in Table 1. An increase in the twist coefficient led to a noticeable improvement in yarn strength (RKM), which can be attributed to enhanced fiber cohesion within the yarn structure at higher twist levels.

In contrast, yarn unevenness parameters (%U and CV%) did not exhibit a significant variation with increasing twist. Similarly, the number of imperfections (thin places, thick places, and neps) did not follow a consistent trend, indicating that twist level had a limited influence on these properties.

Hairiness values showed a slight decreasing tendency with increasing twist, suggesting that higher twist levels contribute to better fiber integration and reduced fiber protrusion from the yarn surface.

A comparison between the blended yarns and 100% cotton yarns at the same alpha level (Figure 3) revealed that 100% cotton yarns demonstrated superior performance in terms of unevenness, imperfections, and hairiness. In addition, the tensile strength values of 100% cotton yarns were significantly higher than those of the blended yarns.

These findings indicate that the inclusion of kapok fiber negatively affects yarn quality parameters, primarily due to its low cohesion and unfavourable structural characteristics. However, the results also confirm that kapok fiber can be incorporated into yarn structures within certain limits, particularly when appropriate spinning parameters are applied.

### **4.CONCLUSION**

This study investigated the spinning performance of 70% cotton / 30% kapok blended yarns produced by a ring spinning system at different twist levels. The results clearly demonstrate that twist level is a critical parameter influencing yarn strength and structural integrity.

An increase in twist level led to a significant improvement in tensile strength and a slight reduction in yarn hairiness, while its effect on yarn unevenness and imperfections remained limited. These findings indicate that twist optimization plays a key role in enhancing the performance of kapok-containing yarns.

Compared to 100% cotton yarns, kapok/cotton blended yarns exhibited lower tensile strength and higher irregularity. This behaviour is mainly attributed to the inherent structural limitations of kapok fiber, such as low cohesion, short fiber length, and smooth surface morphology, which negatively affect fiber-to-fiber interaction and yarn formation.

Despite these limitations, the incorporation of kapok fiber offers several functional advantages, including reduced yarn weight, increased bulkiness, enhanced thermal insulation, and improved hydrophobic properties. These characteristics make kapok fiber a promising component for the development of lightweight, comfort-oriented, and sustainable textile products.



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Overall, the findings suggest that kapok fiber is more suitable for use in blended yarn structures rather than as a standalone spinning material. In addition, the results highlight the importance of adapting conventional spinning parameters when processing non-traditional bio-based fibers.

Future studies should focus on optimizing processing conditions, exploring different blending ratios, and investigating the relationship between fiber structure and end-use performance in kapok-based textile systems.

#### **ACKNOWLEDGMENT**

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## INVESTIGATION OF THE FUNCTIONALIZATION OF DENIM FABRICS WITH BIOMATERIALS AND THEIR EFFECTS ON FABRIC PERFORMANCE

Aysu BALIKÇI<sup>1\*</sup>, Ceren IŞIK<sup>1</sup>, Prof. Dr. Onur BALCI<sup>2</sup>

<sup>1</sup>İskur Denim İşletmeleri Sanayi ve Ticaret Anonim Şirketi, Ar-Ge Merkezi, Kahramanmaraş/Türkiye

<sup>2</sup>İnovaktif Ar-Ge Danışmanlık, Kahramanmaraş TGB, Kahramanmaraş/Türkiye

\*[aysu.balikci@iskurdenim.com](mailto:aysu.balikci@iskurdenim.com)

### ABSTRACT

Denim fabrics have a wide range of applications in the textile industry due to their durability and timeless appearance. Today, not only mechanical properties but also comfort and skin-compatible functional properties have gained importance. Therefore, improving conventional denim fabrics through functional finishing processes has become an important research topic.

In this study, the effects of collagen and aromatic vegetable oil-based coating formulations on the surface properties, moisture management behaviour, biocompatibility and antimicrobial properties of denim fabrics were investigated. Indigo-dyed denim fabric with a 3/1 Z twill structure and a weight of 300 g/m<sup>2</sup> was used. In addition to the reference fabric, a control sample containing a binder system (Formulation 0) and three different biomaterial-based coating formulations (Formulations 1, 2 and 3) were prepared.

After coating, the surface morphology was analysed by scanning electron microscopy (SEM), and chemical structural changes were determined by Fourier transform infrared spectroscopy (FTIR). The liquid moisture transfer behaviour was evaluated by the Moisture Management Test (MMT), while wettability was determined by contact angle measurements. The biocompatibility of the coating systems was analysed by the in vitro biocompatibility/cytotoxicity (MTT cell viability) test, and antibacterial and antifungal properties were evaluated by microbiological tests.

The results showed that biobased coating applications increased the hydrophilicity of the fabric surface and improved moisture management performance. The coating systems were found to be biocompatible, while a limited antibacterial effect and no significant antifungal activity were observed.

**Keywords:** Denim, microcapsule, collagen, coating, biocompatibility, antibacterial

### 1. INTRODUCTION

In recent years, the textile industry has moved beyond products that possess only aesthetic and mechanical properties and has turned toward functional and smart textile products. Especially in textile products that come into direct contact with the skin, properties such as user comfort and biocompatibility have become important. Therefore, research aimed at imparting various functional properties to textile surfaces has been increasing. The natural-based biopolymers are among the materials frequently investigated to provide functional properties to textile surfaces. One of these biopolymers, collagen, is widely used in cosmetic and medical applications due to its biocompatibility, biodegradable structure and high moisture retention capacity [1],[2].

The integration of collagen and other biomaterials into textile surfaces offers an important approach for improving functional properties, especially in products that come into direct contact with the skin. These systems have the potential to impart moisture management, comfort, and skin-friendly properties to textile products. However, the dense and compact structure of denim fabrics makes it difficult to effectively and permanently transfer these components onto the fabric surface. Therefore, it is necessary to use appropriate

application techniques that enable the controlled and homogeneous transfer of biomaterial-based systems onto textile surfaces [3].

Denim fabrics are one of the important products of the textile industry due to their durable structure and wide range of applications. The primary aim of this study is to enhance the biocompatibility properties of denim fabrics by using biomaterial-based microcapsule coating systems. In the second stage, the effects of the coating systems on comfort-related parameters such as moisture management, wettability, and surface morphology were investigated. Within this scope, the effects of collagen and aromatic vegetable oil-based coating systems on the surface properties, biocompatibility, antibacterial, and antifungal behaviour of denim fabrics were evaluated.

## **2. EXPERIMENTAL STUDY**

In this study, coating applications were applied to desized 100% cotton denim fabrics using the knife coating method on a laboratory-type machine. After the coating applications, the biocompatibility, comfort, antibacterial and antifungal properties of the fabrics were evaluated using various analysis methods, and the obtained results were compared with the reference sample.

### **2.1. Materials**

In the coating applications, various commercial chemicals were used. To provide functional properties in the coating formulations, marine collagen and a mixture oil system consisting of aromatic oils were used.

Ruco®-Coat FX 8011 is an anionic crosslinking agent and was used in the coating formulations to ensure the binding of polymer dispersions. Ruco®-Coat TH 5020 is a polyacrylate-based thickener and was used to adjust the viscosity of the coating paste. Ruco®-Coat VA 115 is a vinyl acetate–ethylene copolymer-based polymer dispersion and was used as a binder and film-forming agent in the coating system.

The collagen used in the study is marine collagen obtained from fish waste and contains 5% active substance. Due to its low molecular weight, it can be homogeneously distributed in solution and can easily penetrate textile surfaces. The mixture oil system used in the coating formulations consists of bitter melon (*Momordica charantia*), St. John's wort (*Hypericum perforatum*), calendula (*Calendula officinalis*), and olive oil-based components [4].

### **2.2. Method**

To transfer the active components used in the study to the textile surface in a more stable manner, a collagen and aromatic vegetable oil-based microcapsule system was developed. The microcapsules were produced using the spray drying method, where collagen constituted the outer phase of the capsule and the inner phase consisted of a mixture of aromatic oils. The obtained microcapsules were incorporated into the coating formulations and applied to the fabric surface. The coating processes were carried out using a laboratory-type knife coating method, and the coating paste was prepared in an aqueous medium and applied to the back surface of the fabric as a single-side coating. After coating, the samples were subjected to two different drying/fixation conditions depending on the formulation: samples containing collagen and microcapsules were dried in a single pass at 50°C under a low line speed, while the other samples were first dried at 120°C and then fixed at 180°C.

Within the scope of the study, samples were obtained by preparing different coating formulations together with the reference fabric. The reference sample represents the fabric without any coating application. Formulation 0 was prepared as a control sample containing only binder and auxiliary chemicals. This formulation was used to evaluate the effects of the basic chemicals used in the coating system on fabric performance. Three different coating formulations were developed and samples named as Formulation 1, Formulation 2 and Formulation 3 were obtained. In these formulations, collagen and aromatic vegetable oil-based microcapsules were incorporated into the coating paste at specific ratios, and the microcapsule content was adjusted to 10%, 20% and 40%, respectively. The coating system was prepared together with binder, thickener and polymer dispersion. In this way, homogeneous distribution of the microcapsules within the coating matrix and their effective transfer to the fabric surface were ensured.

After coating, the fabrics were subjected to various characterization tests. In this context, SEM analysis was performed to examine surface morphology, and FTIR analysis was conducted to determine chemical structural changes. The MMT (AATCC 195-2011) was carried out to evaluate moisture management

performance, and contact angle measurements (laboratory method) were performed to determine surface hydrophilicity. In addition, the MTT cell viability test (ISO 10993-5:2021) was conducted at the İstanbul University-Cerrahpaşa Nanotechnology and Biotechnology Laboratory to determine the biocompatibility properties of the coating systems. Antibacterial activity was evaluated according to ASTM E2149-01 and antifungal activity according to AATCC 30 by microbiological tests.

### 3. RESULTS

In this study, the effects of the prepared coating systems on the biocompatibility, surface properties, comfort performance, antibacterial and antifungal behavior of denim fabrics were evaluated using various analysis methods.

#### 3.1. MTT Cytotoxicity Results

In order to evaluate the biocompatibility properties of the coating systems, the MTT cell viability test was performed. The cell viability values obtained as a result of the test are presented in Table 1.

**Table 1.** Cytotoxicity test results

|               |                              | Cell Viability (%) |               |                              | Cell Viability (%) |
|---------------|------------------------------|--------------------|---------------|------------------------------|--------------------|
| Sample        | Extraction Concentration (%) | 72 Hours           | Sample        | Extraction Concentration (%) | 72 Hours           |
| Reference     | 100                          | 89,5               | Formulation 1 | 50                           | 102,97             |
|               | -                            | -                  |               | 25                           | 100,16             |
| Formulation 0 | 50                           | 88,6               | Formulation 2 | 50                           | 103,49             |
|               | 25                           | 85,8               |               | 25                           | 103,81             |
|               |                              |                    | Formulation 3 | 50                           | 107,96             |
|               |                              |                    |               | 25                           | 116,08             |

When the in vitro MTT cytotoxicity test results are examined, it is observed that the cell viability value of the reference fabric sample is 89.5%. In the Formulation 0 sample, which contains only the binder system, the cell viability values were determined to be lower compared to the reference fabric and were found to be in the range of 85.8–88.6%. In contrast, in the Formulation 1, 2 and 3 series samples containing biomaterial-based microcapsules, the cell viability values were observed to be above 100%, and the highest values were obtained particularly in the Formulation 3 sample.

These results indicate that biomaterial-based microcapsule coating systems exhibit a cell proliferation-supporting effect and demonstrate a positive performance in terms of biocompatibility. The increase in cell viability observed with increasing microcapsule content suggests that the biomaterial content improves surface interactions and creates a cell-friendly environment. This finding clearly supports the effectiveness of the coating system in improving the biocompatibility properties of denim fabrics, which is the main objective of the study [5].

In the contact angle and MMT tests carried out to evaluate the effect of the coating system on the comfort properties of the fabric, Formulation 3 was preferred as the representative sample. This is because the Formulation 3 sample showed the highest cell viability values across the concentration range and was therefore evaluated as the most suitable coating system in terms of biocompatibility.

#### 3.2. Contact Angle Results

The contact angle measurements were carried out to determine the effect of coating applications on the wettability behaviour of the fabric surface. The obtained results are presented in Table 2.

**Table 2.** Contact angle test results

| Samples       | Contact Angle (°) |
|---------------|-------------------|
| Reference     | 151               |
| Formulation 0 | 111               |
| Formulation 3 | 90                |

When the contact angle measurements are examined, it is seen that the reference fabric has the highest contact angle value with 151°, indicating that the surface exhibits a more hydrophobic behavior. In the coated samples, it was determined that the contact angle values decreased significantly. Especially in the Formulation 3 sample, the decrease of the contact angle to 90° indicates that the biomaterial-based coating system increased the hydrophilicity properties of the fabric surface. This situation can be associated with the change in the interaction of the water droplet with the surface due to the structure formed by the coating layer on the fiber surface.

### 3.3. Moisture Management Test

The MMT was applied to evaluate the liquid moisture transfer properties of the fabrics. The main parameters obtained because of the test are presented in Table 3.

**Table 3.** MMT test results

| SAMPLES       | MOISTURE MANAGEMENT TEST (MMT) |             |               |               |               |               |                |                |             |      |      |
|---------------|--------------------------------|-------------|---------------|---------------|---------------|---------------|----------------|----------------|-------------|------|------|
|               | TSWT<br>(s)                    | BSWT<br>(s) | TSAR<br>(%/s) | BSAR<br>(%/s) | TSMWR<br>(mm) | BSMWR<br>(mm) | TSSS<br>(mm/s) | BSSS<br>(mm/s) | OWTI<br>(%) | OMMC | OMMP |
| Reference     | 99,14                          | 13,07       | 7,46          | 22,42         | 5             | 5             | 0,05           | 0,39           | 436,21      | 0,51 | 3    |
| Formulation 0 | 120                            | 9,65        | 0             | 30,84         | 0             | 5             | 0              | 0,5            | 461,29      | 0,55 | 3,5  |
| Formulation 3 | 5,71                           | 6,37        | 23,63         | 29,66         | 10            | 15            | 1,41           | 2,097          | 186,52      | 0,4  | 2,5  |

**TSWT:**Top Surface Wetting Time

**BSWT:**Bottom Surface Wetting Time

**TSAR:**Top Surface Absorption Rate

**BSAR:**Bottom Surface Absorption Rate

**TSMWR:**Top Surface Maximum Wetted Radius

**BSMWR:** Bottom Surface Maximum Wetted Radius

**TSSS:** Top Surface Spreading Speed

**BSSS:** Bottom Surface Spreading Speed

**OWTI:** Accumulated One-Way Transport Index

**OMMC:** Overall Moisture Management Capacity

**OMMP:** Overall Moisture Management Performance

When the MMT results are examined, it is observed that the Formulation 3 sample containing biomaterial-based microcapsules exhibits shorter wetting times and higher spreading speeds compared to the reference and Formulation 0 samples. In particular, the significant decrease in the wetting times of the upper and lower surfaces and the increase in liquid spreading speeds indicate that the coating application improved the liquid moisture transfer behavior of the fabric. This situation can be associated with the increase in the hydrophilicity properties of the fabric surface caused by the collagen-containing coating system [6].

### 3.4. Antibacterial/Antifungal Activity

To evaluate the antimicrobial properties of the fabric samples, antibacterial and antifungal tests were performed. Antibacterial analyses were carried out on *Staphylococcus aureus* and *Escherichia coli* bacteria, while antifungal analyses were conducted using the *Candida albicans* microorganism. When the obtained results were examined, it was observed that the antibacterial effect in the coated samples was at a limited level. In the antifungal test results, it was determined that no inhibition zone was formed in the samples and that antifungal activity was not observed. This situation indicates that the coating system used does not exhibit a significant antifungal effect.

### 3.5. SEM Analysis

When the SEM images are examined, it is determined that significant changes are observed in the fiber surface morphologies of the coated fabric samples. In the Formulation 0 sample, coating residues and particle formations irregularly distributed on the fiber surfaces are observed. In the Formulation 1 sample containing biomaterial-based microcapsules, it's observed that a more homogeneous coating layer is formed on the fiber surfaces and the surface gains a smoother structure. In the Formulation 2 sample, particle formations and coating accumulations are noticeable in some regions on the fiber surfaces. In contrast, in the Formulation 3 sample, it is observed that the coating material adheres better to the fiber surface and



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forms a more continuous coating layer on the fibers. Especially at higher magnifications (500× and 1000×), it's observed that the coating material partially covers the fiber surface and significant changes occur in the fiber morphology. The corresponding SEM images are shown in Figure 1.

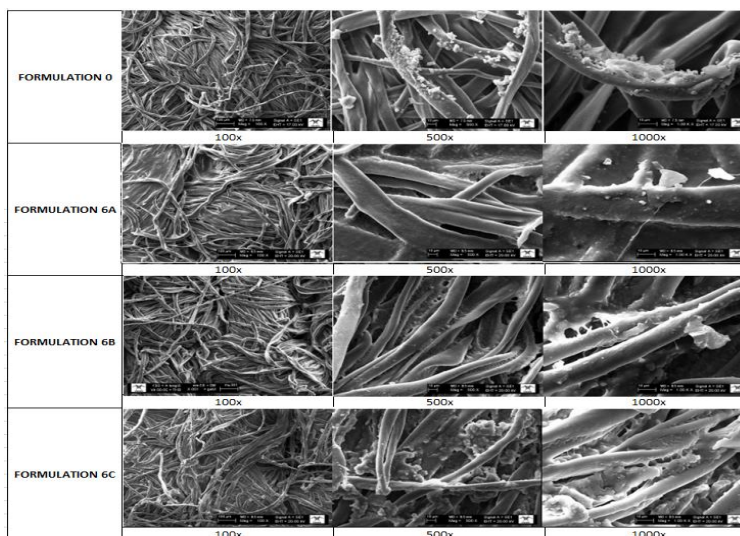


Figure 1. SEM images of samples

### 3.6. FTIR Analysis

When the FTIR spectra are examined, it is observed that the characteristic bands belonging to cotton fibers are preserved in all samples. The broad band observed in the range of 3200–3500  $\text{cm}^{-1}$  corresponds to O–H stretching vibrations. In the range of 2850–2920  $\text{cm}^{-1}$ , C–H stretching vibrations are identified. In the coated samples, the bands observed around 1650  $\text{cm}^{-1}$  and 1540  $\text{cm}^{-1}$  can be associated with amide I and amide II vibrations specific to collagen. In addition, the C–O and C–O–C bands observed in the range of 1000–1150  $\text{cm}^{-1}$  indicate characteristic peaks belonging to the cellulose structure. These results show that the biomaterial-based coating system has been successfully transferred onto the fabric surface. The corresponding FTIR spectra are shown in Figure 2.

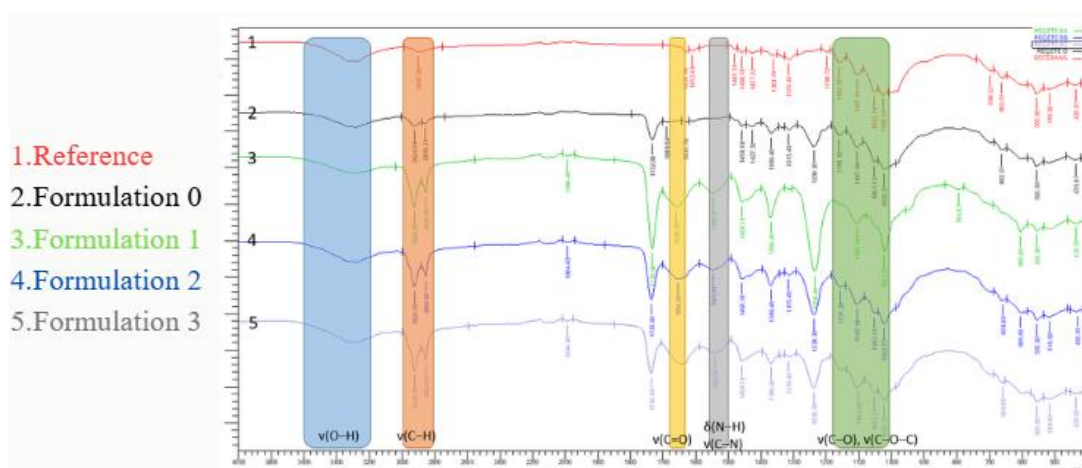


Figure 2. FTIR results

## 4. CONCLUSION

In this study, the effects of coating systems containing biomaterial-based microcapsules on the surface properties, comfort performance, and biocompatibility of denim fabrics were investigated. MTT test results revealed that the coating systems containing collagen exhibited a biocompatible structure by showing high cell viability values. Contact angle and moisture management (MMT) results showed that the coating

application affected the wettability behavior and liquid moisture transfer properties of the fabric surface. SEM and FTIR analyses confirmed that the coating material successfully adhered to the fiber surface and that characteristic bands belonging to collagen were formed. The obtained findings indicate that coating systems containing biomaterial-based microcapsules have the potential to impart functional properties to denim fabrics.

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## INVESTIGATION OF THE POTENTIAL FOR DYEING LUXURY FIBRES OBTAINED FROM CAMELIDS INTO COLOURS OTHER THAN THEIR NATURAL SHADES

Muhammet Emin Şensoy<sup>1</sup>, Özge Çolakoğlu Sever<sup>2</sup>, Durul Büşra Dilden<sup>3(\*)</sup>, Elif Aydın<sup>2</sup>, Rıza Atav<sup>1</sup>

<sup>1</sup>Tekirdağ Namık Kemal University, Çorlu Engineering Faculty, Department of Textile Engineering, Çorlu/Tekirdağ, Türkiye

<sup>2</sup>Özsar Tekstil Örne Kumaş San. ve Tic. Ltd. Şti., Ergene/Tekirdağ, Türkiye

<sup>3</sup>Beymen Perakende ve Tekstil Yatırımları A.Ş., İstanbul, Türkiye

\* durul.dilden@beymen.com

### ABSTRACT

In today's global textile market, increasing demands for higher quality and performance have encouraged manufacturers to focus not only on production costs but also on the functional and aesthetic properties of textile products. In this context, luxury fibres, known for their rarity and superior performance characteristics, offer significant potential for the textile industry. These fibres are obtained from various animal species such as goats, camelids, cattle, and rabbits and are valued for their exceptional aesthetic and mechanical properties. Among them, fibres derived from camelids represent a particularly niche segment within the textile sector. Although these fibres are highly appreciated due to their superior properties, they are generally used in their natural colours because of their inherent pigmentation. However, contemporary textile markets increasingly demand products in a wider range of colours. Therefore, investigating the potential of these fibres to be dyed into colours other than their natural shades is important. Within the scope of this study, seven different fibre types were examined: alpaca (Huacaya and Suri types), llama, guanaco, vicuña, camel fibres, and sheep wool used as a reference material. Two different approaches were applied: direct dyeing of fibres in their natural colours and dyeing after a bleaching process. Light-coloured fibres were dyed directly to obtain different shades, whereas dark-coloured fibres were first mordanted and then bleached with peroxide before dyeing. The results demonstrated that bleaching significantly enhances the dyeability of naturally coloured camelid fibres, enabling the achievement of shades that are otherwise unattainable through direct dyeing. However, bleaching was found to reduce dye uptake due to increased fibre anionicity. Overall, fibre type and pre-treatment were identified as key factors influencing colour yield and final colour properties. The results are expected to contribute to increasing colour diversity in camelid fibre textiles and to support the development of high value-added textile products.

**Keywords:** *Dyeing, colour fastness, alpaca, vicuña, camel fibre*

### 1. INTRODUCTION

In today's global textile market, increasing demands for higher quality and performance have encouraged manufacturers to focus not only on production costs but also on the functional and aesthetic properties of textile products. In this context, luxury fibres, known for their rarity and superior performance characteristics, offer significant potential for the textile industry. These fibres are obtained from various animal species such as goats, camelids, cattle, and rabbits and are valued for their exceptional aesthetic and mechanical properties. Among them, fibres derived from camelids represent a particularly niche segment within the textile sector.

The camelid family is divided into two main groups. The first group includes the true camels, namely the single-humped dromedary (*Camelus dromedarius*) and the double-humped Bactrian camel (*Camelus bactrianus ferus*). The second group comprises the llama family, including the domesticated species llama

(*Lama glama*) and alpaca (*Lama pacos*), as well as the wild species vicuña (*Vicugna vicugna*) and guanaco (*Lama guanicoe*) [1, 2].

The llama (*Lama glama*) is a domesticated, herd-living species of the camelid family, found in South America. Llamas live in herds in Argentina, Bolivia, Chile, Ecuador, and Peru, and are also bred in other continents, including North America, Europe, and Australia. The undercoat fibres are exceptionally fine, reaching down to 20 microns (and occasionally even finer), whereas the protective outer fibres are 30 microns or coarser [3]. In the textile industry, fibres marketed as “Alpaca Wool” come from the alpaca (*Lama pacos*), another member of the camelid family, and occupy a special place in trade. Alpacas inhabit the high plains of the Andes Mountains along the western coast of South America, from 3,000 metres above sea level up to the rugged, steep regions [4]. Alpacas have two distinct types of fleece: Huacaya, with fluffy fibres that protrude from the body, and Suri, with long, lustrous locks that hang elegantly from the body [5]. The guanaco (*Lama guanicoe*) is the smallest species of llama and is not domesticated [6]. Guanacos inhabit the high Andes of South America, with a natural range extending from northern Peru to the southernmost regions of Chile. Their undercoat and outer coat fibres measure 15–19  $\mu\text{m}$  and 25–35  $\mu\text{m}$  in diameter, respectively [7]. The vicuña, along with the guanaco, is one of the two wild camelid species of South America. Vicuñas are found on the high plains of the Andes Mountains along the western coast, from 3,000 metres upwards, in areas covered with pastures. Vicuña fibres are considered the finest natural fibres in the world, with a diameter ranging from 10–13 microns [8].

Although these fibres are highly appreciated due to their superior properties, they are generally used in their natural colours because of their inherent pigmentation. However, contemporary textile markets increasingly demand products in a wider range of colours. Therefore, investigating the potential of these fibres to be dyed into colours other than their natural shades is important. Within the scope of this study, seven different fibre types were examined: alpaca (Huacaya and Suri types), llama, guanaco, vicuña, camel fibres, and sheep wool used as a reference material. Two different approaches were applied: direct dyeing of fibres in their natural colours and dyeing after a bleaching process. Light-coloured fibres were dyed directly to obtain different shades, whereas dark-coloured fibres were first mordanted and then bleached with peroxide [9] before dyeing. Dyeing was carried out using 1:2 metal-complex dyes. The total colour difference ( $\Delta E$ ) was calculated using the initial colour as the reference. A higher  $\Delta E$  value indicates that the obtained colour differs more from the natural colour of the fibre, demonstrating that the fibre has been successfully dyed to a shade different from its original colour. Colour fastness tests were also conducted to evaluate the performance of the dyed fibres. The results are expected to contribute to increasing colour diversity in camelid fibre textiles and to support the development of high value-added textile products.

## 2. EXPERIMENTAL STUDY

In this study, fibre samples consisting of wool, camel, llama, Huacaya alpaca, Suri alpaca, guanaco and vicuña, all sourced from Peru, were utilised. As is known, sheep and alpacas have a single-layer fibre structure. However, camels, llamas, guanacos, and vicuñas possess a dual-layer fibre structure, consisting of fine down fibres and coarse outer hairs. In this study, the fine down fibres were used. Photographs of the fibres used in the experiments are presented in Figure 1. Initial colours of the fibres (CIE  $L^*a^*b^*$  and K/S) were measured to define their colour properties.

Two different approaches were used in this study:

- (i) direct dyeing of fibres (wool, camel, llama, Huacaya alpaca, Suri alpaca, guanaco and vicuña), and
- (ii) dyeing following a bleaching process (camel, llama, guanaco and vicuña).

While light-coloured fibres were dyed directly to obtain different shades, darker fibres were first mordanted and subsequently bleached with hydrogen peroxide, following the method used by Atav and Yurdakul [9], before being dyed.



**Figure 1.** Fibre samples used in the study

## 2.1 Mordanting and Bleaching Procedures

Naturally coloured camel, llama, guanaco and vicuña fibres were subjected to a specific mordanting process recommended in the literature [9], followed by peroxide bleaching. In this experimental group, the fibres were treated sequentially by mordanting → rinsing → peroxide bleaching. The recipes used for mordanting and bleaching are given in Table 1.

**Table 1.** Mordanting and bleaching recipes used in the experiments

| Mordanting                                | Peroxide Bleaching                                        |
|-------------------------------------------|-----------------------------------------------------------|
| %2 Sodium bisulphite                      | 30 mL/L H <sub>2</sub> O <sub>2</sub> (35%)               |
| %3 Iron (II) sulphate                     | 2 g/L Organic stabilizing agent                           |
| %1 Ammonium acetate                       | 1,5 mL/L Ammonia (pH 9)                                   |
| 1 g/L Wool protecting agent               | 2 mL/L Non-ionic wetting agent                            |
| pH 5 (CH <sub>3</sub> COOH ile) 95 °C 1 h | 50 °C 1,5 h (followed by neutralisation with acetic acid) |

## 2.2 Dyeing Procedure

Dyeing processes were carried out in a Thermal dyeing machine at a liquor ratio of 1:50, according to the dyeing profile shown in Figure 2. The pH of the dye bath was adjusted to 5 using acetic acid. Two 1:2 metal-complex dyes supplied by Dystar, namely Isolan Red S-RL and Isolan Blue NHF-S, were used. After dyeing, the samples were rinsed sequentially with cold water (5 min), warm water (5 min), and cold water again (5 min), and then dried.

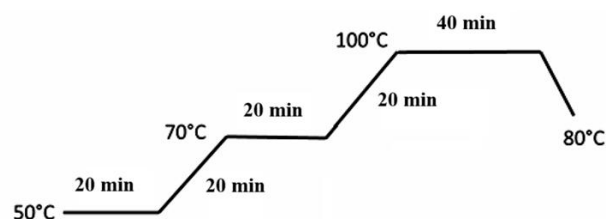


**Figure 2.** Dyeing profile used in experiments

Following the dyeing processes, the total colour difference ( $\Delta E$ ) values were calculated by taking the initial colour of each fibre as the reference. The higher this value, the greater the difference between the newly



obtained colour after dyeing and the initial colour, indicating that the fibre has been successfully dyed to a shade distinct from its original colour.

In addition, dyebath samples were collected before and after dyeing, and their absorbance values were measured spectrophotometrically to determine dye uptake (%) values. Washing fastness tests were also conducted on the samples.

### 2.3 Colour Measurements

A Datacolor Spectro 1000 spectrophotometer (D65/10°) was used to determine the reflectance (R%) and CIE L\*a\*b\* C\*h values of the samples.

L\*: lightness-darkness (0 = ideal black, 100 = ideal white)

a\*: redness–greenness (+ red, – green)

b\*: yellowness–blueness (+ yellow, – blue)

C\*: chroma

h: hue

The total colour difference ( $\Delta E$ ) values of dyed samples were calculated by taking the un-treated samples' colour as a reference.

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

K/S values were calculated using the Kubelka-Munk equation:

$$K/S = \frac{(1-R)^2}{2R}$$

where R is the reflectance value at the wavelength of maximum absorption, K is the absorption coefficient, and S is the scattering coefficient.

### 2.4 UV–Vis Analysis

Dyebath analyses were performed using UV–Vis spectroscopy (Shimadzu UV-2401 PC). Due to the high concentration of the solutions, they were diluted 3-fold prior to measurement. The maximum absorption wavelengths and corresponding absorbance values were then determined.

Dye uptake (%) was calculated using the absorbance values of dyebath samples before and after dyeing according to the following equation:

$$\text{Dye uptake (\%)} = 100 - \left( \frac{(Abs)_f \times 100}{(Abs)_i} \right)$$

where  $(Abs)_i$  is the initial absorbance and  $(Abs)_f$  is the final absorbance.

### 2.5 Fastness Tests

Washing fastness tests (at 40 °C) were carried out in accordance with the ISO 105-C06 standard.

## 3. RESULTS

### 3.1 Results Related to Description of Natural Colours of The Fibres

As is well known, fibre colour is an important characteristic of protein fibres. White is considered the most valuable, as it can be dyed to achieve any desired shade. However, fibres obtained from animals such as camel and llama are often found in a variety of natural colours. In this study, the colours of the fibres examined were measured, and the results are presented in Table 2.

**Table 2:** Results of colour measurements of the fibres

| Fibre Type       | L*   | a*   | b*   | C    | h    | K/S  |
|------------------|------|------|------|------|------|------|
| 1 Wool           | 85.6 | -0.3 | 9.1  | 9.2  | 91.8 | 0.4  |
| 2 Camel          | 63.9 | 5.6  | 16.3 | 17.2 | 71.2 | 2.1  |
| 3 Llama          | 16.6 | 2.5  | 2.8  | 3.7  | 48.4 | 25.9 |
| 4 Huacaya alpaca | 69.1 | 3.4  | 12.5 | 12.9 | 74.7 | 1.3  |
| 5 Suri alpaca    | 84.6 | 0.1  | 10.2 | 10.2 | 89.3 | 0.4  |
| 6 Guanaco        | 44.9 | 9.4  | 19.6 | 21.8 | 64.4 | 8.1  |
| 7 Vicuña         | 37.5 | 12.9 | 23.7 | 26.9 | 61.4 | 16.9 |

Upon examining Table 2, it can be seen that the white fibres, namely wool, Huacaya alpaca, and Suri alpaca, exhibit the highest L\* values and the lowest K/S values as expected. The b\* values of around 10 indicate that these fibres possess a yellowish nuance in their colour. Indeed, unbleached white wool typically has a creamy, yellowish appearance. In contrast, the camel and guanaco down fibres, which display light brown tones, as well as the golden-yellowish brown vicuña fibres, show lower L\* values and considerably higher K/S values. This clearly indicates that these fibres are darker in colour. The llama fibre used in this study is black, and therefore it is expected that it exhibits the lowest L\* value and the highest K/S value among all samples. All these findings can be clearly observed in the Main Effects Plot for K/S presented in Figure 3.

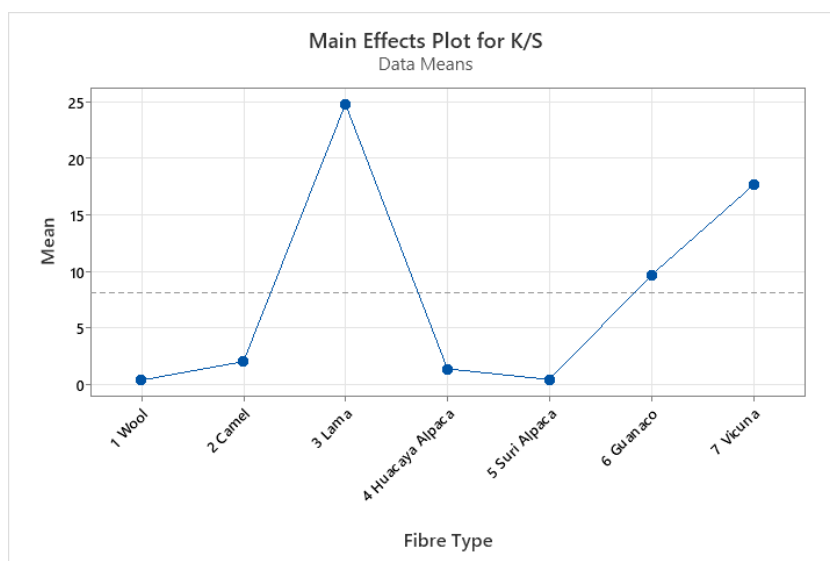


**Figure 3.** Main Effects Plot for K/S

### 3.2 Results Related to Bleaching of Naturally Coloured (Pigmented) Fibres

Naturally coloured camel, llama, guanaco and vicuña fibres were subjected to a specific mordanting process, followed by peroxide bleaching. Before hydrogen peroxide bleaching, mordanting with iron(II) sulphate is carried out to enhance the bleaching efficiency through a radical-based mechanism. By the effect of the mordant,  $\text{HO}\cdot$  and  $\text{HO}_2\cdot$  radicals are generated, which are highly reactive and capable of decomposing the pigments responsible for the colour of the fibres. Furthermore, the presence of iron ions accelerates the decomposition of hydrogen peroxide according to a radical chain mechanism, thereby intensifying the bleaching action [9]. Photographs of the samples are presented in Table 3.

**Table 3.** Photographs of untreated, mordanted, and bleached fibre samples

| Treatment  | Camel                                                                             | Llama                                                                             | Guanaco                                                                            | Vicuña                                                                              |
|------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Un-treated |  |  |  |  |
| Mordanted  |  |  |  |  |
| Bleached   |  |  |  |  |

Upon examining Table 3, it is evident that, compared to their original states, the fibres exhibit a noticeable darkening following mordanting with iron(II) sulphate. This is to be expected, as iron(II) interacts with the fibre structure, leading to a deepening of colour. Subsequently, when hydrogen peroxide bleaching is applied, a significant lightening relative to the initial colour is observed. Fibres that are naturally pale in colour, such as camel and guanaco, become almost completely white. In contrast, the originally black llama fibres shift to a dark brown shade, while the golden-yellowish brown vicuña fibres transform into a much lighter brown tone. Based on these visual assessments, it may be inferred that vicuña fibres are the most resistant to the bleaching process, requiring more intensive treatment to achieve comparable lightening.

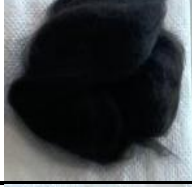
### 3.3 Results Related to Dyeing Processes

Photographs of the dyed samples and their dye uptake (%) values are presented in Table 4. When Table 4 is examined, the first point that stands out is that dyeing with a mixture of red and blue produces a purple shade on originally white fibres (wool, Huacaya alpaca, and Suri alpaca). In contrast, naturally coloured fibres (black or brown), such as camel hair, llama, guanaco, and vicuña, do not develop a purple shade under the same conditions. This observation indicates that naturally coloured luxury fibres are typically limited to being used in their inherent colours. However, when a specialised peroxide bleaching process, preceded by mordant activation, is applied prior to dyeing, the base colour is sufficiently lightened, allowing a purple shade to be achieved with relative ease. This finding is noteworthy, as it removes the limitation of using high-value luxury fibres such as vicuña and guanaco only in their natural colours. Nevertheless, in the case of black llama fibre, the bleaching process results in only limited lightening, making it impossible to obtain a true purple shade.

In terms of dye uptake percentages, two main conclusions can be drawn. First, brown-coloured fibres (camel, guanaco, and vicuña) exhibit higher dye uptake values compared to white fibres such as wool, Huacaya alpaca, and Suri alpaca. When wool is compared with alpaca fibres, wool demonstrates a higher dye uptake. Considering that the average scale count per 100  $\mu\text{m}$  follows the order Huacaya alpaca > Suri alpaca > wool, it is reasonable that wool—having the lowest scale density—absorbs dye more readily. In addition, Huacaya and Suri alpaca fibres contain a higher percentage of sulphur compared to sheep wool. This indicates a greater content of cystine cross-links, which helps to explain their relatively lower dye uptake rates [11].

The second important finding concerns the comparison of dye uptake in naturally coloured fibres (camel, llama, guanaco, and vicuña) before and after bleaching. It is observed that bleached fibres exhibit reduced dye uptake. As is well known, protein fibres contain hydroxy amino acids (such as serine and tyrosine), which are oxidised to carboxylic acids under the influence of oxidising agents such as peroxide. This reaction increases the number of terminal  $-\text{COOH}$  groups in the fibre. In aqueous media, these groups ionise to  $-\text{COO}^-$ , thereby increasing the anionic character of the fibre. Since the dyes used in this study are also anionic in nature ( $\text{D-SO}_3^-$ ), it is expected that dye uptake decreases following bleaching due to electrostatic repulsion.

**Table 4.** Photographs of untreated, mordanted, and bleached fibre samples

| Fibre          | Un-treated                                                                          | Direct dyeing                                                                       |                | Dyeing after bleaching                                                               |                |
|----------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|----------------|--------------------------------------------------------------------------------------|----------------|
|                |                                                                                     | Photo                                                                               | Dye-uptake (%) | Photo                                                                                | Dye-uptake (%) |
| Wool           |    |    | 81.0           | -                                                                                    | -              |
| Camel          |    |    | 82.1           |    | 33.9           |
| Llama          |   |   | 35.4           |   | 26.9           |
| Huacaya alpaca |  |  | 76.5           | -                                                                                    | -              |
| Suri alpaca    |  |  | 59.8           | -                                                                                    | -              |
| Guanaco        |  |  | 86.4           |  | 36.6           |
| Vicuña         |  |  | 83.3           |  | 38.7           |

The results of the two-way analysis of variance (ANOVA) for the colour yield (K/S) are presented in Table 5. According to the analysis, both fibre type and treatment (bleaching) had statistically significant effects on the measured parameter ( $p < 0.05$ ). The treatment effect ( $F = 119.57$ ) was found to be more pronounced than the fibre type effect ( $F = 13.48$ ), indicating that bleaching plays a dominant role in influencing the colour characteristics of the fibres.

**Table 5.** Two-way ANOVA results for fibre type and treatment effects

| Source     | DF | Adj SS  | Adj MS   | F-Value | P-Value |
|------------|----|---------|----------|---------|---------|
| Fibre Type | 6  | 0,39855 | 0,066426 | 13,48   | 0,000   |
| Treatment  | 1  | 0,58907 | 0,589067 | 119,57  | 0,000   |
| Error      | 25 | 0,12317 | 0,004927 |         |         |
| Total      | 32 | 0,84675 |          |         |         |

Post-hoc multiple comparison results for K/S values are presented in Table 6. Camel, llama, and guanaco fibres were grouped together in the highest category (Group A), indicating higher colour yield values. Vicuña fibre showed partial overlap between Groups A and B, whereas wool and alpaca fibres (Huacaya and Suri) were generally associated with lower K/S values and classified in Groups B and C. Among all fibres, Suri alpaca exhibited the lowest mean K/S value. These findings suggest that darker natural fibres tend to retain higher colour yield even after treatment, whereas lighter fibres exhibit lower K/S values.

**Table 6.** Multiple comparison results for K/S values according to fibre type

| Fibre Type       | N | Mean    | Grouping |
|------------------|---|---------|----------|
| 2 Camel          | 6 | 4,17000 | A        |
| 3 Llama          | 6 | 4,15500 | A        |
| 6 Guanaco        | 6 | 4,11833 | A        |
| 7 Vicuña         | 6 | 4,06667 | A B      |
| 1 Wool           | 3 | 3,94333 | B C      |
| 4 Huacaya Alpaca | 3 | 3,90333 | B C      |
| 5 Suri Alpaca    | 3 | 3,78667 | C        |

All these findings can be clearly observed in the Main Effects Plot for K/S presented in Figure 3.

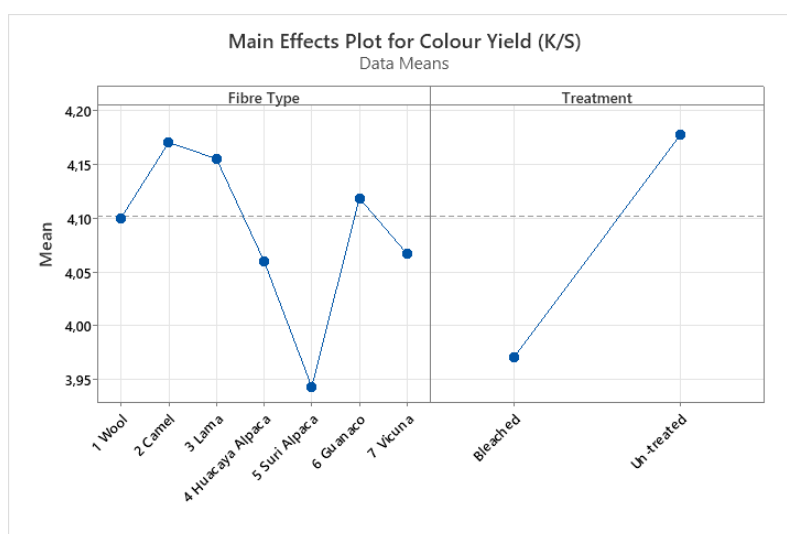


**Figure 4.** Main Effects Plot for K/S of dyed samples

The total colour difference ( $\Delta E$ ) values were also calculated by taking the directly dyed (unbleached) samples as the reference. Therefore, a higher  $\Delta E$  value indicates a greater deviation of the colour obtained after bleaching and subsequent dyeing from that achieved by direct dyeing. When the  $\Delta E$  values are examined (Table 7), it is clearly observed that bleaching prior to dyeing leads to high colour differences compared to direct dyeing. This indicates that the colours obtained after bleaching are markedly different from those achieved without bleaching. In contrast, low  $\Delta E$  values would indicate that bleaching does not



significantly alter the final colour compared to direct dyeing. The total colour difference ( $\Delta E$ ) values varied depending on fibre type, with guanaco fibres showing the highest  $\Delta E$  (3.0), followed by camel (1.9) and vicuña (1.6), while llama fibres exhibited the lowest  $\Delta E$  (1.0). These findings indicate that, among the brown-coloured fibres, vicuña exhibits the smallest colour change after bleaching, suggesting that the bleaching treatment is least effective for this fibre type. On the other hand, the very low  $\Delta E$  value observed for llama fibres can be attributed to their initial black colour, for which the bleaching process provides only limited lightening prior to dyeing.

In addition, bleaching resulted in slight decreases in K/S values for all fibres, suggesting a reduction in colour depth. Changes in hue (h) and chroma (C) values were also observed, indicating that bleaching not only lightens the fibres but also alters their colour nuance.

**Table 7.** Colour parameters of fibres before and after bleaching

| Fibre Type |            | L*   | a*  | b*   | $\Delta E$ | C   | h   | K/S |
|------------|------------|------|-----|------|------------|-----|-----|-----|
| Camel      | Un-treated | 37.1 | 1.3 | -1.4 | Std.       | 1.9 | 312 | 4.3 |
|            | Bleached   | 38.3 | 1.3 | -2.9 | 1.9        | 3.2 | 293 | 4.0 |
| Llama      | Un-treated | 37.2 | 0.2 | -0.4 | Std.       | 0.5 | 300 | 4.2 |
|            | Bleached   | 38.0 | 0.7 | -0.7 | 1.0        | 1.0 | 312 | 4.1 |
| Guanaco    | Un-treated | 37.3 | 1.5 | -0.5 | Std.       | 1.6 | 341 | 4.3 |
|            | Bleached   | 38.7 | 1.6 | -3.2 | 3.0        | 3.5 | 297 | 3.9 |
| Vicuña     | Un-treated | 37.4 | 1.2 | -0.1 | Std.       | 1.2 | 353 | 4.3 |
|            | Bleached   | 38.8 | 1.0 | -0.9 | 1.6        | 1.3 | 317 | 3.9 |

The washing fastness results of the dyed samples are summarised in Table 8.

**Table 8.** Washing fastness results of dyed fibre samples

| Fibre          | Treatment  | Washing Fastness |     |     |     |     |     |
|----------------|------------|------------------|-----|-----|-----|-----|-----|
|                |            | WO               | PAC | PES | PA  | CO  | CA  |
| Wool           | Un-treated | 4/5              | 4   | 3/4 | 4/5 | 4/5 | 4/5 |
|                | Bleached   | 4/5              | 4   | 3/4 | 4   | 4/5 | 4/5 |
| Camel          | Un-treated | 4/5              | 4/5 | 3   | 4   | 4/5 | 4/5 |
|                | Bleached   | 4/5              | 4/5 | 3   | 4   | 4/5 | 4/5 |
| Llama          | Un-treated | 3/4              | 4   | 3/4 | 4   | 4/5 | 4/5 |
|                | Bleached   | 4                | 4   | 3/4 | 4/5 | 4/5 | 4/5 |
| Huacaya alpaca | Un-treated | 4/5              | 4/5 | 3   | 4/5 | 4/5 | 4/5 |
|                | Bleached   | 4/5              | 4   | 3   | 4   | 4/5 | 4/5 |
| Suri alpaca    | Un-treated | 4/5              | 4/5 | 4   | 4/5 | 4/5 | 4/5 |
|                | Bleached   | 4/5              | 4   | 3   | 3/4 | 4/5 | 4/5 |
| Guanaco        | Un-treated | 4/5              | 4   | 3   | 3/4 | 4/5 | 4/5 |
|                | Bleached   | 4/5              | 4   | 3   | 3/4 | 4/5 | 4/5 |

The washing fastness results indicate that all dyed fibres generally exhibit good to very good fastness properties, with ratings predominantly in the range of 4 to 4/5. This demonstrates that the applied dyeing processes ensure satisfactory fixation of the dyes on the fibre surface. No significant deterioration in washing fastness was observed after bleaching for all fibres except vicuña. In the case of vicuña, a decrease in fastness was observed, which can be attributed to its higher susceptibility to oxidative damage. Structural degradation of the fibre likely reduces dye fixation stability, resulting in increased dye desorption during washing. Overall, the results confirm that the developed dyeing approach is not only effective in terms of colour modification but also reliable in maintaining acceptable durability performance.

#### 4. CONCLUSION

This study investigated the dyeing behaviour of various luxury fibres derived from camelids, with particular emphasis on overcoming the limitations imposed by their natural pigmentation. The findings clearly demonstrate that while naturally coloured fibres exhibit restricted dyeability when dyed directly, the application of a mordant-assisted peroxide bleaching process significantly enhances their ability to be dyed into alternative shades.

Among the fibres studied, lighter fibres such as wool and alpaca showed lower dye uptake compared to darker camelid fibres, whereas brown fibres such as camel, guanaco, and vicuña exhibited higher initial dye affinity. However, bleaching led to a noticeable decrease in dye uptake across all fibre types, primarily due to the increased anionic character of the fibre structure resulting from oxidative treatment.

Statistical analysis confirmed that both fibre type and treatment method significantly affect colour yield, with bleaching emerging as the dominant factor.

Fastness results indicated that acceptable washing fastness levels can be maintained even after bleaching and dyeing processes, suggesting that the proposed method is viable for practical applications.

Overall, this study provides a valuable contribution to expanding the usability of high-value camelid fibres in the textile industry by enabling greater colour diversity. Future studies may focus exploring alternative dye classes to further improve performance.

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## INVESTIGATION OF THE USE OF LAHOR TREE ROOT, WHICH GIVES COLOUR TO MARDIN BLUE ALMOND CANDY, IN TEXTILE DYEING

Sıraç Bakay<sup>1</sup>, Öner Gündüz<sup>2(\*)</sup>, Durul Büşra Dilden<sup>3</sup>, Rıza Atav<sup>1</sup>

<sup>1</sup>Tekirdağ Namık Kemal University, Çorlu Engineering Faculty, Department of Textile Engineering, Çorlu/Tekirdağ, Türkiye

<sup>2</sup>Erak Giyim, Tekirdağ, Türkiye

<sup>3</sup>Beymen Perakende ve Tekstil Yatırımları A.Ş., İstanbul, Türkiye

\* [oner.gunduz@erak.com](mailto:oner.gunduz@erak.com)

### ABSTRACT

In natural dyeing, yellow and earthy tones can be obtained from many plants, while red is typically derived from madder and blue from the indigo plant. In this context, investigating the potential use of Lahor tree root, which has the capacity to produce blue hues, in textile dyeing is considered to contribute to the existing literature. A review of the literature revealed no studies addressing the use of Lahor tree root in textile dyeing. In this study, the dyeing performance of Lahor tree root on different fibre types was investigated. Multifibre fabric samples containing wool, polyacrylonitrile, polyester, polyamide, cotton, and acetate fibres were dyed. After dyeing, the samples were washed and dried, and colour yield (K/S) values were measured. In addition, washing, rubbing and light fastness tests were conducted, and the obtained data were statistically analysed. The results indicated that Lahor tree root was able to dye all fibres with high efficiency except polyester. The colour yield increased in the following order: polyamide < cotton < acetate < polyacrylonitrile < wool. Furthermore, the obtained washing and rubbing fastness values were at a fairly good level.

**Keywords:** *Natural dye, Lahor tree root, sustainable dyeing, colour yield, multifibre*

### 1. INTRODUCTION

Natural dyes derived from plants, animals, bacteria, and fungi are considered bio-compatible, safe, and renewable alternatives to synthetic colourants due to their biodegradability and low risk of allergic reactions (Sajed et al., 2018). Historically, natural dyes obtained from the roots, stems, bark, leaves, fruits, and flowers of various plants, as well as from certain animal sources, were widely used in textile dyeing (Haji et al., 2016). However, the discovery of the synthetic mauve dye by William Henry Perkin in 1856 led to a significant decline in the use of natural dyes (Haji et al., 2020). In recent years, increasing environmental concerns and the growing importance of sustainable production practices have renewed interest in natural dyes (Bulut et al., 2013). “Lahor tree”, scientifically known as *Haematoxylum campechianum*, is a plant that grows in warm climates and contains natural dye compounds in blue–purple tones. When the dried Lahor root is boiled in water, it releases a natural blue pigment. This pigment can be applied to sugar or almonds to achieve natural colouring. In Türkiye, particularly in the province of Mardin, Lahor root is traditionally used to obtain the blue colour in the production of “blue almond candy” (locally also referred to as “ghost almond candy”).

Inspired by this traditional practice, the idea for this study emerged: to investigate the potential use of this natural dye source in textile applications. *Haematoxylum campechianum* contains a benzofuran-based natural dye (Market Survey, 2020). It includes approximately 10% haematoxylin, a colourless compound, which upon oxidation is converted into haematein, a compound exhibiting colours ranging from red to violet-blue (Natural Colouring Agents, 2020).

In natural dyeing, yellow and earthy tones can be obtained from many plants, while red is typically derived

from madder and blue from the indigo plant. The fact that blue is typically obtainable only from plants such as indigo, which require a vat dyeing process, prevents it from being mixed with other colours in a single bath. However, if a bluish tone—though not a true blue—can be achieved using Lahor root, this limitation may be overcome. Since this dye does not require a vatting process, it would be possible to combine it with yellow and red dyes in a single bath. This would address a significant gap in the existing literature. In this context, investigating the potential use of Lahor tree root, which has the capacity to produce blue hues, in textile dyeing is considered to contribute to the existing literature. A review of the literature revealed no studies addressing the use of Lahor tree root in textile dyeing.

In this study, the dyeing performance of Lahor tree root on different fibre types was investigated. Multifibre fabric samples containing wool, polyacrylonitrile, polyester, polyamide, cotton, and acetate fibres were dyed. After dyeing, the samples were washed and dried, and colour yield (K/S) values were measured. In addition, washing, rubbing and light fastness tests were conducted, and the obtained data were statistically analysed.

## **2. EXPERIMENTAL STUDY**

In this study, standard multifibre fabric containing wool, polyacrylonitrile, polyester, polyamide, cotton, and acetate components, respectively, were used.

### **2.1 Preparation of Dye Extract**

0.1 g of Lahor tree root was boiled in 1 L of distilled water for 30 minutes, followed by filtration through muslin cloth. A commercially available powdered natural dye was used in the study. The filtered dye extract was used as dye liquors in the experiments.

### **2.2 Dyeing Procedure**

5 g samples of multifibre fabrics were dyed using the prepared dye extracts at a liquor ratio of 1:20 in a Thermal HT dyeing machine. The filtered dye extracts were used directly as the dye bath. Dyeing processes were carried out at three different pH levels: pH 5, pH 7, and pH 9. In addition, dyeing was performed both without mordants and with two different mordants: potassium aluminium sulphate (10%) and copper (II) sulphate (2%).

After dyeing, the fabric samples were washed and dried. Subsequently, colour yield (K/S) and CIE L\* a\*b\* values of the samples were measured. The samples were divided into two portions; one half was left untreated, while the other half was subjected to an after-treatment with 2% cationic fixing agent at pH 5 (with acetic acid), at 40°C for 20 minutes. Furthermore, washing, rubbing (dry and wet) and light fastness tests were performed. The obtained data were statistically analysed.

### **2.3 Colour Measurements**

A Datacolor Spectro 1000 spectrophotometer (D65/10°) was used to determine the reflectance (R%) values of the samples. K/S values were calculated using the Kubelka–Munk equation:

$$K/S = \frac{(1-R)^2}{2R}$$

where R is the reflectance value at the wavelength of maximum absorption, K is the absorption coefficient, and S is the scattering coefficient.

### **2.4 Fastness Tests**

Washing (at 60° C), rubbing (dry and wet) and light fastness tests of samples were carried out in accordance with ISO-105 C06 (according to subvariant of A1M) (ISO, 2010), ISO 105-X12 (ISO, 2016) and ISO 105 B02 (ISO, 2014) standards, respectively.

### **2.5 Statistical Evaluation**

In this study, the dependent variables are the K/S, L\*, a\*, and b\* values, as well as the fastness test results. The independent variables are as follows:

- dyeing pH (three levels: 5, 7, and 9), and

- mordant usage (three levels: none, potassium aluminium sulphate and copper sulphate).

Analysis of variance (ANOVA) was conducted according to the General Linear Model using Minitab 19 software. Tukey tests were performed to determine the source of differences, and main effects plots were generated to present the results visually.

### 3. RESULTS

Photographs of the multifibre fabrics dyed under different pH levels and mordant usage are presented in Figure 1.

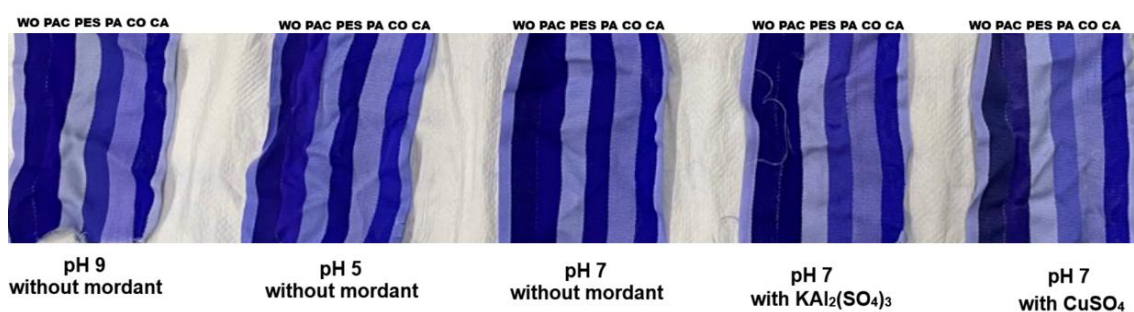


**Figure 1.** Photographs of the multifibre fabrics dyed under different pH levels and mordant usage

Upon examining the Figure 1, the first noticeable point is that the Lahor tree root was able to dye all fibres except polyester. In terms of the colour yield obtained from the dyeing, the fibres can be ranked from highest to lowest as follows: wool > polyacrylonitrile > acetate > polyamide > cotton > polyester. Statistical analyses were conducted to better interpret the results. Table 1 presents the results of the analysis of variance (ANOVA) performed on the colour yield (K/S) values of the dyed multifibre fabrics. The table summarises the effects of fibre type, pH, and mordant usage on the colour yield.

**Table 1.** ANOVA results for colour yield (K/S) of dyed multifibre fabrics

| Source     | DF | Adj SS  | Adj MS  | F-Value | P-Value |
|------------|----|---------|---------|---------|---------|
| Fibre Type | 5  | 6335,53 | 1267,11 | 41,07   | 0,000   |
| pH         | 2  | 105,01  | 52,51   | 1,70    | 0,193   |
| Mordant    | 2  | 584,14  | 292,07  | 9,47    | 0,000   |
| Error      | 50 | 1542,53 | 30,85   |         |         |
| Total      | 59 | 8642,73 |         |         |         |

As observed in Table 1, the fibre type and mordant usage have a statistically significant effect on colour yield ( $p < 0.05$ ), whereas the pH did not show a significant effect ( $p > 0.05$ ). To determine the source of these differences, Tukey multiple comparison tests were conducted, and the results are presented in Tables 2–3.

**Table 2.** Tukey grouping for fibre type

| Fibre Type        | N  | Mean    | Grouping |
|-------------------|----|---------|----------|
| Wool              | 10 | 25,6865 | A        |
| Polyacrylonitrile | 10 | 20,4167 | A B      |
| Acetate           | 10 | 13,9775 | B C      |
| Polyamide         | 10 | 11,9640 | C        |



|           |           |   |
|-----------|-----------|---|
| Cotton    | 10 0,9038 | D |
| Polyester | 10 0,5925 | D |

From Table 2, it can be seen that wool exhibits the highest colour yield, followed by polyacrylonitrile and acetate, while cotton and polyester show the lowest values.

**Table 3.** Tukey grouping for mordant usage

| Mordant                      | N  | Mean    | Grouping |
|------------------------------|----|---------|----------|
| Without                      | 36 | 16,1565 | A        |
| Potassium aluminium sulphate | 12 | 11,8872 | A        |
| Copper sulphate              | 12 | 6,3181  | B        |

From Table 3, it can be seen that, in terms of mordant usage, samples without a mordant and those treated with potassium aluminium sulphate show similarly higher colour yields, while samples treated with copper sulphate exhibit significantly lower values.

A main effects plot was constructed to provide a clearer visual summary of all the results and is presented in Figure 2.

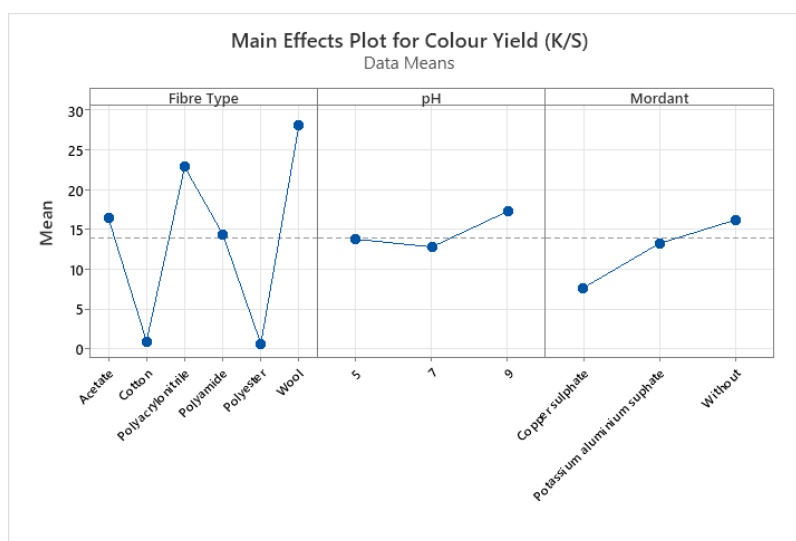


**Figure 2.** Main effects plot for colour yield (K/S)

Upon examining Figure 2, the first noticeable point is that the Lahor tree root was able to dye all fibres except polyester. In terms of colour yield obtained from the dyeing, the fibres can be ranked from highest to lowest as follows: wool > polyacrylonitrile > acetate > polyamide > cotton. As is well known, the main colouring compounds present in the Lahor tree root are Brazilin, Haematoxylin, and Sappanin (Atav, 2025). All these compounds can generally be represented by the formula Dye–OH. Considering that they ionise as Dye–O<sup>−</sup> in aqueous solutions, it can be concluded that the dye has an anionic character. Cotton fibres in the dyeing medium are also anionic, existing as Cell–O<sup>−</sup> (or Cell–COO<sup>−</sup>). In contrast, wool and polyamide fibres exhibit cationic behaviour due to the presence of positively charged ammonium groups. This explains why the dye shows higher affinity for wool and polyamide than for cotton, as the negatively charged dye molecules are attracted to the positively charged wool or polyamide fibres through electrostatic interactions.

Regarding acetate and polyester fibres, the dye molecules also contain components [10] with disperse dye characteristics. This explains why acetate fibres could be successfully dyed. Furthermore, acetate fibres have lower glass transition temperatures compared to polyester fibres, making them easier to dye under the same conditions. Polyester fibres, on the other hand, can only be dyed under high-temperature (HT) conditions; under atmospheric boiling conditions, only slight staining occurs, and no significant dyeing is achieved.

When Figure 2 is examined, it can be seen that the effect of pH on the colour yield obtained in dyeing is negligible. On the other hand, considering the effect of mordant use, it is evident that the colour yield decreases, particularly when copper sulphate is used, resulting in a lighter appearance of the fabric. Washing, rubbing, and light fastness tests were also carried out on the samples, and the results are presented in Tables 4 and 5.

**Table 4:** Washing fastness test results

| Sample            | Fixing Agent | CA  | CO  | PA  | PES | PAC | WO  |
|-------------------|--------------|-----|-----|-----|-----|-----|-----|
| Wool              | Without      | 4-5 | 2-3 | 2   | 3-4 | 3-4 | 3-4 |
|                   | With         | 5   | 3   | 2-3 | 4-5 | 4   | 4   |
| Polyacrylonitrile | Without      | 5   | 3-4 | 3   | 5   | 4-5 | 4   |
|                   | With         | 5   | 4   | 4   | 5   | 4-5 | 4-5 |
| Polyester         | Without      | 5   | 4   | 3-4 | 5   | 5   | 4-5 |
|                   | With         | 5   | 4-5 | 4-5 | 5   | 5   | 5   |
| Polyamide         | Without      | 5   | 3-4 | 2-3 | 5   | 4   | 3-4 |
|                   | With         | 5   | 4-5 | 3-4 | 5   | 5   | 4-5 |
| Cotton            | Without      | 5   | 4-5 | 4-5 | 5   | 5   | 5   |
|                   | With         | 5   | 4-5 | 4-5 | 5   | 5   | 5   |
| Acetate           | Without      | 5   | 3-4 | 3   | 5   | 5   | 4   |
|                   | With         | 5   | 4-5 | 4-5 | 5   | 5   | 5   |

**Table 5:** Rubbing and light fastness test results

| Sample            | Dry Rubbing |              | Wet Rubbing |              | Light        |
|-------------------|-------------|--------------|-------------|--------------|--------------|
|                   | -           | Fixing agent | -           | Fixing agent | Fixing agent |
| Wool              | 4-5         | 4-5          | 3           | 3-4          | 2            |
| Polyacrylonitrile | 4-5         | 5            | 4-5         | 4-5          | 2            |
| Polyester         | 4-5         | 5            | 4           | 4-5          | 1            |
| Polyamide         | 4-5         | 5            | 4           | 4-5          | 1-2          |
| Cotton            | 4-5         | 5            | 3           | 4            | 1            |
| Acetate           | 4-5         | 5            | 3-4         | 4            | 2            |

When examining the fastness values, it was observed that the washing fastness was fairly good for all samples except wool and improved noticeably after the after-treatment with the cationic fixing agent. Dry and wet rubbing fastness values were already at a fairly good level even in the untreated state, and increased by approximately half a point following the after-treatment with the cationic fixing agent.

When the light fastness properties are taken into consideration, it can be observed that, as is typically expected of natural dyes, the levels remain rather modest. Consequently, their use in garments such as summer T-shirts may not be the most suitable choice; instead, they would be more appropriately employed in autumn and winter apparel, where exposure to intense light is comparatively limited.

#### 4. CONCLUSION

The present study demonstrates that the root of the Lahor tree (*Haematoxylum campechianum*) is a promising natural dye source for textile applications. The dye exhibited high affinity for wool and polyacrylonitrile fibres, moderate affinity for acetate and polyamide, and minimal uptake on cotton, while it does not dye polyester. Mordant usage influenced the colour yield, with copper sulphate leading to lighter shades, whereas potassium aluminium sulphate had a negligible effect. pH variations between 5, 7, and 9 had minimal impact on dyeing performance. It is important to note that these results were obtained under competitive dyeing conditions, where all six fibre types were dyed simultaneously in the same bath. Dye uptake and colour yield might differ if each fibre were dyed in separate baths under identical conditions. It can be stated that the obtained washing and rubbing fastness values were at a generally good level.

Furthermore, after-treatment with a 2% cationic fixing agent significantly improved washing fastness and slightly enhanced rubbing fastness across all fibre types.

These findings indicate that Lahor root can be effectively used to produce blue hues on a variety of textile fibres without requiring complex vat dyeing processes, providing an environmentally friendly alternative to synthetic dyes. Future studies may focus on optimizing extraction methods and exploring combinations with other natural dyes to expand the colour palette.

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## INVESTIGATION OF VARIOUS PERFORMANCE AND DYEABILITY PROPERTIES OF COTTON BLEND YARNS PRODUCED USING NEXT-GENERATION REGENERATED FIBRES AND SILVER

Yasemin Balseven<sup>1</sup>, Seda Keskin Atak<sup>2,\*</sup>, Sümeyra Demirtaş Özkaya<sup>3</sup>, Rıza Atav<sup>1</sup>

<sup>1</sup> Tekirdağ Namık Kemal University, Textile Engineering, Çorlu/Tekirdağ, Türkiye

<sup>2</sup> Eren Perakende ve Tekstil A.Ş., Research and Development Centre, Ergene/Tekirdağ, Türkiye

<sup>3</sup> Devanlay Eren Tekstil San. Tic. A.Ş., Design Centre, Ergene/Tekirdağ, Türkiye

\* seda.keskinatak@erenperakende.com

### ABSTRACT

Umorfil®, a next-generation regenerated fibre, is produced from waste fish scales. In this study, Ne 30/1 yarns with compositions of 35% cotton / 60% Umorfil / 5% silver; 60% cotton / 30% Umorfil / 20% silver; and 88% Umorfil / 12% silver were produced and evaluated in terms of yarn unevenness, thin and thick places, nep count, tensile strength, and elongation at break. The yarns were subsequently dyed using reactive dyes, and their dye uptake, colour characteristics, and colour fastness properties were assessed. The results indicated that as the cotton content decreased and the proportion of Umorfil or silver increased, yarn unevenness, thin and thick places, and nep count increased, while tensile strength and elongation at break showed improvement. No statistically significant differences were observed among the yarn samples with respect to dye uptake (%) or colour and fastness properties.

**Keywords:** *Umorfil, Silver, Neps, Tensile Strength, Dye Uptake, Colour*

### 1. INTRODUCTION

Textile manufacturers have numerous responsibilities, including ensuring a healthy and safe working environment, reducing water consumption, promoting recycling, adopting a “less but better” production philosophy, encouraging reuse, and minimising environmental footprints. Among these responsibilities, waste valorisation and the use of natural raw materials are key focus areas [1].

Umorfil® is a next-generation protein fibre derived from waste fish scales [1,2]. UMORFIL® is the first fibre to combine both animal- and plant-based characteristics [3]. It is an upcycled yarn technology created by incorporating collagen peptides obtained from waste fish scales into fibres using supramolecular technology [1, 2]. Waste fish scales are utilised as the raw material in the production of Umorfil® bionic fibres. The use of waste as a raw material offers significant advantages in terms of sustainability and the efficient use of limited resources. Moreover, depending on its structure, the waste material contributes positively to the performance properties of the final product. For instance, waste fish scales enhance the moisture management properties of textile products. The term Umorfil is derived from the words “moisture” and “fibre”. Umorfil® technology combines ocean collagen peptide amino acids extracted from waste fish scales with various fibres through supramolecular technology. When integrated into a viscose-based fibre, it is referred to as Umorfil® Beauty Fibre®; when polyester-based, as Umorfil® T; and when polyamide-based, as Umorfil® N6U™. According to the fibre manufacturer, these fibres exhibit softness comparable to silk and wool, high moisture management capability, and natural deodorising properties. It is also stated that skin-friendly Umorfil® Beauty Fibre® can provide protection against UV radiation and skin ageing [1]. The chemical structure of Umorfil fibres is shown in Figure 1, and the production process is presented in Figure 2.

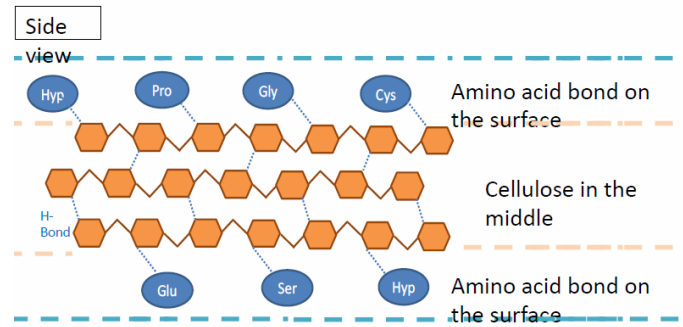


**Figure 1.** Chemical structure of Umorfil fibres [3]

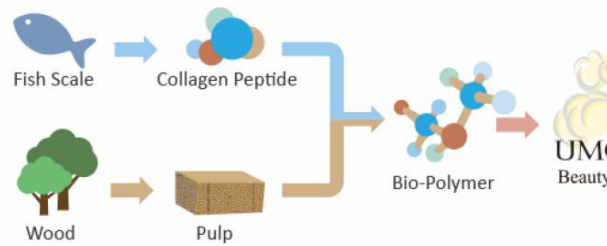


**Figure 2.** UMOFIL production process [4]

Table 1 presents a comparison of the physical properties of Umorfil fibres with various conventional fibres.

**Table 1.** Comparison of the physical properties of Umorfil fibres with various fibres [2]

| Fibre Property          | Umorfil® | Rayon | Wool     | TENCEL®  | Cotton |
|-------------------------|----------|-------|----------|----------|--------|
| Tenacity (g/d)          | 2.75     | 2.5   | 1.6      | 3.3      | 4.0    |
| Elongation at break (%) | 20–25    | 10–20 | 25–35    | 13–15    | 6–10   |
| Moisture regain (%)     | 16–18    | 11–13 | 14–18    | 8–11     | 7.5    |
| UV resistance           | Good     | Poor  | Moderate | Moderate | Poor   |

Usluoğlu and Özoğuz investigated the dyeing and performance properties of Umorfil® N6U fibres. Due to the higher number of amine groups in its molecular structure, Umorfil® fibres exhibited better colour fastness properties than conventional polyamides. In addition, products manufactured from Umorfil® N6U fibres demonstrated improved softness and a cooler handle [5].

In a study conducted by Yıldız, single jersey fabrics knitted from cotton, viscose, polyester, Umorfil®, and Umorfil®/cotton blended yarns were evaluated in terms of thermal conductivity, air permeability, relative water vapour permeability, water vapour resistance, and physical properties such as bursting strength, pilling, and dimensional stability. The results revealed that fabrics knitted from 100% Umorfil® yarns exhibited higher air and water vapour permeability, better pilling resistance, and lower thermal conductivity [6].

Çeven and Günaydın conducted a study to evaluate the thermal comfort, vapour permeability, water vapour resistance, air permeability, and bursting strength of single jersey knitted fabrics produced from 100% cotton, Cupro, Lyocell®, Modal, and Umorfil® yarns. The effect of dyeing (undyed and dyed fabrics) on the investigated properties was also examined. Fabrics produced from Umorfil® yarns exhibited the lowest thermal conductivity and bursting strength, as well as the lowest thermal resistance, while showing the highest thermal absorptivity and air permeability values [7].

Kırcı et al. utilised biodegradable Umorfil polyamide 6 (Umorfil® N6U) fibres to improve the comfort properties of compression stockings. Their findings demonstrated that it is possible to produce comfortable travel socks with adequate pressure performance [8].

Soydan et al. investigated the moisture management, antimicrobial, and air permeability properties of plain knitted fabrics produced with 100% collagen peptide addition [9].



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Şen and Gürel provided detailed information on Umorfil® fibres and examined the structural and performance properties of fabrics developed using these fibres [2].

Hou et al. presented a novel polymerisation method for producing collagen-modified polyester using collagen peptides extracted from upcycled fish scale waste. The resulting fibre combines the strength, durability, and wrinkle resistance of conventional polyester with improved hydrophilicity, antistatic properties, softness, and a natural champagne-like colour [10].

Bedež Üte and Ertekin examined the thermal comfort properties of single jersey fabrics produced from Umorfil® yarns and their 50/50 blends with Tencel®, wool, acrylic, and polyester. Measurements of thermal comfort, air permeability, and moisture management showed that 100% Umorfil® and Umorfil®/Tencel® fabrics exhibited superior thermal and moisture-related performance, indicating their suitability for hot-climate applications due to their enhanced comfort and moisture transport characteristics [1].

In the present study, Ne 30/1 yarns with compositions of 35% cotton / 60% Umorfil / 5% silver, 60% cotton / 30% Umorfil / 20% silver, and 88% Umorfil / 12% silver were compared in terms of yarn unevenness, thin and thick places, nep count, tensile strength, and elongation at break. Subsequently, the yarns were dyed using reactive dyes, and their dye uptake, colour characteristics, and colour fastness properties were evaluated.

## 2. MATERIALS AND METHODS

In this study, the viscose-based version of Umorfil fibre (1.25 dtex/38 mm and 3 dtex/76 mm) was used. The yarns listed in Table 2 were employed within the scope of the experimental work.

**Table 2.** Yarns used in the experiments

| Yarn count | Cotton (%) | Umorfil (%) | Silver (%) |
|------------|------------|-------------|------------|
| Ne 30/1    | 35         | 60          | 5          |
| Ne 30/1    | 60         | 30          | 10         |
| Ne 30/1    | 0          | 88          | 12         |

The yarns were first tested for unevenness, thin places, thick places, neps, tensile strength, and elongation at break using an Uster Tester 6. The obtained results were statistically evaluated using Minitab 22 software. Subsequently, bleaching and dyeing processes were carried out using softened process water at a liquor ratio of 1:10. Dyeing was performed with 1.5% Colorsol Blue NFR reactive dye in a dye bath containing 0.5 g/L sequestering agent, 50 g/L NaCl, and 20 g/L soda ash, following the dyeing profile shown in Figure 3.

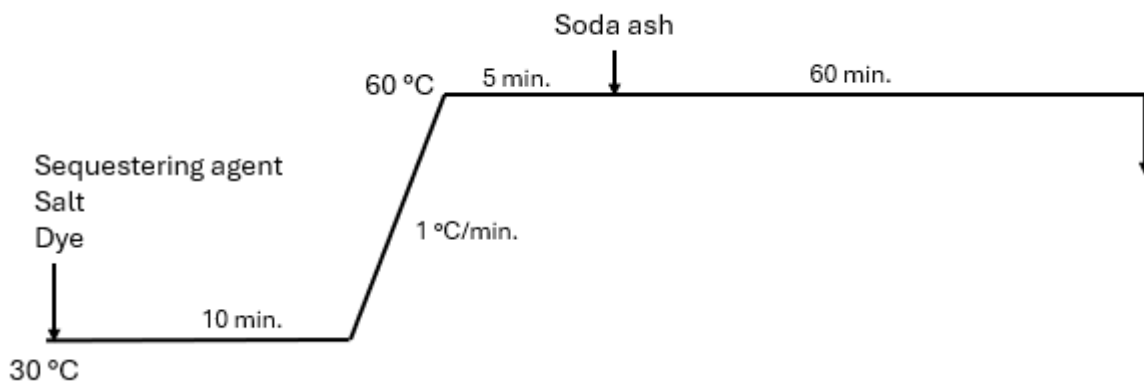


**Figure 3.** Dyeing profile used in the experiments

After dyeing, the samples were washed and dried, followed by colour measurements and colour fastness tests. Washing, water, and perspiration (acidic and alkali) fastness tests were carried out in accordance with ISO 105-C06 [11], ISO 105-E01 [12], and ISO 105-E04 [13] standards, respectively. In addition, dye bath samples taken at the beginning and end of the dyeing process were analysed spectrophotometrically to

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measure the initial absorbance ((Abs)<sub>initial</sub>) and final absorbance ((Abs)<sub>final</sub>). The dye uptake percentage was calculated using the Eq. 1:

$$\text{Dye uptake (\%)} = [(Abs)_{\text{initial}} - (Abs)_{\text{final}}] \times 100 / (Abs)_{\text{initial}} \quad \text{Eq. 1}$$

Furthermore, CIE L\*a\*b\*, C, and h colour values were measured in the spectral range of 400–700 nm and at the wavelength of maximum absorption (minimum remission) using a spectrophotometer (D65/10°):

L\*: lightness (100 = ideal white, 0 = ideal black)

a\*: red–green coordinate (+ red, – green)

b\*: yellow–blue coordinate (+ yellow, – blue)

C: chroma (colour saturation)

h: hue

### 3. RESULTS AND DISCUSSION

The yarn unevenness (Um%, Uster Uniformity Measure), neps (+200%), thin places (–30%) and thick places (+35%) are presented in Figures 4-5.

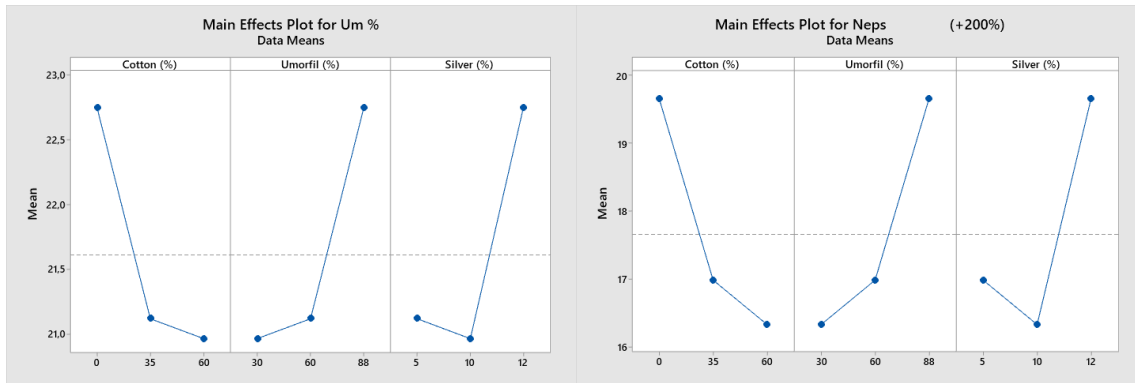


Figure 4. Um% values and Neps (+200%) of the yarns

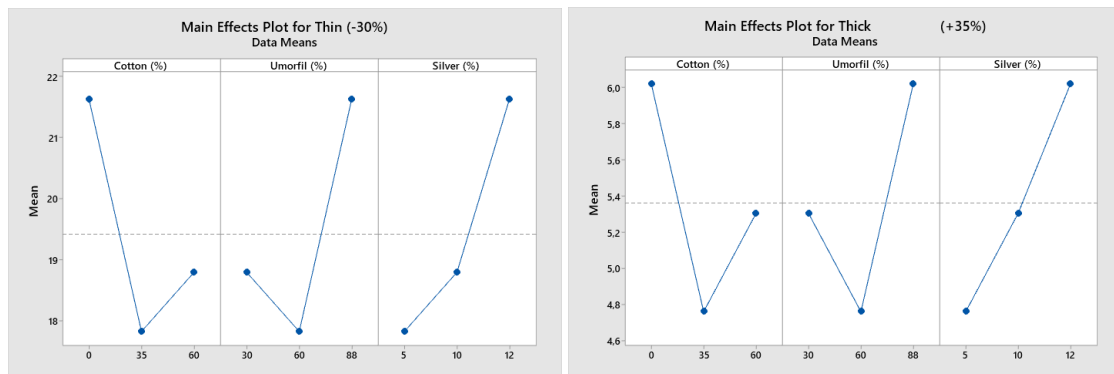


Figure 5. Thin places (–30%) and thick places (+35%) of the yarns

As shown in Figures 4-5, a clear increase in yarn unevenness, thin and thick places, and nep count is observed as the cotton content decreases and the Umorefil or silver content increases. Since silver-containing yarns technically include metallic filaments, higher unevenness values compared with conventional cotton yarns are expected due to spinning mechanics and potential filament breakage.

The tensile strength (cN/tex, Rkm) and elongation at break (%) of the yarns are presented in Figure 6.

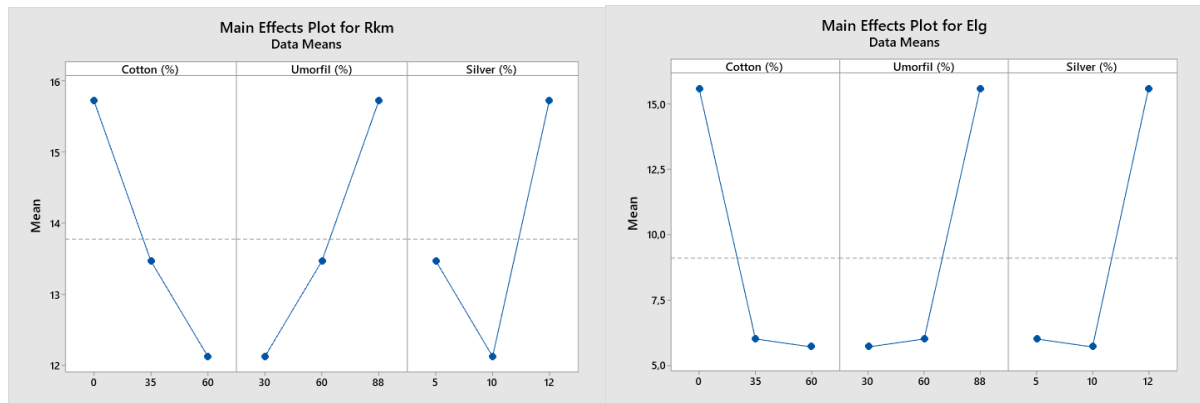


**Figure 6.** Tensile strength (cN/tex) and elongation at break (%) of the yarns

Figures 8 and 9 indicate that tensile strength and elongation at break increase as the cotton content decreases and the Umorfil or silver content increases. Although Umorfil fibre is essentially a regenerated cellulose-based fibre similar to viscose, it also contains peptide (amino acid) components. This protein-based structure provides greater softness and elasticity, which explains the observed increase in elongation at break with higher Umorfil content. In addition, the increase in tensile strength with increasing silver content is an expected outcome.

The yarns were subsequently dyed under identical conditions using reactive dyes. Photographs of the dyed yarn samples are shown in Figure 10, while dye uptake (%) and colour measurement results are presented in Table 3.



**Figure 10.** Photographs of yarn samples dyed with reactive dye

**Table 3.** Dye uptake (%) and colour measurement results of yarn samples dyed with reactive dyes

| Cotton (%) | Umorfil (%) | Silver (%) | Dye Uptake (%) | L*   | a*   | b*    | C    | h   |
|------------|-------------|------------|----------------|------|------|-------|------|-----|
| 35         | 60          | 5          | 96.4           | 38.6 | -3.0 | -26.8 | 27.0 | 264 |
| 60         | 30          | 10         | 95.7           | 39.5 | -3.4 | -22.7 | 22.9 | 262 |
| 0          | 88          | 12         | 95.6           | 39.7 | -4.0 | -23.5 | 23.9 | 260 |

Examination of Figure 10 and Table 3 shows that the yarn samples exhibit very similar colour depths. However, a slight decrease in dye uptake and a lighter colour tone (higher L\* values) are observed as the silver content increases. No significant difference in hue (h) is observed, with all samples exhibiting h values around 270°, indicating a blue colour. As the silver content increases, the colour tends to shift slightly towards greener tones (lower a\* values) and less blue tones (higher b\* values).

The fastness results of the yarn samples dyed with reactive dyes are presented in Tables 3 and 4.

**Table 3:** Washing and water fastness results of yarn samples dyed with reactive dyes

| Cotton (%) | Umorfil (%) | Silver (%) | Washing Fastness |     |     |     |     |     | Water Fastness |     |     |     |     |     |
|------------|-------------|------------|------------------|-----|-----|-----|-----|-----|----------------|-----|-----|-----|-----|-----|
|            |             |            | WO               | PAC | PES | PA  | CO  | CA  | WO             | PAN | PES | PA  | CO  | CA  |
| 35         | 60          | 5          | 5                | 4/5 | 4/5 | 4/5 | 4/5 | 4/5 | 4/5            | 4   | 4/5 | 4/5 | 4   | 4/5 |
| 60         | 30          | 10         | 5                | 4/5 | 4/5 | 4/5 | 4/5 | 4/5 | 5              | 4/5 | 4/5 | 4/5 | 4/5 | 4/5 |
| 0          | 88          | 12         | 5                | 4   | 4/5 | 4   | 4   | 4   | 4/5            | 4   | 4/5 | 4   | 4   | 4   |

**Table 4:** Acidic and alkali perspiration fastness results of yarn samples dyed with reactive dyes

| Cotton (%) | Umorfil (%) | Silver (%) | Alkali Perspiration Fastness |     |     |     |     |     | Acidic Perspiration Fastness |     |     |     |    |     |
|------------|-------------|------------|------------------------------|-----|-----|-----|-----|-----|------------------------------|-----|-----|-----|----|-----|
|            |             |            | WO                           | PAC | PES | PA  | CO  | CA  | WO                           | PAN | PES | PA  | CO | CA  |
| 35         | 60          | 5          | 4/5                          | 4   | 4/5 | 4/5 | 3/4 | 4/5 | 5                            | 4/5 | 4/5 | 4/5 | 4  | 4/5 |
| 60         | 30          | 10         | 4/5                          | 4/5 | 4/5 | 4/5 | 3/4 | 4/5 | 5                            | 4/5 | 4/5 | 4/5 | 4  | 4/5 |
| 0          | 88          | 12         | 4                            | 4   | 4/5 | 4   | 3/4 | 4   | 4/5                          | 4   | 4/5 | 4   | 4  | 4   |

When Tables 3 and 4 are examined, in general, although there is no significant difference between the fastness values of the samples, it can be said that an increase in cotton content improves the fastness by about half a grade, whereas an increase in silver content reduces it by about half a grade. Moreover, the overall fastness levels are generally considered to be good.

#### 4. CONCLUSIONS

The results demonstrate that as the cotton content in the yarn decreases and the Umorfil or silver content increases, yarn unevenness, thin and thick places, and nep count increase, while tensile strength and elongation at break also improve. No significant differences were observed among the yarn samples in terms of dye uptake (%) or overall colour and fastness properties. Future studies should focus on producing fabrics from these yarns and evaluating their properties, particularly thermal comfort and handle, to better determine their potential application areas.

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## MAPPING THE INVISIBLE: A NOVEL APPROACH TO DETECT ADDITIVE DISTRIBUTION IN COMPOSITE FIBERS

İlkkar Karaoğlu<sup>1</sup>, Mert Yüçetürk<sup>2</sup>, Umit Halis Erdogan<sup>3</sup>

<sup>1</sup>Intertek Test Hizmetleri AŞ, İzmir, Türkiye

<sup>2</sup>Budin Group, İzmir, Türkiye

<sup>3</sup>Dokuz Eylul University Department of Textile Engineering, İzmir, Türkiye

### ABSTRACT

Currently, extensive research is being conducted to enhance the properties of textile fibers and impart additional functionalities. These studies improve the technical performance of fibers and create new application areas. Modifications carried out during and after the production of textile fibers are becoming increasingly important in determining their end-use applications. Composite fibers are obtained by incorporating additives in various forms and sizes into the polymer matrix during the production of synthetic fibers. The performance of composite fibers is intrinsically linked to the spatial distribution of functional additives within the polymer matrix. While additives, such as microparticles or microcapsules, are integrated to enhance functional properties, achieving and verifying a homogenous dispersion remains a significant challenge in textile engineering. Traditional characterization methods often fail to provide a comprehensive and quantifiable map of these additives at the microscale. This study introduces a novel methodology designed to visualize and quantify the internal distribution of additives in composite fibers. The homogeneity of the additive distribution within the fiber is a decisive factor in the physical and chemical properties of the composite fiber. Furthermore, the agglomeration of additives is a critical parameter affecting the uniformity of the distribution. The primary goal is to bridge the gap between microscopic observations, image processing, and statistical data to ensure product consistency and performance optimization. The objective of this study was to establish a new approach for continuously monitoring the dispersion and homogeneity of additives in composite fibers via optical microscopy. In this context, melt-spun polypropylene composite fibers were produced using natural additives with auto-fluorescent characteristics. Various surface treatment methods were also applied to the additives to prevent agglomeration and achieve a more uniform distribution. Longitudinal images of the fibers were captured via fluorescence and stereo microscopes, and changes in agglomeration and distribution were analyzed using image processing methods. This study is significant for the characterization of composite fibers and provides a foundational framework for future research in this field.

**Keywords:** Additive Distribution, Auto-fluorescence, Composite Fibers, Image Analysis, Melt spinning

## MORPHOLOGICAL AND CHEMICAL CHARACTERIZATION OF DRUG-LOADED ELECTROSPUN PCL SCAFFOLDS

Suzan Özdemir<sup>1,\*</sup>, Janset Öztumur-Sezgin<sup>1</sup>, Hande Sezgin<sup>1</sup>, İpek Yalçın-Eniş<sup>1</sup>

<sup>1</sup> Istanbul Technical University, Textile Engineering, Istanbul, Turkey

\* ozdemirsu@itu.edu.tr

### ABSTRACT

Intimal hyperplasia remains one of the primary causes of failure in small-diameter vascular grafts, motivating the development of drug-eluting scaffolds capable of locally suppressing restenosis. Electrospinning offers a versatile platform for producing biomimetic fibrous structures that mimic the extracellular matrix while enabling controlled incorporation of therapeutic agents. In this study, paclitaxel-loaded poly( $\epsilon$ -caprolactone) (PCL) nanofibrous structures were developed to investigate how polymer concentration influences fiber morphology and to verify drug incorporation through chemical characterization. PCL solutions at two different concentrations (8% and 10% w/w) were prepared and loaded with 0.25% (w/w) paclitaxel to obtain drug-loaded electrospun fibrous mats. Electrospinning parameters were optimized to produce uniform and bead-free fibers. Morphological evaluation was performed using scanning electron microscopy, and fiber diameter distributions were quantitatively analysed. Chemical characterization was carried out using Fourier transform infrared spectroscopy (FTIR) to confirm paclitaxel incorporation and to evaluate potential interactions between the drug and polymer matrix. The results demonstrated that polymer concentration strongly affected fiber morphology, leading to more homogeneous fibers with reduced bead formation. Fiber diameter analysis indicated that the incorporation of paclitaxel modified the relationship between polymer concentration and fiber diameter, demonstrating that drug addition can either increase or decrease fiber diameter depending on solution properties. FTIR spectra showed the characteristic functional groups of both PCL and paclitaxel, confirming successful drug incorporation. Overall, these findings highlight the importance of polymer concentration in tailoring the structural properties of paclitaxel-loaded electrospun PCL scaffolds and provide preliminary design insights for drug-eluting vascular grafts with potential anti-restenotic functionality.

**Keywords:** *Intimal hyperplasia, Vascular grafts, Electrospinning, Drug-eluting scaffolds*

### 1. INTRODUCTION

Small-diameter artificial vascular grafts are widely employed to restore blood flow in arterial occlusive conditions, including coronary and peripheral arterial diseases (Zizhou et al., 2022). However, despite significant progress in synthetic vascular graft engineering, their clinical performance in small-diameter applications remains limited, primarily due to the persistent challenge of thrombosis and intimal hyperplasia (IH) (Jeong et al., 2020; Yao et al., 2023).

Non-biodegradable grafts, such as expanded polytetrafluoroethylene (ePTFE), have demonstrated favorable outcomes in large-diameter vessels (>6 mm); however, their translation to small-diameter applications (<6 mm) has been unsuccessful, primarily owing to limited remodeling capacity and increased risk of occlusion. Biodegradable polymers, including poly(lactic acid) (PLA), poly(glycolic acid) (PGA), and polycaprolactone (PCL), have emerged as promising alternatives due to their ability to degrade into non-toxic byproducts with tunable kinetics. Nevertheless, these materials still face significant challenges, such as early mechanical instability, calcification, and susceptibility to neointimal tissue formation (Xie et al., 2022). To address these challenges, a variety of strategies have been proposed to develop hemocompatible surfaces, promote endothelialization, and suppress IH (Feng et al., 2022). IH, particularly at anastomotic sites, is characterized by the proliferation and migration of vascular smooth muscle cells (VSMC) along with the accumulation of extracellular matrix and supporting cellular components, ultimately leading to graft stenosis (Lim et al., 2008). In this context, rapid endothelial layer formation together with the controlled inhibition of excessive VSMC proliferation is considered a critical factor for

effective arterial repair following bypass surgery (Feng et al., 2022). Localized delivery of antiproliferative agents emerges as a more effective and safer strategy than systemic administration, as it enables targeted inhibition of these processes while minimizing systemic side effects (Lim et al., 2008). For instance, Innocente et al. (2009) demonstrated that the release of the antiproliferative agent paclitaxel from electrospun polycaprolactone scaffolds effectively suppressed smooth muscle cell (SMC) proliferation, thereby contributing to improved *in vivo* graft patency (Innocente et al., 2009). Similarly, Talimi et al. (2022) developed a multilayer electrospun nanofibrous system enabling localized and sustained sirolimus release to prevent post-surgical vascular stenosis. Their findings demonstrated that controlled drug delivery from the scaffold significantly reduced neointimal hyperplasia while preserving endothelialization, highlighting the potential of such systems for effective perivascular therapeutic applications (Talimi et al., 2022). In this study, paclitaxel-loaded PCL electrospun nanofibrous scaffolds were fabricated to investigate the effect of polymer concentration on fiber morphology and to confirm drug incorporation through chemical characterization.

## 2. EXPERIMENTAL STUDY

### 2.1 Materials

PCL (Mn 80,000) was used for the fabrication of the surfaces in this study. To impart antiproliferative properties to the PCL-based surfaces, paclitaxel (PTX) (Deva İlaç, Turkey) was incorporated into the polymer matrix. For PCL-based solution systems, a chloroform:ethanol solvent mixture (9:1, w/w) was employed. The polymer and organic solvents were purchased from Sigma-Aldrich.

### 2.2 Methods

#### 2.2.1. Solvent preparation and fabrication of PTX-loaded webs

For the optimization of neat PCL and PTX-loaded PCL fibrous webs, PCL polymer concentrations of 8 and 10 wt% were selected. PTX was incorporated at a concentration of 0.25% relative to the final PCL solution. Subsequently, the drug-loaded electrospinning solution was further stirred at room temperature to ensure homogeneity prior to electrospinning.

The tubular electrospun constructs were fabricated using a custom-designed electrospinning system with a vertical solution feed (Nanospinner Ne100+, Inovenso, Turkey). Cylindrical rotating mandrel collectors with a diameter of 6 mm were employed to obtain tubular samples. A rotational speed of 200 rpm was selected, enabling the production of scaffolds with randomly distributed fibers. The sample codes and electrospinning parameters are provided in Table 1.

**Table 1.** Sample codes and electrospinning parameters.

| Sample codes  | Polymer Concentration (%) | Drug Concentration (%) | Voltage (kV) | Feed rate (mL/h) | Tip-to-collector distance (cm) |
|---------------|---------------------------|------------------------|--------------|------------------|--------------------------------|
| PCL8          | 8                         | -                      | 9.3          | 1                | 20                             |
| PCL10         | 10                        | -                      | 11.5         | 1.3              | 20                             |
| PCL8+PTX0.25  | 8                         | 0.25                   | 11           | 0.7              | 20                             |
| PCL10+PTX0.25 | 10                        | 0.25                   | 11           | 0.8              | 20                             |

#### 2.2.2 Morphological assessment

Morphological characterization of the electrospun samples was performed using scanning electron microscopy (SEM; Zeiss Evo MA10). Also, fiber diameter measurements were performed using the ImageJ software based on SEM micrographs, with at least 50 individual fibers analyzed for each sample. The results are reported as mean fiber diameters accompanied by their standard deviations.

#### 2.2.3 Chemical characterization

Fourier transform infrared spectroscopy (FTIR; UATR Two, Perkin Elmer) was employed to confirm successful incorporation of drugs into polymeric webs.

### 3. RESULTS

#### 3.1 SEM and fiber diameter analysis

Figures 1(a) and 1(b) present SEM images of PCL8 and PCL10 samples at 2kx magnification. The PCL8 sample exhibits a fibrous structure characterized by relatively thinner fibers and a less uniform morphology, with noticeable variations in fiber diameter and the presence of local fiber junctions. A decrease in solution viscosity due to lower polymer concentration, associated with a higher solvent content, may hinder complete solvent evaporation during fiber formation, leading to the development of interconnected fibers and an increased number of fiber-fiber junctions (Salimbeigi et al., 2022). The observed nonhomogenous morphology is consistent with the fiber diameter analysis given in Table 2, which revealed an average fiber diameter of  $1.132 \pm 0.732 \mu\text{m}$  for PCL8, indicating a broad diameter distribution.

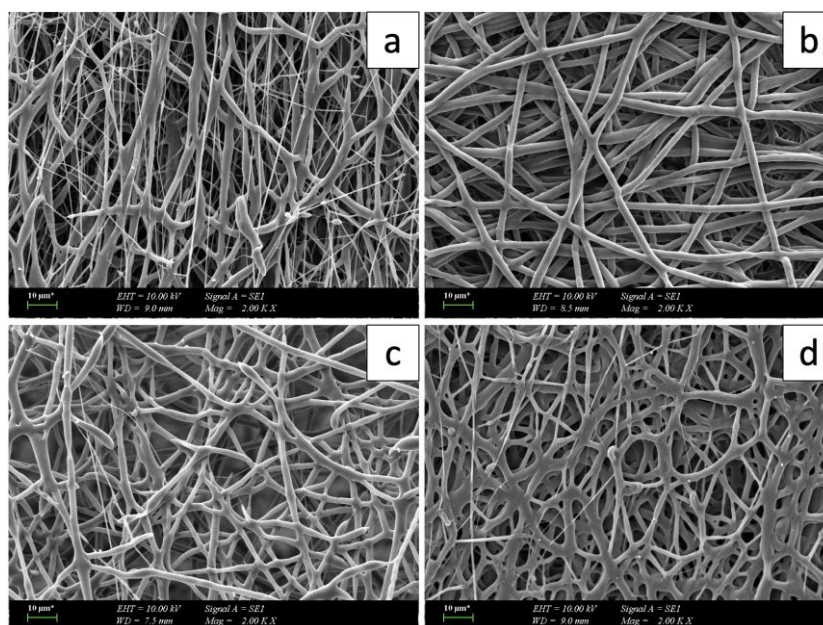


**Figure 1.** SEM images of neat PCL samples at 2kx magnification: (a) PCL8, (b) PCL10, (c) PCL8+PTX0.25, and (d) PCL10+PTX0.25.

In contrast, the PCL10 scaffold displays a more homogeneous fibrous architecture with thicker and more uniformly distributed fibers. Correspondingly, PCL10 exhibited a significantly higher average fiber diameter of  $2.312 \pm 0.246 \mu\text{m}$  (Table 2), accompanied by a markedly narrower distribution. An increase in polymer concentration is reported to elevate solution viscosity and promote molecular chain entanglement, which stabilizes the electrospinning jet and yields more uniform and continuous fiber morphology, reducing bead formation in the resulting nanofibers (Islam et al., 2025).

When the SEM images of the PTX-loaded PCL samples are evaluated (Figure 1(c) and 1(d)), clear polymer- and drug-concentration-dependent changes in fiber morphology and diameter become evident. In comparison with neat PCL8, which exhibits relatively thin fibers with a broad diameter distribution and local fiber thinning, the PTX-loaded PCL8 sample (Figure 1(c)) shows visibly thicker fibers with more pronounced fiber junctions and a denser fibrous network, consistent with the measured increase in average fiber diameter to  $1.695 \pm 0.646 \mu\text{m}$  at PTX loading of 0.25%. A comparable behavior was reported by Innocente et al. (2009), who showed that drug-free PCL grafts fabricated at polymer concentrations of 7.5, 9, and 12% (wt/vol) exhibited fiber diameters of  $500 \pm 290 \text{ nm}$ ,  $640 \pm 540 \text{ nm}$ , and  $1640 \pm 1000 \text{ nm}$ , respectively. When PTX was incorporated into PCL solutions with polymer concentrations of 7.5 and 9 wt%, bead formation disappeared, and the average fiber diameters increased by approximately 80%. In contrast, for PCL solutions prepared at a higher polymer concentration of 12 wt%, PTX incorporation did not induce any significant changes in either bead formation or fiber diameter. These findings indicate that the effect of PTX incorporation on fiber thickening is strongly dependent on the polymer concentration.

In contrast, PTX incorporation into PCL10 resulted in a reduction in fiber diameter to  $1.375 \pm 0.526 \mu\text{m}$  at PTX loading of 0.25%. This observation is further supported by the results reported by Zhu et al. (2013), who demonstrated a monotonic decrease in fiber diameter from  $1.51 \pm 0.67 \mu\text{m}$  to  $1.15 \pm 0.36 \mu\text{m}$  with

increasing PTX content (0-2%) in electrospun PCL matrices. Furthermore, Chi et al. (2020) attributed the formation of thinner PTX-loaded nanofibers compared to drug-free counterparts to a reduction in solution viscosity and an increase in surface charge density, which collectively enhance electrostatic stretching and overcome surface tension during electrospinning. Taken together, these results demonstrate that the influence of PTX on fiber diameter is not unidirectional but highly dependent on the polymer concentration. At lower PCL concentrations near the chain entanglement threshold (PCL8), PTX incorporation may alter solution viscosity, thereby promoting fiber thickening, whereas at higher PCL concentrations (PCL10), PTX addition favors charge-mediated jet thinning, resulting in reduced fiber diameters and increased diameter heterogeneity.

**Table 2.** Fiber diameters of produced webs.

| Sample codes  | Fiber diameter (μm) |
|---------------|---------------------|
| PCL8          | 1.132 ± 0.732       |
| PCL10         | 2.312 ± 0.246       |
| PCL8+PTX0.25  | 1.695 ± 0.646       |
| PCL10+PTX0.25 | 1.375 ± 0.526       |

### 3.2 FTIR analysis

Figure 2 presents the overlaid FTIR spectra of neat PCL, PTX, and PTX-loaded PCL nanofibrous webs. The FTIR spectrum of pure PCL exhibits characteristic absorption bands corresponding to C–O and C=O stretching vibrations at 1241 and 1722 cm<sup>-1</sup>, respectively. In addition, the peaks observed at 2864 and 2942 cm<sup>-1</sup> are attributed to the symmetric and asymmetric stretching vibrations of CH<sub>2</sub> groups (Oztemur & Yalcin-Enis, 2021). The principal infrared bands of PTX include N–H stretching vibrations in the range of 3479-3300 cm<sup>-1</sup> and CH<sub>2</sub> asymmetric and symmetric stretching vibrations between 2976 and 2885 cm<sup>-1</sup>. The absorption band at 1734 cm<sup>-1</sup> corresponds to C=O stretching associated with ester functional groups, while the amide bond is identified at approximately 1645 cm<sup>-1</sup>. The C–N stretching vibration appears at 1244 cm<sup>-1</sup>, and the bands at 1645, 1073, 966, and 709 cm<sup>-1</sup> are assigned to the aromatic structures of PTX. The FTIR spectrum of PTX-loaded PCL closely resembles that of neat PCL, which can be attributed to the overlap of characteristic drug absorption bands with those of the polymer matrix. The dominant polymer bands likely mask the spectral features of PTX, suggesting that the drug is molecularly dispersed within the PCL nanofibers and that no chemical interaction occurs between PTX and the polymer matrix (Hiremath et al., 2013; Rehman et al., 2025).

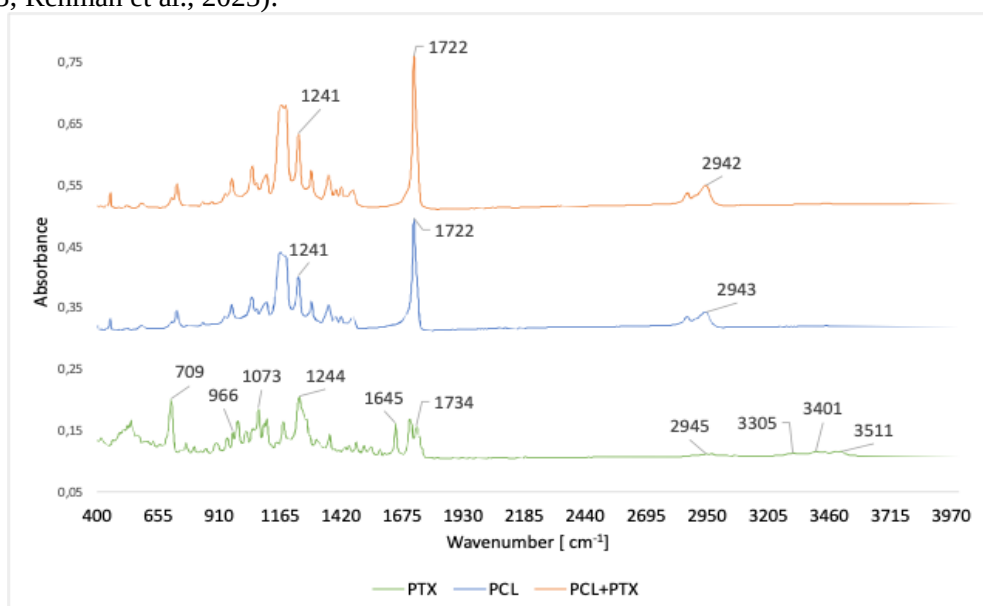


**Figure 2.** Transmission FTIR spectra of neat PCL, PTX, and PTX loaded PCL samples.



#### 4. CONCLUSION

In conclusion, the results demonstrate that polymer concentration plays a decisive role in governing the morphology and fiber diameter of electrospun PCL scaffolds. Lower polymer concentration resulted in thinner and less uniform fibers, whereas higher concentration promoted the formation of more homogeneous and stable fibrous structures. Furthermore, paclitaxel incorporation was found to alter fiber morphology in a concentration-dependent manner, leading to either fiber thickening or thinning depending on the initial polymer concentration. FTIR analysis confirmed the successful incorporation of paclitaxel without significant chemical interaction with the polymer matrix. Overall, these findings highlight the importance of optimizing polymer-drug system parameters for the design of electrospun drug-eluting scaffolds with controlled structural properties.

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## **MULTI-CRITERIA ANALYSIS APPLICATION FOR EVALUATION OF THE SPECIALIZED TEXTILE PRODUCTS COMMERCIALIZATION POTENTIAL**

**Marcin Struszczyk<sup>1</sup>, Dominika Kamińska<sup>1</sup>, Agnieszka Gutowska<sup>1</sup>, Marzena Fejdyś<sup>1</sup>**

<sup>1</sup>Instytut Technologii Bezpieczeństwa "MORATEX"

### **ABSTRACT**

The research evaluates the commercialization potential of specialized textile products and technologies, especially those with dual-use applications and high market prospects like fibrous composites. It outlines essential performance, safety, ergonomics, and sustainability requirements for user protection and product viability. The study used multi-criteria analysis (MCA) to identify technological advancements with the greatest commercial promise, considering dimensions such as technological readiness, innovation, competitiveness, and sustainable development. This approach helped highlight products—such as protective vests and anti-smog masks—that are ready for both civilian and military use. Findings also indicate a need for further improvements in sustainability and innovation for some technologies not yet fully mature. The assessment included financial and market factors, such as development costs, net present value (NPV), potential user base, and licensing scope, to gauge overall competitiveness and market potential. In conclusion, the study provides actionable insights and recommendations to support innovative, safe, and sustainable textile solutions for diverse sectors.

**Keywords:** advanced textiles, composites, multi-criteria analysis, special area of the applications

# OPTIMIZATION OF MULTI-LAYERED 3D SPACER FABRICS FOR IMPACT PROTECTION AND THERMAL COMFORT IN WINTER OUTERWEAR

Banu Bornovalı<sup>1</sup>, Demet Ateş<sup>1</sup>, Ayça Gözükara<sup>1</sup>, Emine Dilara Koçak<sup>2</sup>, Özgür Atalay<sup>3,\*</sup>

<sup>1</sup> Boyner Büyük Mağazacılık A.Ş., İstanbul, Türkiye

<sup>2</sup> Marmara University, Textile Engineering Department, İstanbul, Türkiye

<sup>3</sup> Istanbul Technical University, Textile Engineering Department, İstanbul, Türkiye

\* atalayoz@itu.edu.tr

## ABSTRACT

This study investigates the performance of multi-layered 3D spacer fabrics (2, 3, and 4 layers) for protective winter outerwear. The research evaluates the synergy between impact protection and physiological comfort. Impact tests were conducted at a 20 J energy level, while thermal properties and air permeability were measured using Alambeta and Prowwhite devices. The results show that the 3-layer configuration provides the most effective impact protection, achieving the highest energy absorption (12.869 J) and the lowest peak force (1.261 kN). In contrast, the 4-layer structure exhibited a decline in impact performance (10.770 J) due to increased structural stiffness. Thermally, the 4-layer assembly offered the maximum insulation ( $336.63 \times 10^{-3} \text{ m}^2 \cdot \text{K/W}$ ), but significantly reduced air permeability to  $41.53 \text{ cm}^3/\text{cm}^2/\text{s}$ . The 3-layer configuration maintained a balanced breathability of  $54.57 \text{ cm}^3/\text{cm}^2/\text{s}$ . The findings indicate that the 3-layer spacer structure is the optimal functional unit, offering the best balance of safety, thermal efficiency, and breathability for winter protective apparel.

**Keywords:** 3D spacer fabrics, Impact protection, Thermal insulation, Air permeability, Winter outerwear.

## 1. INTRODUCTION

The demand for functional clothing that provides both protection and comfort has increased significantly, particularly for outdoor activities performed under harsh environmental conditions [1]. Winter jackets are expected to offer effective thermal insulation against cold climates while simultaneously providing protection against external mechanical impacts. Achieving both functions within a single garment remains a challenge, as conventional impact-protective materials such as rigid foams or plastic plates often reduce flexibility, breathability, and ergonomic comfort [2]. These materials may also limit moisture transport, leading to overheating and discomfort during physical activity. Therefore, there is a growing need for alternative material solutions that can provide both thermal insulation and impact protection without compromising wearability.

3D spacer fabrics, also known as sandwich fabrics, have emerged as promising candidates for multifunctional protective clothing[3]. These textile structures consist of two knitted outer layers connected by spacer monofilament yarns, forming a three-dimensional porous architecture. This structure allows efficient dissipation of impact energy through the compression and bending of the spacer yarns. At the same time, the air trapped within the internal cavities contributes to thermal insulation, while the porous network promotes air circulation and moisture transfer, enhancing thermophysiological comfort. Due to these combined properties, spacer fabrics offer significant potential for applications where both protection and comfort are required [4].

Previous research has mainly focused on the mechanical performance of spacer fabrics in medical and sports applications [5-6]. However, their potential use in winter outerwear, where both impact resistance and thermal insulation are critical, has not been extensively studied. Increasing the thickness of spacer fabrics through multilayer configurations may improve their ability to absorb impact energy while also enhancing thermal insulation due to the increased volume of entrapped air. At the same time, maintaining adequate air permeability is important to prevent excessive heat accumulation during movement. In this study, multilayer spacer fabric assemblies were produced by stacking identical 3D spacer fabrics and

joining the layers by stitching. Two-layer, three-layer, and four-layer structures were created using the same fabric type in order to evaluate the effect of layer number on performance without altering the fundamental fabric structure. The main objective of this research is to investigate the suitability of multilayer spacer fabrics as impact-protective components for winter jackets, with particular emphasis on impact energy absorption and thermal insulation properties. By examining the relationship between structural thickness and functional performance, this study aims to contribute to the development of protective winter garments that provide an effective balance between safety and thermal comfort.

## 2. EXPERIMENTAL STUDY

### 2.1. Materials

In this study, a 100% polyester 3D spacer fabric was utilized as the base material. To evaluate the effect of layered architecture on thermal and impact performance, four different configurations were prepared by stacking the base fabrics: single-layer (1L), double-layer (2L), triple-layer (3L), and quadruple-layer (4L). The structural integrity of the multi-layered samples was maintained through high-tenacity stitching. The thickness of each configuration was characterized using a digital thickness gauge. Based on the experimental measurements, the base single-layer fabric had a thickness of  $4.22 \pm 0.04$  mm. For the stacked configurations, the average thicknesses were determined as  $7.86 \pm 0.23$  mm for 2-layers,  $12.99 \pm 0.27$  mm for 3-layers, and  $16.45 \pm 1.02$  mm for 4-layers. The cross-sectional views and the general appearance of the prepared samples are presented in Figure 1.

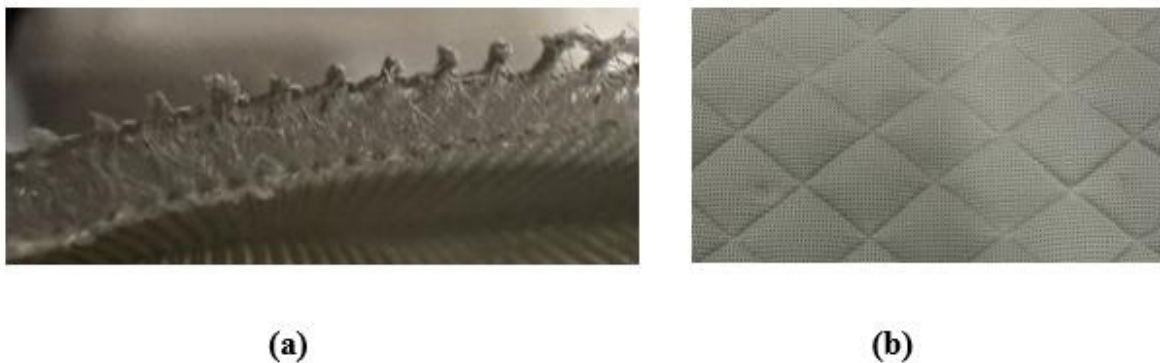


**Figure 1.** Morphological characteristics of the 3D spacer fabric: (a) Surface top view showing the porous knit structure, (b) Cross-sectional view showing the spacer monofilaments.

### 2.2. Impact Testing

The energy absorption capacity and impact resistance of the layered spacer fabric configurations were evaluated using a Besmak drop-weight impact tester. The experimental procedure was conducted in accordance with the ASTM D7136 standard. The test specimens were prepared with dimensions of  $59 \times 88$  mm. A hemispherical striker with a diameter of 16 mm was utilized to deliver a controlled impact. All samples were subjected to a constant impact energy level of 20 Joules to ensure a consistent comparison of the peak force and energy dissipation performance across the multi-layered structures.

### 2.3. Thermal Insulation Testing

The thermal comfort properties of the multi-layered spacer fabrics were characterized using an Alambeta thermal conductivity tester. The measurements were conducted in accordance with the ISO 11092 standard. This non-destructive testing method allowed for the simultaneous determination of key thermal parameters, including:

- **Thermal resistance ( $R_{ct}$ ):**  $m^2 \cdot K/W$
- **Thermal conductivity ( $\lambda$ ):**  $W/(m \cdot K)$
- **Thermal diffusivity (a):**  $mm^2/s$
- **Thermal absorption (b):**  $W \cdot s^{1/2}/(m^2 \cdot K)$

All tests were performed under controlled laboratory conditions ( $20 \pm 2$  °C temperature and  $65 \pm 5\%$  relative humidity).



## 2.4. Air Permeability Testing

The air permeability of the samples was measured using a Prowhite air permeability tester. The tests were performed in accordance with the ASTM D737 standard. A test pressure of 100 Pa was applied over a test area of 20 cm<sup>2</sup>. Multiple measurements were taken for each configuration to ensure statistical accuracy, and the results were recorded in \$mm/s\$ to evaluate the breathability of the layered structures.

## 3. RESULTS

### 3.1. Impact Performance Analysis

The impact performance of the multi-layered spacer fabrics at a 20 J energy level was evaluated based on peak force and energy absorption capacity (Table 2). The experimental data reveals that the 3-layer configuration provides superior protection, achieving the lowest peak force (1.838 kN) and the highest energy absorption (12.869 J) as shown in Table 1.

**Table 1.** Impact Results of Layered Spacer Fabrics

| <i>Configuration</i> | <i>Peak Force (kN)</i> | <i>Energy Absorption (J)</i> |
|----------------------|------------------------|------------------------------|
| 2 layers             | 2.502                  | 6.330                        |
| 3 layers             | 1.838                  | 12.869                       |
| 4 layers             | 2.012                  | 10.770                       |

A critical observation is the decline in performance for the 4-layer sample, which showed an increase in peak force to 2.012 kN and a decrease in energy absorption to 10.770 J compared to the 3-layer sample. This indicates that increasing the number of layers beyond three does not linearly enhance impact protection under these specific conditions. The reduction in energy dissipation for the 4-layer structure can be attributed to increased structural compaction and bending stiffness. At the 20 J energy level, the 4-layer assembly likely acts more as a rigid body, failing to utilize the buckling mechanism of the internal monofilaments as effectively as the 3-layer assembly. Therefore, the 3-layer configuration is identified as the optimal structure for impact-protective winter apparel.

### 3.2. Thermal Comfort and Performance Analysis

The thermal insulation properties of the layered spacer fabrics, characterized by thermal resistance ( $r$ ), conductivity ( $\lambda$ ), and absorption ( $b$ ), are detailed in Table 2.

**Table 2.** Thermal Properties of the Samples

| <i>Configuration</i> | <i>Thermal Conductivity <math>\lambda</math> (mW/m·K)</i> | <i>Thermal Resistance <math>r</math> (<math>10^{-3}</math> m<sup>2</sup>·K/W)</i> | <i>Thermal Absorption <math>b</math> (W·s<sup>1/2</sup>/m<sup>2</sup>·K)</i> |
|----------------------|-----------------------------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| 2 Layers             | 46.97                                                     | 167.43                                                                            | 73.80                                                                        |
| 3 Layers             | 50.47                                                     | 257.57                                                                            | 57.20                                                                        |
| 4 Layers             | 48.97                                                     | 336.63                                                                            | 52.77                                                                        |

As expected, the thermal resistance increased linearly with the number of layers, reaching a maximum of  $336.63 \times 10^{-3} \text{ m}^2 \cdot \text{K/W}$  for the 4-layer configuration. This significant enhancement in insulation is primarily due to the increased volume of stationary air trapped within the multiple spacer gaps. while the 3-layer structure provided the highest energy absorption in impact tests, its thermal conductivity was slightly higher (50.47 mW/m·K) than that of the 4-layer structure (48.97 mW/m·K). The lower conductivity of the 4-layer structure indicates a superior insulation capacity per unit thickness, likely due to more efficient "dead air" entrapment within the denser multi-layered assembly. Furthermore, the thermal absorption ( $b$ )—which represents the "cool/warm feel" upon initial contact—decreased from 73.80 to 52.77 W·s<sup>1/2</sup>/m<sup>2</sup>·K as the layers increased. This decrease indicates that the 4-layer structure provides a significantly "warmer" feel, which is a desirable characteristic for winter outerwear.

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### 3.3. Air Permeability Analysis

The results, shown in Table 3, demonstrate a clear trade-off between the number of layers and breathability.

**Table 3.** Air Permeability Results (ASTM D737)

| Configuration | Air permeability (cm <sup>3</sup> /cm <sup>2</sup> /s) | Standard deviation |
|---------------|--------------------------------------------------------|--------------------|
| 2 Layers      | 68.47                                                  | 1.50               |
| 3 Layers      | 54.57                                                  | 1.60               |
| 4 Layers      | 41.53                                                  | 1.27               |

The air permeability decreased from 68.47 cm<sup>3</sup>/cm<sup>2</sup>/s (2 layers) to 41.53 cm<sup>3</sup>/cm<sup>2</sup>/s (4 layers). While the 4-layer structure provides superior thermal insulation, its lower air permeability may limit the transport of metabolic heat and moisture during active use. The 3-layer configuration, with an air permeability of 54.57 cm<sup>3</sup>/cm<sup>2</sup>/s, offers a balanced physiological comfort level for functional winter garments.

## 4. CONCLUSION

In this study, the synergistic effects of multi-layered 3D spacer fabric architectures (2, 3, and 4 layers) on the impact protection and thermal comfort of winter outerwear were investigated. Based on the experimental results, the following conclusions were drawn:

- **Impact Protection Performance:** The 3-layer configuration was identified as the most effective structure for impact mitigation at a 20 J energy level. It achieved the highest energy absorption (12.869 J) and the lowest peak force (1.838 kN). The 4-layer assembly exhibited a decline in protective performance, likely due to increased structural stiffness.
- **Thermal Insulation:** A linear correlation was observed between the number of layers and thermal resistance. The 4-layer configuration provided the maximum thermal insulation (336.63 x 10<sup>-3</sup> m<sup>2</sup>·K/W), significantly reducing heat loss and providing a warmer initial contact feel with a thermal absorption value of 52.77 W·s<sup>1/2</sup>/m<sup>2</sup>·K.
- **Physiological Comfort:** Air permeability tests revealed a trade-off between insulation and breathability. While the 4-layer structure offered superior warmth, its air permeability (41.53 cm<sup>3</sup>/cm<sup>2</sup>/s) was the lowest among the tested samples. The 3-layer structure maintained a more balanced breathability level of 54.57 cm<sup>3</sup>/cm<sup>2</sup>/s.

In summary, the 3-layer spacer fabric architecture is recommended as the optimal design unit for functional winter jackets. This configuration provides the best overall balance by ensuring maximum safety against physical impacts while maintaining sufficient thermal insulation and breathability for the wearer in cold environments.

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## PREDICTING PHYSICAL PROPERTIES OF DENIM FABRICS FOLLOWING LOCAL BLEACHING USING POTASSIUM PERMANGANATE

Ebru Çalışkan<sup>1\*</sup>, İbrahim Erdem Kalkan<sup>2</sup>, Onur Balcı<sup>1</sup>, Cenk Şahin<sup>2</sup>, Esra Tabaş Asiltürk<sup>3</sup>

<sup>1</sup> Kahramanmaraş Sutcu Imam University, Textile Engineering Dep., K.Maras, Turkey

<sup>2</sup> Cukurova University, Department of Industrial Engineering, Adana, Turkey

<sup>3</sup> Baykan Denim, R&D Center, Malatya, Turkey

\* clskn.ebruu@gmail.com

### ABSTRACT

Denim is a fabric that stands out in the fashion industry for both its durability and timeless aesthetic. With advancements in production technologies, efforts to create different visual effects on denim surfaces have increased; in particular, localized bleaching techniques have become an important means of expression for designers and manufacturers. Local bleaching is a technique that creates a unique character by selectively lightening specific areas of the fabric. This method gives denim garments a unique character while creating a natural, lived-in look desired by consumers. The most commonly used chemical in the local bleaching process is potassium permanganate (KMnO<sub>4</sub>). Despite the growing popularity of environmentally friendly technologies in recent years, chemical-based local bleaching still plays a significant role in production. This is because the process is cost-effective. However, since the chemicals, application time, and fiber reactions in denim directly affect the final appearance, the process must be carefully managed.

This study aims to advance local denim bleaching processes by developing an AI-based module to predict their physical effects on fabric. Prediction models were created the process conditions of potassium permanganate local bleaching and the properties of the finished fabric serve as inputs, and the performance values of the final garment serve as outputs. Prediction models were developed and trained using various machine learning methods. The machine learning methods used include Extreme Gradient Boosting (XGB), random forests (RF), and artificial neural network (ANN) models. Quality output values were predicted using four different machine learning methods based on quality input data regarding fabric, process, and pre-potassium permanganate conditions. For this purpose, 1,200 data points were generated under controlled conditions. Of these data points, 70% were used for model training, and 30% were used for testing. Model performance was evaluated using average absolute percentage error values on the test data. The model to be developed will simultaneously predict physical effects such as weight, elasticity, shrinkage, tear strength, and tensile strength by combining process parameters and fabric properties, thereby increasing production consistency and contributing to reducing environmental impact by optimizing the use of potassium permanganate in local bleaching processes.

**Keywords:** Denim physical performance, Local bleaching, Machine learning, Potassium permanganate

### 1. INTRODUCTION

Denim fabric is a cotton twill fabric widely used in the textile industry due to its durability and unique surface characteristics; the result of dyeing the warp threads primarily with indigo while leaving the weft threads undyed creates blue tones on the front and lighter tones on the back [1]. This characteristic structure and the unique distribution of indigo dye on the textile surface allow denim fabric to develop different visual effects over time due to fading and mechanical abrasion [2]. With the rise in consumer demand in the fashion industry, various finishing methods have been developed to enhance the aesthetic appeal of denim surfaces; one such method is localized bleaching. Local bleaching enables the creation of a distressed

or “used” appearance by providing controlled lightening of specific areas of the denim fabric, and in the industry, it is frequently achieved by locally applying a potassium permanganate ( $\text{KMnO}_4$ ) solution via spraying [3, 4]. Potassium permanganate is a strong oxidizing agent that breaks down the indigo dye, causing localized fading on the fabric surface; parameters such as chemical concentration and processing time can affect both the visual result and the fabric’s physical and mechanical performance [1–3]. Artificial intelligence (AI) studies aimed at predicting the impact of production process conditions on a product’s physical performance have become quite widespread today.

In industrial production, AI and machine learning (ML) techniques are increasingly being used in the textile sector for applications such as quality control, production planning, parameter estimation, and process optimization. AI-based methods go beyond traditional statistical techniques, enabling learning from multivariate datasets, modeling complex relationships, and predicting process outputs with high accuracy [5]. AI and ML models enable the prediction of fabric properties, production quality parameters, and process outputs by learning from multivariate data [5]. For example, studies aimed at uncovering the relationships between production parameters and mechanical and quality properties in denim products have demonstrated that hybrid models such as artificial neural networks (ANN) and artificial bee colony can predict these properties by learning from production data [6]. Such approaches utilize process data collected on the production line, along with inputs such as yarn type and weave density, to predict the fabric’s physical and performance outputs, and model performance evaluations are conducted using statistical metrics such as Mean Absolute Percentage Error (MAPE) [6]. AI-based forecasting models go beyond manual time estimates in production planning, providing faster and more repeatable forecasts; this contribution helps guide key production objectives such as quality control, efficiency, and waste reduction [5]. Consequently, AI and ML in the textile industry emerge as strategic tools for data-driven production optimization, control of process parameters, and the reliable prediction of final product performance.

In this study, the aim is to predict not only the visual results of local bleaching processes performed on denim products using potassium permanganate, but also their effects on the fabric’s physical performance, using data-driven approaches. While there are studies in the literature on AI applications in textile production processes, research aimed at predicting the effects of local chemical finishing processes on fabric performance properties is limited. The approach developed in this context aims to predict process outcomes by modeling the complex relationships between production parameters and fabric properties using machine learning methods. The goal is to reduce trial-and-error methods in the production process, manage process parameters more effectively, and make the quality of the final product more predictable. In this context, the predictive model developed has been evaluated as a decision-support tool that could contribute to production efficiency, quality control, and sustainable chemical use in the local bleaching process.

## **2. EXPERIMENTAL STUDY**

### **2.1 Material**

A total of 50 denim woven fabrics with different characteristics were used in this study. In selecting the fabrics, specific criteria were applied to increase the diversity of the dataset and ensure that the models developed could represent different production conditions. In this regard, four key characteristics were considered: warp yarn dyeing technique, warp yarn dyeing machine type, fabric elasticity, and fabric weight. In terms of warp yarn dyeing techniques, fabrics dyed using pure indigo, bottom-dyeing, and top-dyeing methods were selected. Additionally, fabrics produced from dyed yarns using slasher and rope dyeing systems depending on the type of machine used to dye the warp yarns were included in the scope of the study. In terms of fabric elasticity, fabric types with different elasticity levels classified as rigid (elastane-free), comfort (18–25% elasticity), power elastic (30–40% elasticity), and super elastic (40–60% elasticity) were evaluated. In addition, the 8–12 oz weight range, commonly used in denim products, was included in the study. This selection approach ensured that fabric inputs were represented across a wide range of parameters, with the aim of enhancing the generalizability of the resulting dataset.

### **2.2 Method**

#### **2.2.1. Potassium Permanganate Bleaching Process**

As part of the experimental study, the denim fabrics obtained were cut and sewn to simulate industrial production conditions, completing the garment manufacturing process and resulting in denim garments for

use in the experiments. Following sewing, a dry finishing process was applied to impart localized effects to the products and create a uniform base for subsequent bleaching processes. In this context, a laser treatment was performed on all products using the same pattern on a VAV 900 Power model laser machine with a resolution of 32 DPI and a laser power of 60. During this process, a portion of the indigo dye on the fabric surface was removed.

The fabric panels obtained after the laser treatment were subjected to pretreatment to prepare the fabric surface prior to the bleaching processes. In this context, a process was applied that included a pre-wash at 50°C, an enzymatic treatment, and a mechanical stone wash. During the pretreatment, amylase enzyme, neutral enzyme, anti-fraying chemicals, and pumice stone were used to create both chemical and mechanical effects on the fabric surface. All processes were carried out in an industrial-grade drum washing machine, thereby preparing a suitable substrate for the sodium hypochlorite bleaching process prior to local bleaching applications. Following these pretreatments, a bleaching experiment was designed using sodium hypochlorite to achieve different substrate shades. In the experimental design, bleaching time, chemical concentration, and application level were identified as variable parameters, and 24 formulations were obtained by applying different combinations of these parameters. This resulted in denim garments with different shades and effects.

**Table 1.** Experiment Plan

| FACTOR                             | LEVEL |    |    |    |
|------------------------------------|-------|----|----|----|
| NUMBER OF BLEACHING PROCESS CYCLES | 1     | 2  | -  | -  |
| DURATION (minutes)                 | 3     | 5  | 7  | -  |
| BLEACH CONCENTRATION (mL/L)        | 10    | 15 | 20 | 25 |

Three-stage local bleaching treatments using potassium permanganate were performed on the 1,200 samples obtained from these different substrates. A 3 g/L potassium permanganate solution was applied to the denim garments via the spray method, and tests for weight (ASTM D3776), tear strength (EN ISO 13937-1:2000), tear strength (TS EN ISO 13934-1), elasticity (BS 4952), and perspiration resistance (ASTM D3107). The effect of potassium permanganate on the physical performance of different fabric shades was investigated.

### 2.2.3 Artificial Intelligence Research

*Random Forests (RF):* RF is an ensemble learning method that aims to achieve superior performance compared to a single predictor by combining the outputs of multiple individual estimators, particularly decision trees. These models are typically constructed using the “bagging” (bootstrap aggregating) technique, which involves building many specialized decision trees and aggregating their predictions.

*Extreme Gradient Boosting (XGB):* XGB is a widely used implementation of the Gradient Boosting Machines (GBM) method [7]. Alongside deep learning, it became one of the dominant approaches in competitive machine learning for structured data problems, particularly in 2016 and 2017. XGB is an ensemble learning method belonging to the boosting family. Boosting methods construct the final model in a sequential manner by iteratively training multiple base learners, typically decision trees. The core idea behind GBM, as implemented in XGB, is that each new learner focuses on correcting the residual errors made by the previous model. This is achieved by training each subsequent estimator to fit these errors [8]. By combining many weak base learners, the boosting approach forms a strong and highly accurate ensemble model.

*Artificial Neural Network (ANN):* ANN typically consists of an input layer, one or more hidden layers, and an output layer, where all layers are fully connected in a feed-forward manner. When an ANN contains two or more hidden layers, it is classified as a Deep Neural Network (DNN), forming the foundation of deep learning. In the context of deep learning, data is conceptually represented as vectors (points in a geometric space), and each layer applies a simple geometric transformation to these representations [7, 8]. Typically, network architecture for regression problems includes hidden layers and an output layer. Hidden layers consist of nonlinear processing units using activation functions such as Rectified Linear Unit (ReLU) or Hyperbolic Tangent (Tanh). For scalar regression tasks, the final layer or output layer typically consists of a single unit without an activation function. The model is commonly trained by minimizing a loss function such as Mean Squared Error (MSE) or Mean Absolute Error (MAE). The primary training mechanism is backpropagation, which efficiently computes the gradient of the loss with respect to network weights,



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enabling iterative weight updates via gradient descent [7, 8]. ANN architecture has led to significant advancements due to their ability to effectively model both structured and unstructured data.

### 3. RESULTS

#### 3.1 Modeling

Two modeling configurations were used to understand the effect of the input on the prediction model, based on physical test data measured before and after potassium permanganate treatment.

**Table 2.** Experimented Modeling Configurations

|                                    | Model-1 | Model-2 |
|------------------------------------|---------|---------|
| Weight (onz/yd <sup>2</sup> )      | ✓       | ✓       |
| Yarn Count (Ne)                    | ✓       | ✓       |
| Fabric Density (picks/cm)          | ✓       | ✓       |
| Coloring Type                      | ✓       | ✓       |
| Twill (3/1 Z)                      | ✓       | ✓       |
| Potassium Permanganate Status      | ✓       | ✓       |
| Number of Bleaching Process Cycles | ✓       | ✓       |
| Duration (minutes)                 | ✓       | ✓       |
| Bleach Concentration (mL/L)        | ✓       | ✓       |
| Raw Fabric Values                  | ✓       | ✓       |
| Pre-Hypo Values                    |         | ✓       |
| Actual Values After Bleaching      | ✓       | ✓       |

Table 2 presents all variables included in the collected dataset. The first five variables correspond to the properties of the raw garment fabric, while the following four variables represent the bleaching treatment parameters. The raw fabric values and pre-hypo values denote the initial and intermediate states of the properties to be predicted, whereas the final values correspond to the actual measurements obtained after the bleaching process.

Among these, the pre-hypo values serve as mid-treatment indicators and are expected to have a significant influence on the final outcomes. Therefore, their role is specifically examined by differentiating input–output modeling configurations to evaluate their impact on prediction performance.

To better clarify the experimental modeling setup, both configurations were formulated within a supervised learning framework where the objective is to predict the final fabric properties after the bleaching process. In this context, the input variables consist of fabric structural characteristics and bleaching process parameters, while the target outputs correspond to the post-treatment measured properties. Within Model-1, the prediction is carried out using only the raw fabric properties together with the process-related variables, without incorporating any intermediate-stage information. This configuration therefore represents a direct mapping from initial material and process conditions to final outcomes. In contrast, Model-2 extends this structure by including intermediate measurements (pre-hypo values) within the input space. These variables reflect the state of the fabric during the bleaching process and provide additional information about the ongoing transformation. As a result, Model-2 enables the model to learn not only from initial and process conditions but also from intermediate process evolution.

Accordingly, the two configurations differ in terms of the level of process information embedded in the input space, allowing a comparative evaluation of how intermediate-stage data affects prediction performance.

### 3.2 Prediction Results

In the study, the prediction performance of the RF, XGB, and ANN models were evaluated using the Mean Absolute Percentage Error (MAPE) metric. The evaluation results were compared and are presented in Table 3.

**Table 3.** Performance Comparison of Models by MAPE (%)

| Method | Model   | Tear Strength-Weft cN | Tear Strength-Warp cN | Tensile Strength-Weft kgf | Tensile Strength-Warp kgf | Elasticity % | Growth %     | Weight gr/m <sup>2</sup> |
|--------|---------|-----------------------|-----------------------|---------------------------|---------------------------|--------------|--------------|--------------------------|
| RF     | Model-1 | 17,32                 | 10,50                 | 9,85                      | 10,04                     | 15,88        | <b>15,38</b> | 2,39                     |
|        | Model-2 | 17,66                 | 10,45                 | 9,85                      | 10,04                     | <b>15,72</b> | 15,43        | 2,47                     |
| XGB    | Model-1 | <b>16,24</b>          | 10,24                 | <b>9,66</b>               | <b>9,42</b>               | 16,50        | 15,82        | <b>2,34</b>              |
|        | Model-2 | <b>16,24</b>          | <b>10,15</b>          | <b>9,66</b>               | <b>9,42</b>               | 16,62        | 15,82        | 2,39                     |
| ANN    | Model-1 | 23,52                 | 12,40                 | 19,76                     | 15,28                     | 37,49        | 23,29        | 7,55                     |
|        | Model-2 | 22,26                 | 12,71                 | 19,85                     | 15,25                     | 26,17        | 20,58        | 3,02                     |

The findings indicate that the XGB and RF models exhibited the lowest error rates across all datasets; in particular, they achieved a very high accuracy of 2.34% in weight prediction. While the ANN model demonstrated overall prediction success, it showed higher deviations compared to tree-based algorithms in parameters such as elasticity (37.49%) and tear strength. Overall, the models consistently predict the mechanical effects of the local bleaching process using potassium permanganate on denim fabric.

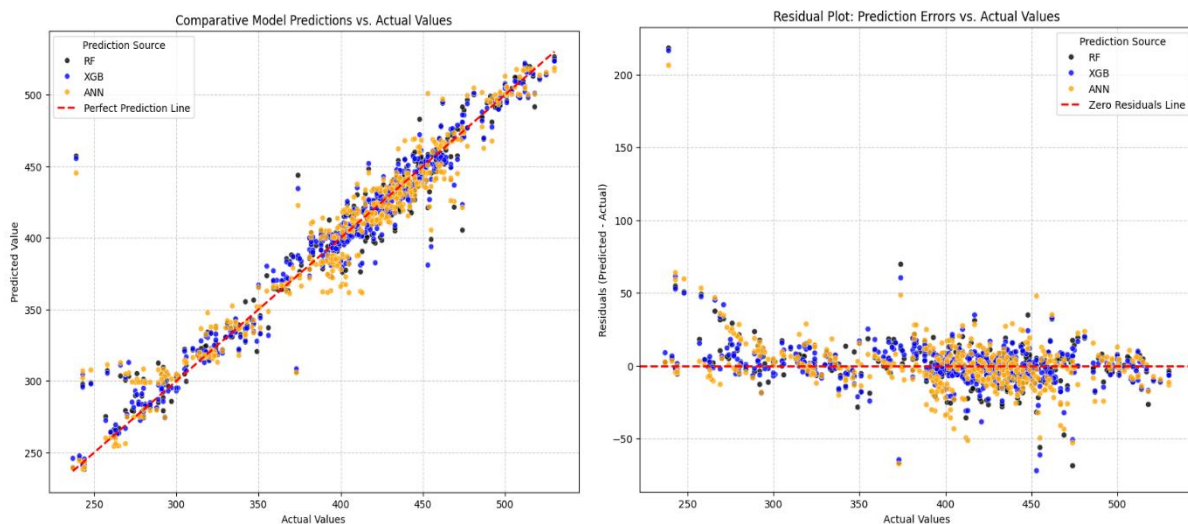


**Figure 1.** Weight Prediction Actual vs. Prediction Diagrams

Figure 1 presents the prediction scatter plots of the best-predicted variable, weight, comparing predicted values against the actual values (left). On the right, the corresponding residual plots are shown for three different methods, including the best-performing model, illustrating the distribution of prediction errors.

### 4. CONCLUSION

Although the local bleaching process in denim fabrics causes changes in the fiber structure, it has been demonstrated that the developed machine learning models can simulate this process with high accuracy. In

particular, the ability to predict critical parameters such as loss of strength and elasticity in advance indicates that quality losses associated with the use of potassium permanganate and trial-and-error costs can be minimized during the production phase. The results demonstrate that digital models can be effectively utilized as a decision-support mechanism in denim garment bleaching processes and contribute to sustainable quality control processes.

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## PROCESS–STRUCTURE–PROPERTY RELATIONSHIPS IN SOLUTION-BASED EXTRUSION PRINTING OF PLLA AND TPU

Özlem Yüksel<sup>1</sup>, İnkilem Göcek<sup>1</sup>

<sup>1</sup> Istanbul Technical University, Faculty of Textile Technologies and Design, Department of Textile Engineering, İstanbul, Turkey

[yukselozle@itu.edu.tr](mailto:yukselozle@itu.edu.tr), [goceki@itu.edu.tr](mailto:goceki@itu.edu.tr)

### ABSTRACT

Extrusion-based bioprinting using solution-based inks enables the fabrication of polymer structures with tunable mechanical properties, yet the combined influence of material selection and printing parameters remains unclear. In this study, poly(L-lactic acid) (PLLA) and thermoplastic polyurethane (TPU) structures were fabricated via solution-based direct ink writing (DIW). The effects of infill density, layer height, extrusion diameter (needle size), and layer count on tensile mechanical behavior were systematically investigated. The results demonstrate a strong material-dependent response, with PLLA exhibiting higher stiffness but brittle deformation, while TPU showed extremely high elongation and tensile strength despite low stiffness. For PLLA, non-monotonic trends in mechanical performance were observed with varying infill density, and a threshold infill level was required to achieve stable structures at higher layer heights. In addition, increasing extrusion diameter and layer count significantly improved stiffness and load transfer efficiency. Overall, the findings emphasize the need for coordinated optimization of material properties and processing parameters to achieve mechanically robust extrusion-printed polymer structures.

**Keywords:** 3D Printing, Bioprinting, TPU, PLLA, Wound dressing substrates

### 1.INTRODUCTION

Tissue engineering and regenerative medicine aim to develop functional substitute tissues capable of restoring damaged physiological structures [1]. By engineering tissues *in vitro*, biomimetic analogs can be generated under controlled conditions [2]. Advanced biomanufacturing strategies enable the creation of 3D biodegradable scaffolds with well-controlled spatial organizations, providing requisite mechanical support and guiding endogenous tissue ingrowth [3]. Within this framework, biofabrication integrates living cells and bioactive molecules using high-precision techniques [4, 5]. Among these technologies, printing strategies based on direct ink deposition have gained considerable interest due to their ability to allow systematic control of processing parameters.

Bio printing, among these modalities, is particularly distinguished by its capacity to generate living constructs with customized architectures through the spatially controlled deposition of multiple bio inks [6]. Coupled with computer-aided design (CAD), bioprinting facilitates the replication of anatomically relevant biological structures [7, 8]. Unlike conventional manufacturing, it allows precise control over material selection and processing kinetics [9].

Extrusion-based bioprinting (EBB) is widely employed owing to its capability to process a broad spectrum of biomaterials [10–12]. In EBB, bioinks are extruded through a nozzle via pneumatic or mechanical forces and deposited layer-by-layer [13, 14]. Despite limitations regarding printing resolution [15], hydrodynamic shear stresses can negatively impact cellular viability [16]. Recent studies have demonstrated the

biomedical potential of EBB, such as using 3D-printed CMC scaffolds [17] and PLLA mats [18] for enhanced wound healing and controlled drug delivery.

Bioinks serve as critical carriers for precise spatial placement [19], derived from natural and synthetic polymers [20]. They must satisfy stringent physicochemical requirements [21] where swelling behavior, degradation, and rheology determine printability and in vivo performance [22]. Cell-free biomaterial inks can achieve higher printing resolutions without concerns related to cell damage [23]. An optimal balance is required: viscosity must be low enough to prevent clogging but allow rapid structural recovery after deposition [24, 25].

Synthetic polymers offer highly controllable mechanical properties. TPU scaffolds demonstrate high elongation and tear resistance [26], whereas PLLA exhibits high strength, favorable degradation, and widespread biomedical utility [27]. Evaluating printability necessitates quantitative metrics such as filament height, width, and pore size [28, 29]. Recent studies have focused on optimizing ink compositions and nozzle designs [30]; however, systematic investigations examining how multiple printing parameters collectively affect mechanical performance remain limited. In this study, solution-based DIW was employed to fabricate TPU and PLLA structures. The effects of key printing parameters (infill density, layer height, extrusion diameter, layer number) on tensile mechanical behavior were systematically investigated to provide insights for developing robust wound dressing scaffolds.

## **2.. EXPERIMENTAL STUDY**

### **2.1.Materials**

Thermoplastic polyurethane (TPU, Elastollan C 59 D) in pellet form (BASF, Germany) and 2.85 mm natural transparent PLLA filament (Ultimaker, USA) were used. Solvents included Dimethylformamide (DMF), ethyl acetate (EA), and Dichloromethane (DCM). All experiments were carried out at 65% RH and 21 °C.

### **2.2.Solution Preparation**

Solutions were optimized for adequate gelation to ensure continuous filament extrusion. A 6 wt% PLLA solution was obtained by dissolving PLLA in a 7:3 (v/v) mixture of DCM and DMF, stirred at room temperature for 3 h. An 8 wt% TPU solution was dissolved in a 1:1 (w/w) mixture of EA and DMF, heated to 90 °C and stirred at 800 rpm for 6 h.

### **2.3.Printing and Imaging**

A multi-head 3D bioprinter (Axolotl Biosystems) equipped with UV curing and temperature-controlled printheads was utilized. Straight lines were printed by systematically varying one processing parameter at a time (layer height, infill density, layer count, or needle fineness) while keeping the others constant to evaluate their individual effects [31]. Microscopic images of the lines were captured to assess printability based on extrudability, filament formation, and shape fidelity. All polymer formulations demonstrated shear-thinning flow behavior, which facilitated smooth extrusion [32]. Extrusion through G22 and G25 blunt needles was achieved at 0.1–10 psi and 2 ml/s speed. The print bed was heated to 60 °C to facilitate solvent evaporation, while the extrusion heads remained unheated. The general fabrication setup and components of the extrusion system are illustrated in Figure 1.





**Figure 1:** Extrusion Based Bioprinting setup for the Axo Biosystem Printer

## 2.4. Characterization

Directional alignment of the scaffolds was qualitatively analyzed at 10x magnification using a polarized light microscope (BA300, Motic).

## 2.5. Tensile Strength Test

To evaluate the mechanical performance of the scaffolds, tensile testing was performed using a Zwick Roell universal testing machine according to EDANA 20.2.89. Rectangular test samples with dimensions of 1.5 cm × 2.5 cm were cut from the 3D printed constructs. Tests were carried out at a constant rate of 10 mm/min with a gauge length of 30 mm. Two independent measurements were taken for each sample to calculate the average values of tensile strength at break, elongation at break, and Young's modulus.

# 3. RESULTS

## 3.1. Visual Examination of Scaffolds

3D TPU and PLLA scaffolds were successfully fabricated with regular geometries. Macroscopic analysis confirmed that the pores were large, uniformly distributed, and interconnected, demonstrating high shape fidelity and structural integrity suitable for cell bioprinting applications.

## 3.2. Mechanical Strength Test

Mechanical performance was evaluated through tensile testing by systematically varying printing parameters.

### 3.2.1. Effect of Layer Count:

Comparing samples printed with 30% infill, 0.05 mm layer height, and a 25G needle, the 10-layer sample exhibited limited maximum tensile strength (1.11–1.24 MPa) and elongation at maximum force (0.39–0.69%), confirming a mechanically weak and brittle response. In contrast, the 12-layer sample exhibited a markedly improved mechanical response (Young's modulus: 292–734 MPa; tensile strength: 1.73–3.50 MPa). Increasing layer count enhances structural continuity and inter-layer bonding, resulting in better load transfer efficiency. Sample 2 exhibited a Young's modulus ranging between 50–290 MPa, indicating low stiffness with pronounced variability between repeated tests. The maximum tensile strength values were limited to 1.11–1.24 MPa, reflecting a reduced load-bearing capability. Elongation at maximum force ranged between 0.39–0.69%, confirming a mechanically weak and brittle response.

### 3.2.2. Influence of Extrusion Diameter:

The influence of extrusion diameter was evaluated by comparing structures printed at a 0.08 mm layer height with 8 layers. Structures printed with a finer 25G needle (35% infill) exhibited a very low and highly scattered Young's modulus (0.24–86 MPa), indicating an unstable elastic response. Their maximum tensile strength values remained limited (0.90–1.41 MPa), while elongation at maximum force varied widely

between 0.56–4.54%, suggesting non-uniform deformation behavior associated with weak inter-layer bonding and filament discontinuities. In contrast, the use of a larger 22G needle (30% infill) drastically improved structural integrity, demonstrating substantially higher stiffness (Young’s modulus: 299–1090 MPa) and enhanced tensile strength (5.64–9.88 MPa). This highlights that larger extrusion diameters promote filament continuity and improved inter-layer fusion.

### **3.2.3. Material-Dependent Behavior:**

Under identical printing conditions (30% infill, 0.05 mm height, 10 layers, 25G needle), PLLA exhibited moderate stiffness but limited tensile strength and low elongation (~0.6%), confirming a brittle response. Conversely, TPU showed a highly compliant elastic response with very low Young’s modulus (4.77–5.91 MPa) accompanied by exceptionally high tensile strength (26.14–27.75 MPa) and elongation exceeding 97%, confirming its elastomeric nature.

### **3.2.4. Effect of Infill Density at 0.05 mm Layer Height:**

The effect of infill density at a layer height of 0.05 mm was assessed across 30%, 35%, and 40% infill levels. Structures printed with 30% infill exhibited moderate stiffness (Young’s modulus of 50.38–289.85 MPa), limited tensile strength (1.11–1.24 MPa), and restricted elongation (0.39–0.69%), indicating a mechanically weak and brittle response. At an intermediate 35% infill, the structures showed a highly scattered stiffness response (398–2320 MPa) but consistently high tensile strength (7.79–8.03 MPa), suggesting improved filament bonding and efficient stress transfer. In comparison, increasing the infill density to 40% displayed moderate stiffness (597.07–728.54 MPa) but resulted in a reduced tensile strength (2.47–2.51 MPa), despite the higher material content. These results indicate a non-linear relationship, suggesting that an intermediate infill density (35%) may provide an optimal balance between structural integrity and material distribution.

### **3.2.5. Effect of Infill Density at 0.08 mm Layer Height:**

Infill density effects at a higher layer height (0.08 mm) were investigated across 30%, 35%, and 40% infill levels with 8 layers. Structures printed with 30% infill (using a 22 gauge needle) exhibited markedly higher stiffness, with Young’s modulus values ranging from 299 to 1090 MPa, accompanied by significantly improved tensile strength (5.64–9.88 MPa). The elongation at maximum force remained within a narrow range (0.42–0.56%), indicating a stable yet relatively brittle deformation behavior. In contrast, structures printed with 35% infill (also using a 22 gauge needle) demonstrated extremely low and highly variable Young’s modulus values (0.03–31.45 MPa), together with limited tensile strength and a broad elongation range (0.91–3.06%), suggesting poor interlayer bonding and structural heterogeneity within the printed scaffold. Conversely, upgrading to a 40% infill (using a 25 gauge needle) displayed a pronounced stiffness response (2612–3176 MPa) along with consistently high tensile strength (7.08–8.46 MPa), while maintaining comparatively low elongation values. These results suggest that increasing infill density at higher layer heights generally improves structural rigidity and load-bearing capacity, though the mechanical response does not follow a strictly monotonic trend due to variations in filament deposition and interlayer bonding.

## **4. CONCLUSION**

This study demonstrates that the mechanical performance of extrusion-based additively manufactured polymer structures is governed by a complex interplay between material type, extrusion continuity, infill density, and structural integrity. Material selection dictates the fundamental deformation behavior—ranging from brittle stiffness in PLLA to highly ductile responses in TPU. Printing parameters such as needle size, layer count, and infill density critically control load transfer efficiency and inter-layer bonding. The results reveal the presence of optimal threshold values rather than monotonic trends, indicating that achieving mechanically stable structures requires coordinated optimization of both material properties and processing parameters. These insights provide practical guidelines for tailoring the mechanical performance of extrusion-printed polymer systems for targeted biomedical applications.

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## **QUANTITATIVE ASSESSMENT OF JACQUARD FABRIC STRUCTURES: COMPARING KNIT AND WOVEN COTTON DESIGNS**

**Md Imranul Islam<sup>1</sup>, Grace Yip<sup>1</sup>, Sarah Nguyen<sup>1</sup>, Cheuk Tung Zoe Wong<sup>1</sup>, Whitney Crutchfield<sup>1</sup>**

<sup>1</sup>Fashion Institute of Technology

### **ABSTRACT**

The global jacquard fabric market, projected to grow from an estimated USD 3.7 billion in 2023 to USD 6.4 billion by 2030, reflects the rising demand for intricately designed textiles across fashion and home sectors. This research discusses how the structural differences between the woven and knitted jacquard fabrics affect their mechanical and performance properties when similar cotton yarns and designs are used for home textile applications. Two three-color woven jacquards and two knit jacquards were created using 20/2 Ne cotton yarns; the same type of yarn, color repeat, and production parameters were used in each so that only fabric construction varied. The construction for the woven jacquard was created in Pointcarre® and Adobe Photoshop® and then produced on a TC2 digital jacquard loom, while knit jacquards were programmed in Stoll M1 Plus® and knitted on a Stoll CMS 12-gauge machine. Fabrics were assessed using standard test methods for fabric weight and density, thickness, tensile/bursting strength, shrinkage, abrasion resistance, pilling, snagging, and stretch. Results depicted strong resistance to abrasion, no holes, and shade change value of 3.5 to 4.5 were obtained by all samples after 25,000 cycles. Pilling resistance varied from partially formed pills to no pills, with a snagging resistance of 3.5 to 4.5, respectively. For knit jacquard, stretchability was 50% in length direction and 120% in width direction under 5 lbs. tension. Woven jacquards were more stable in dimensions. All samples surpassed 200 lbf in tensile and bursting strength. Overall, findings proved that even under an equal visual and fiber composition, there are differences in both the mechanical and physical properties for the knit and woven jacquard fabrics. These results can help in selecting fabrics for home decor purposes such as decorative pillows, throws, and home bedding.

**Keywords:** cotton, home textiles, jacquard, product development



## RECYCLING OF PRE-VULCANIZED RUBBER WASTE FOR SUSTAINABLE HEEL COUNTER APPLICATIONS IN FOOTWEAR PRODUCTION

Barış BEKİROĞLU<sup>1,\*</sup>, Sezen UZUNOĞLU<sup>1</sup>, Eren OĞUZ<sup>1</sup>, Mustafa YENER<sup>1</sup>

<sup>1</sup> Eren Perakende ve Tekstil A.Ş., Footwear R&D Center, Tekirdağ, Türkiye

\*baris.bekiroglu@erenperakende.com

### ABSTRACT

Heel counters are critical structural components in footwear, providing dimensional stability and rearfoot support. Conventionally, these components are manufactured using resin–textile composite materials, which present limitations in terms of recyclability and environmental sustainability. In parallel, rubber-based foxing strips used in vulcanized footwear production generate a significant amount of pre-vulcanized rubber waste during size-dependent cutting and assembly processes. Despite their high material value, these wastes are typically discarded. In this study, a sustainable alternative heel counter material was developed by recycling multi-colored pre-vulcanized rubber waste generated during foxing production and assembly operations. The collected rubber scraps were reprocessed through controlled blending with virgin fillers and appropriate additives to obtain a composite structure capable of replacing conventional heel counter materials. The developed material was evaluated in terms of structural rigidity, dimensional stability, form retention, and process compatibility during footwear manufacturing. Comparative analyses were conducted between the recycled rubber-based heel counter and conventional resin–textile composite counterparts. The results indicate that the proposed recycled material provides sufficient mechanical performance while significantly reducing production waste and raw material consumption. This study demonstrates a circular production approach that transforms in-process rubber waste into a value-added functional footwear component, contributing to sustainable material innovation in the footwear industry.

**Keywords:** Sustainability, Footwear, Heel counter, Rubber recycling, Circular production

### 1. INTRODUCTION

The increasing demand for polymeric and elastomeric materials in industrial applications has led to a substantial rise in rubber waste generation worldwide. Due to their crosslinked three-dimensional structure, vulcanized rubber products are highly resistant to natural degradation and cannot be easily reprocessed like thermoplastics, which makes their disposal and recycling a major environmental and technical challenge [1]. Conventional waste management routes such as landfilling, stockpiling, and combustion are associated with environmental burdens, resource loss, and limited material recovery potential [1], [8].

In rubber recycling studies, one of the most common approaches is the incorporation of ground or reclaimed rubber into new composite systems. However, previous studies have shown that the use of waste rubber may lead to reductions in tensile performance, elongation, and overall structural consistency when interfacial compatibility between the recycled phase and the matrix is insufficient [5]. The utilization of rubber waste in composite materials has been shown to support circular economy principles while delivering acceptable mechanical performance for structural applications [8]. For this reason, the selection of elastomer systems, fillers, and curing conditions plays a critical role in determining the final performance of recycled rubber-based materials [2], [3]. In particular, the synergistic effect of silica as a primary reinforcing filler has been extensively documented in rubber composite systems, where filler–matrix compatibility plays a determining role in mechanical performance [7]. Reinforcing fillers such as silica have been reported to improve stiffness, hardness, and durability through better filler–matrix interaction, while alternative or non-reinforcing fillers such as calcium carbonate may remain insufficient for demanding structural applications [4], [7].

The footwear industry represents a relevant but relatively underexplored field for high-value rubber waste reutilization. Recent studies have demonstrated the feasibility of incorporating functionalized rubber waste into polymer composites for value-added applications in the leather and footwear sector [6]. In vulcanized footwear manufacturing, pre-vulcanized rubber waste is generated during foxing production and assembly processes, especially in size-dependent trimming operations. Since foxing strips are not always produced in exact size-specific lengths, excess material is cut during assembly, creating multi-colored pre-vulcanized rubber waste. Although this waste still retains functional material potential, it is generally removed from the production cycle.

At the same time, heel counters are essential structural components used to provide dimensional stability, rearfoot support, and form retention in footwear. These components are conventionally produced from resin–textile composite materials, which are functionally effective but limited in terms of recyclability and material circularity. This creates a material contradiction within the same production ecosystem: rubber-based in-process waste is discarded, while a different composite structure is introduced for a structural footwear part.

In this context, the present study investigates the development of a recycled rubber-based alternative heel counter material by upcycling pre-vulcanized foxing waste generated in footwear production. The study focuses on the optimization of elastomer selection, filler system, and curing behavior in order to achieve the targeted hardness, bending resistance, and process compatibility required for heel counter applications. The originality of the study lies in transforming in-process rubber waste into a value-added structural footwear component through an industrially applicable circular material approach. The findings are expected to contribute to sustainable footwear manufacturing and to the broader literature on recycled rubber-based functional composites [1], [6], [8].

## **2. EXPERIMENTAL STUDY**

### **2.1 Materials**

Pre-vulcanized rubber waste used in this study was collected from foxing production and footwear assembly lines. The waste consisted of multi-colored rubber scraps generated during size-dependent trimming operations. Due to their application in internal structural components, visual heterogeneity was not considered a limiting factor. The collected waste materials were processed within a maximum of 15 days to maintain compound consistency.

Three different virgin elastomer systems were evaluated in the experimental design: natural rubber (NR), styrene-butadiene rubber (SSBR), and high styrene rubber. These elastomers were selected to investigate the effects of stiffness, processability, and cost-performance balance on the final material properties.

Two different filler systems were considered: calcium carbonate ( $\text{CaCO}_3$ ) and silica. Calcium carbonate was evaluated as an economical filler option, while silica was selected as a reinforcing filler candidate due to its known ability to improve mechanical strength and durability through enhanced filler–matrix interaction [3], [7]. PEG4000 was incorporated as a silica dispersing agent to improve filler distribution within the compound.

In addition, stearic acid was used as a processing aid. Since the pre-vulcanized foxing waste retains residual vulcanization agents from its original compound — including zinc oxide and sulfur — these components were not separately added to the formulations. TBBS80 (N-tert-butyl-2-benzothiazolesulfenamide) was incorporated as the accelerator to control cure kinetics and ensure processing stability.

### **2.2 Material Preparation**

The collected rubber waste was size-reduced and homogenized prior to processing. The recycled rubber was then blended with selected elastomers, fillers, and additives using conventional rubber compounding techniques.

The initial formulation design, including the targeted recycled rubber content levels, is presented in Table 1. The virgin elastomer type and filler system were left as variables to be determined through systematic experimental evaluation.

**Table 1.** Initial formulation design for recycled rubber-based heel counter compounds (wt %).

| Component                   | F1  | F2  | F3  |
|-----------------------------|-----|-----|-----|
| Pre-vulcanised foxing waste | 50  | 60  | 70  |
| Virgin elastomer*           | 20  | 15  | 10  |
| Filler*                     | 13  | 13  | 13  |
| Process oil                 | 5   | 5   | 5   |
| ZnO                         | 3   | 3   | 3   |
| Stearic acid                | 2   | 2   | 2   |
| Sulfur                      | 1,5 | 1,5 | 1,5 |
| Accelerator                 | 1   | 1   | 1   |

The compounds were subsequently shaped into heel counter forms and subjected to controlled vulcanization conditions.

### 2.2.1. Composition Definition

To clearly distinguish the recycled material ratio within the rubber phase from its proportion in the total compound, two different definitions were used. The recycled rubber fraction in the total rubber phase was calculated according to Eq. (1), while the recycled rubber fraction in the total compound was defined according to Eq. (2).

$$RRF(\%) = \frac{W_{rr}}{W_{rr} + W_{ve}} \times 100 \quad \text{Eq. 1}$$

$$RCF(\%) = \frac{W_{rr}}{W_{rr} + W_{ve} + W_f + W_a} \times 100 \quad \text{Eq. 2}$$

where  $W_{rr}$  is the weight of recycled rubber,  $W_{ve}$  is the weight of virgin elastomer,  $W_f$  is the weight of filler, and  $W_a$  is the total weight of additives used in the compound.

### 2.3 Experimental Design

A systematic design of experiments (DOE) was conducted to evaluate the effects of three main parameters: recycled rubber ratio (50%, 60%, 70%), virgin elastomer type (NR, SSBR, high styrene rubber), and filler system (none,  $\text{CaCO}_3$ , silica). The experimental matrix and key observations are summarized in Table 2.

**Table 2.** Design of experiments (DOE) and evaluation of elastomer and filler systems.

| Trial | Recycled Rubber (%) | Elastomer Type      | Filler Type     | Key Observation                                             |
|-------|---------------------|---------------------|-----------------|-------------------------------------------------------------|
| T1    | 50                  | Natural Rubber (NR) | None            | Low stiffness; insufficient structural performance          |
| T2    | 50                  | High styrene rubber | $\text{CaCO}_3$ | Economical but inadequate toughness                         |
| T3    | 50                  | SSBR                | Silica          | Improved reinforcement; acceptable performance              |
| T4    | 60                  | Natural Rubber (NR) | $\text{CaCO}_3$ | Hardness limited (~77 Shore A)                              |
| T5    | 60                  | High styrene rubber | Silica          | Target hardness achieved (~90 Shore A); optimal performance |
| T6    | 60                  | SSBR                | None            | Acceptable performance but economically unfavorable         |
| T7    | 70                  | Natural Rubber (NR) | Silica          | Improved strength but insufficient stiffness                |
| T8    | 70                  | High styrene rubber | None            | Reduced rigidity due to absence of reinforcement            |

|           |    |      |                   |                                                    |
|-----------|----|------|-------------------|----------------------------------------------------|
| <b>T9</b> | 70 | SSBR | CaCO <sub>3</sub> | Moderate performance; not suitable for application |
|-----------|----|------|-------------------|----------------------------------------------------|

Regarding filler systems, calcium carbonate provided cost advantages but showed poor toughness performance, with fracture observed under repeated bending conditions. In contrast, silica-filled systems demonstrated significantly improved bending resistance and structural integrity.

## 2.4 Curing Behavior and Optimization

Due to the variability in curing history and storage conditions of pre-vulcanized rubber waste, curing behavior was carefully controlled throughout the study. Since the pre-vulcanized foxing waste retains residual zinc oxide and sulfur from its original compound, these components were not separately added. Instead, TBBS80 was selected as the primary accelerator due to its safer and less aggressive curing profile compared to more reactive accelerator systems. Its curing response is also less sensitive to small dosage variations, making it particularly suitable for compounds containing heterogeneous pre-vulcanized rubber waste.

A second experimental matrix was developed to evaluate the combined effects of silica content (10%, 13%, 16% w/w) and TBBS80 level (low: 0.5 kg, medium: 1.5 kg, high: 2.5 kg) on curing stability. The results are summarized in Table 3.

**Table 3.** Effect of silica content and TBBS level on curing behavior and process stability.

| Trial     | Recycled Rubber (%) | Silica Content (% w/w) | TBBS Level | Target TS2 | Observation                  |
|-----------|---------------------|------------------------|------------|------------|------------------------------|
| <b>C1</b> | 50                  | 10                     | Low        | ~1:25      | Slower curing tendency       |
| <b>C2</b> | 50                  | 13                     | Medium     | ~1:25      | Stable curing behavior       |
| <b>C3</b> | 50                  | 16                     | High       | ~1:25      | Risk of early curing         |
| <b>C4</b> | 55                  | 10                     | Medium     | ~1:25      | Acceptable curing stability  |
| <b>C5</b> | 55                  | 13                     | High       | ~1:25      | Increased curing rate        |
| <b>C6</b> | 55                  | 16                     | Low        | ~1:25      | Delayed curing tendency      |
| <b>C7</b> | 60                  | 10                     | High       | ~1:25      | Fast curing; scorch risk     |
| <b>C8</b> | 60                  | 13                     | Low        | ~1:25      | Controlled and stable curing |
| <b>C9</b> | 60                  | 16                     | Medium     | ~1:25      | Balanced curing behavior     |

The curing onset time (TS2) was targeted at approximately 1 minute and 25 seconds for all formulations. TBBS80 levels were adjusted accordingly to maintain this target value across different compositions.

In silica-containing systems, TBBS80 was introduced in a controlled manner during the initial mixing stage to ensure uniform filler distribution and balanced crosslink formation. This approach was particularly critical for the production of heel counter plates (~1.4 mm thickness), where uncontrolled curing could lead to processing defects.

## 2.5 Performance Evaluation

Shore A hardness measurements were performed using a LOYKA LX-A-1 durometer in accordance with ISO 7619-1.

Flexural performance was evaluated through a comparative bending test in which specimens were subjected to 100 repeated flexion cycles (alternating inward and outward bending). The degree of permanent deformation and surface integrity after cycling were assessed visually and compared against a conventional resin–textile composite heel counter used as the reference material. Results were categorized according to the criteria presented in Table 4.

**Table 4.** Bending performance evaluation criteria.

| Result   | Description                                |
|----------|--------------------------------------------|
| Pass     | No visible deformation or cracking         |
| Marginal | Minor surface deformation, shape retained  |
| Fail     | Permanent deformation or fracture observed |

### 3. RESULTS

The experimental study demonstrated that the mechanical performance of recycled rubber-based heel counter materials is strongly dependent on elastomer selection, filler system, and curing conditions.

#### 3.1 Effect of Elastomer System

As presented in Table 2, the type of virgin elastomer had a significant influence on the hardness and structural performance of the developed materials. Natural rubber (NR)-based formulations were initially considered due to their cost advantage; however, these systems failed to achieve the target hardness range, with measured values remaining around 77 Shore A. This level of hardness was insufficient to provide the required dimensional stability for heel counter applications.

SSBR-based formulations demonstrated comparable mechanical performance to high styrene rubber systems in terms of hardness and structural behavior. However, due to their higher cost relative to performance gain, SSBR was not considered suitable for industrial implementation and was excluded from further optimization.

High styrene rubber-based formulations demonstrated the best potential for achieving the required stiffness and structural integrity. Therefore, this elastomer system was selected as the primary matrix for the subsequent optimization stages.

#### 3.2 Effect of Filler System

The selection of filler type played a critical role in determining the mechanical behavior of the developed material. As shown in Table 2, calcium carbonate ( $\text{CaCO}_3$ )-filled formulations provided economic advantages but exhibited insufficient toughness under dynamic loading conditions. When subjected to the bending test described in Section 2.5,  $\text{CaCO}_3$ -based specimens showed permanent deformation and surface cracking within 100 cycles, resulting in a Fail assessment according to the criteria in Table 4. This behavior indicates poor resistance to repeated flexural loading, which is a critical requirement for heel counter applications.

In contrast, silica-filled systems demonstrated significantly improved mechanical performance. The addition of silica enhanced both stiffness and fracture resistance, which can be attributed to improved filler–matrix interaction and more efficient stress transfer within the composite structure [3], [7]. Silica-reinforced specimens subjected to 100 bending cycles showed no visible deformation or cracking, receiving a Pass assessment according to Table 4.

Experimental observations indicated that a silica content of approximately 13% (w/w) provided an optimal balance between hardness and flexibility. At this level, the material achieved the target hardness range of 85–88 Shore A while maintaining bending resistance without visible cracking or plastic deformation [4].

#### 3.3 Combined Effect of Elastomer and Filler System

The combined use of high styrene rubber and silica filler, as presented in Table 2 (Trial T5), yielded the most favorable performance among all evaluated combinations. This improvement is attributed to the reinforcing effect of silica and the stiffness contribution of high styrene elastomer, consistent with previous findings in rubber composite systems [3], [7].

Flexural performance evaluations confirmed that silica-reinforced formulations exhibited superior resistance to repeated deformation compared to non-reinforced or  $\text{CaCO}_3$ -based compositions. This behavior further confirms the importance of filler–matrix interactions in determining structural performance [3].

Based on these findings, the selected formulation was established and is presented in Table 5.



**Table 5.** Selected formulation for the recycled rubber-based heel counter compound.

| Component                   | Role                    | Content (wt%) |
|-----------------------------|-------------------------|---------------|
| Pre-vulcanized foxing waste | Recycled rubber matrix  | 75,4          |
| SBR                         | Virgin elastomer        | 9,4           |
| Silica                      | Reinforcing filler      | 13,2          |
| PEG4000                     | Silica dispersing agent | 0,57          |
| Stearic acid                | Processing aid          | 1,13          |
| TBBS                        | Accelerator             | 0,28          |
| <b>Total</b>                |                         | <b>100</b>    |

It is noted that the recycled rubber content in the selected formulation corresponds to a recycled rubber fraction (RRF) of 88.9% within the rubber phase, and a recycled compound fraction (RCF) of 75.4% within the total compound, as defined by Eq. (1) and Eq. (2) respectively.

### 3.4 Effect of Recycled Rubber Content

The recycled rubber ratio had a direct influence on both mechanical properties and process stability. The relationship between recycled rubber content and hardness, derived from the DOE trials prior to accelerator optimization, is presented in Figure 1.

Among the evaluated compositions, formulations with recycled rubber content around 60% within the rubber phase provided the most balanced performance during the DOE stage. However, following curing and filler optimization, the final selected formulation achieved a recycled rubber content of 75.4% in the total compound while maintaining the target hardness range, demonstrating that higher recycled content is achievable through systematic process optimization.

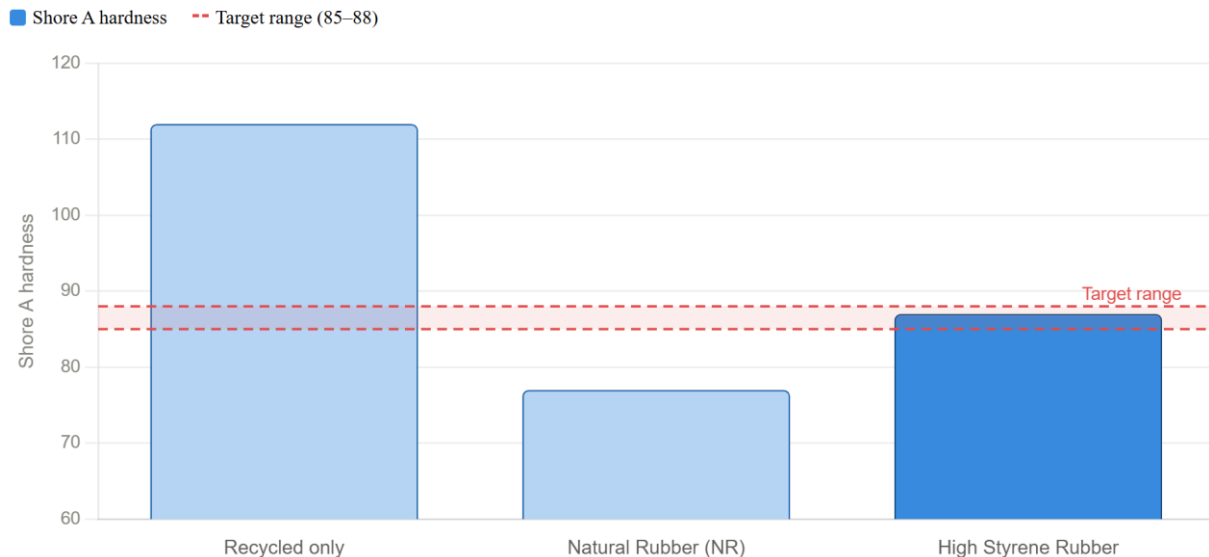


**Figure 1.** Effect of elastomer system on Shore A hardness of recycled rubber-based heel counter compounds (silica filler, 60% recycled rubber content, prior to accelerator optimization).

### 3.5 Effect of Filler System on Bending Performance

A comparative assessment of silica and calcium carbonate filler systems under repeated bending conditions is presented in Figure 2. Silica-reinforced specimens consistently achieved a Pass result, while  $\text{CaCO}_3$ -filled specimens resulted in Fail outcomes due to fracture and permanent deformation within 100 cycles.

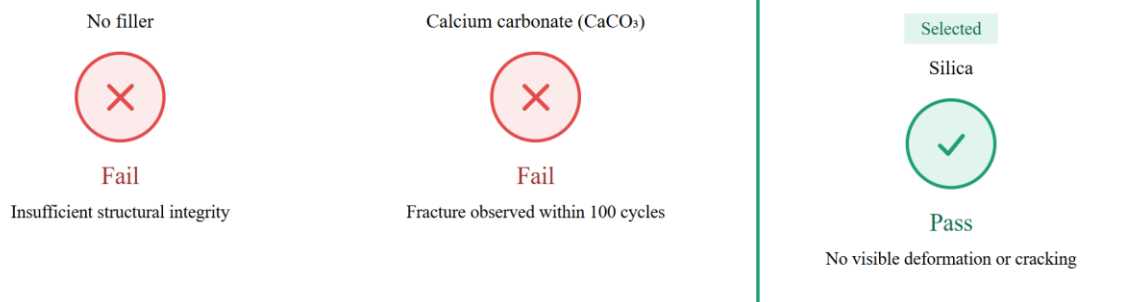


**Figure 2.** Comparative bending performance of recycled rubber-based heel counter compounds with different filler systems after 100 repeated flexion cycles.

### 3.6 Curing Behaviour and TBBS80 Optimization

The results summarized in Table 3 demonstrate that silica content and TBBS80 level significantly affect curing stability. The TS2 value was successfully maintained at approximately 1 minute and 25 seconds across all formulations by adjusting TBBS80 levels, ensuring consistent processing conditions and minimizing batch-to-batch variability.

TBBS80 optimization contributed to stabilization of curing kinetics, reduction of premature vulcanization risk, and improvement of curing homogeneity. The effect of TBBS80 level on curing stability is illustrated in Figure 3. Target TS2: ~1 min 25 sec. Conditions: silica 13% w/w, recycled rubber 60%, heel counter plate thickness ~1.4 mm.

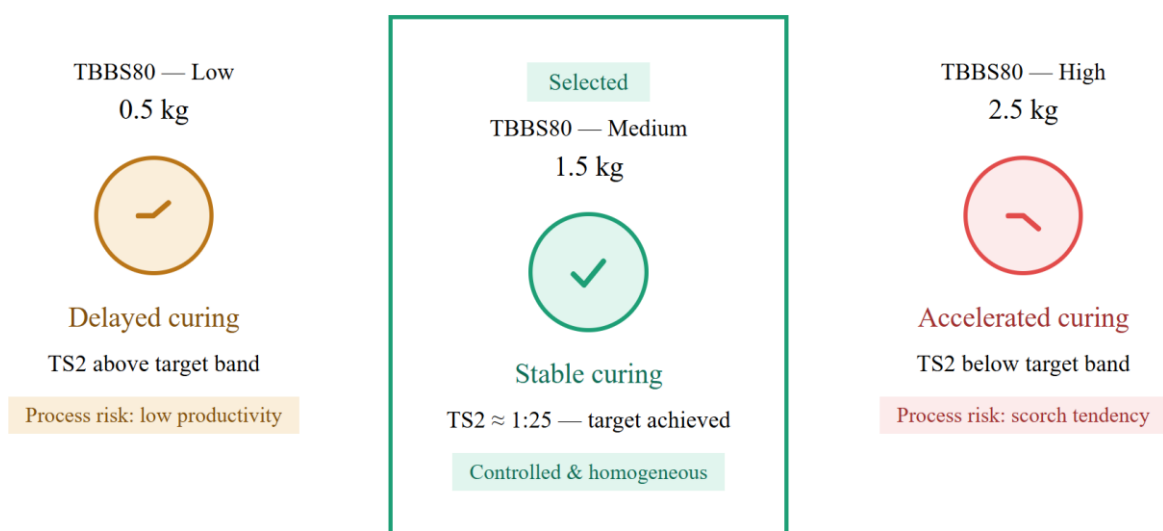


**Figure 3.** Effect of TBBS80 accelerator level on curing stability of recycled rubber-based heel counter compounds (silica 13% w/w, recycled rubber 60%).

### 3.7 Industrial Applicability

From an industrial perspective, the selected formulation demonstrated good compatibility with existing footwear manufacturing processes. No significant deviations were observed during shaping, forming, or assembly operations. The developed material maintained its structural integrity during processing and provided adequate form retention, confirming its suitability for heel counter production.

#### 4. CONCLUSION

This study presented a sustainable material development approach by utilizing pre-vulcanized rubber waste generated during footwear production as a functional heel counter component. A systematic experimental design was conducted to evaluate the effects of elastomer type, filler system, recycled rubber ratio, and curing behavior on the performance of the developed material.

Among the evaluated elastomer systems, high styrene rubber was identified as the most suitable option due to its ability to provide the required stiffness and hardness. Natural rubber-based systems remained around 77 Shore A, insufficient for structural heel counter applications, while SSBR-based formulations were excluded due to economic limitations.

The filler system evaluation demonstrated that silica provided significant improvements in mechanical performance compared to calcium carbonate. At an optimal silica content of approximately 13% (w/w), the material achieved the target hardness range of 85–88 Shore A while maintaining bending resistance without fracture or plastic deformation under 100 repeated flexion cycles. Calcium carbonate-filled systems consistently failed the bending performance criteria due to insufficient toughness.

Curing behavior was successfully controlled by optimizing TBBS80 levels to maintain a stable TS2 value of approximately 1 minute and 25 seconds. This approach ensured consistent processing conditions and minimized the risk of premature vulcanization across different batches.

Following systematic optimization of elastomer selection, filler system, and curing conditions, the selected formulation achieved a recycled rubber content of 75.4% in the total compound and 88.9% within the rubber phase, demonstrating that high recycled content is achievable without compromising mechanical performance.

From an industrial perspective, the developed material demonstrated good compatibility with existing footwear manufacturing processes, confirming its applicability for heel counter production.

Overall, this study demonstrates that pre-vulcanized rubber waste can be effectively upcycled into a value-added structural footwear component through appropriate material selection and process optimization. The proposed approach contributes to circular production strategies and offers a practical pathway for sustainable material innovation in the footwear industry [1], [6], [8].

Future work will focus on large-scale production validation, long-term durability performance, and further optimization of material formulations.

#### ACKNOWLEDGMENT

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## RESEARCH ON THE PERFORMANCE OF YARNS AND FABRICS DESIGNED AND PRODUCED WITH NATURAL VEGAN FIBER BLENDS FOR SUSTAINABILITY

Gökhan GÜNEŞ<sup>1,\*</sup>, Osman BABAARSLAN<sup>2</sup>

<sup>1,\*</sup> Calık Denim Textile A.Ş. R&D Department, Yeşilyurt/Malatya, Türkiye

<sup>2</sup> Cukurova University, Engineering Faculty, Department of Textile Engineering, Balcalı/Adana, Türkiye

\* gokhan.gunes@calikdenim.com

### ABSTRACT

This study investigates the potential of Pineapple Leaf Fiber (PALF) as a sustainable alternative in denim fabric production within the textile industry. The research methodology involves producing fabric samples made from palf-containing yarns from various Ne and subjecting them to comprehensive physical testing. Ne 10/1 Siro Spun Yarn 85%Cotton/15%PALF, Ne 12/1 Ring Spun Yarn 85%Cotton/15%PALF, Ne 20/1 Siro Spun Yarn 85%Cotton/15%PALF samples were subjected to comparative analysis.

Results validate Pineapple Leaf Fiber's suitability for high-performance sustainable textiles. The textile industry is accelerating its search for sustainable materials due to increasing global consumption and environmental concerns. In this context, fibers obtained from agricultural waste are distinguished by their advantages of renewable resource utilization and low environmental impact. Pineapple Leaf Fiber, derived from the leaves of the pineapple plant (*Ananas comosus*), has emerged as a promising alternative for sustainable textile production. PALF differentiates itself from conventional fibers through minimal agricultural input requirements, low water consumption, natural antibacterial properties, and high moisture retention capacity. In the study, yarn and fabric samples containing different PALF ratios were produced, and their physical and mechanical properties were comprehensively evaluated. Comparative analyses, weight dry, weight wash, stiffness, pH, tensile warp, tensile weft, tear warp, tear weft, shrinkage properties of the produced fabrics were evaluated.

This study aims to demonstrate the viability of PALF as a sustainable alternative to conventional fibers in denim fabric production. Experimental results show that PALF integration enhances fabric performance while contributing to environmental sustainability. The research seeks to lead the wider adoption of sustainable materials in the textile industry and promote a more environmentally conscious manufacturing approach. The findings indicate that PALF is not only an ecological alternative but also a competitive raw material in high-performance textile production.

The research also addresses the growing demand for sustainable textiles within the context of circular economy principles. By utilizing agricultural by-products that would otherwise be discarded, PALF represents an exemplary model of resource efficiency and waste reduction in textile manufacturing. This approach aligns with global sustainability goals while offering technical solutions that meet the demanding requirements of modern textile applications.

**Keywords:** *Pineapple Leaf Fiber (PALF), Cellulosic Fibers, Life Cycle Assessment (LCA), Sustainable Fabric Design, Agricultural Waste Valorization, Fabric Performance Analysis.*

### 1. INTRODUCTION

The textile industry is accelerating its search for sustainable materials due to increasing global consumption and environmental concerns. In this context, fibers obtained from agricultural waste are distinguished by their advantages of renewable resource utilization and low environmental impact. Pineapple Leaf Fiber



(PALF), derived from the leaves of the pineapple plant (*Ananas comosus*), has emerged as a promising alternative for sustainable textile production.

PALF differentiates itself from conventional fibers through minimal agricultural input requirements, low water consumption, natural antibacterial properties, and high moisture retention capacity. As noted by Mishra et al. PALF is characterized by high cellulose content (70-82%), which contributes to its high strength values. Studies conducted by Bozacı et al. emphasize PALF's thermal comfort properties and moisture management capability.

From a Life Cycle Assessment (LCA) perspective, the environmental impacts of producing 1kg Ready-to-Spin Pineapple Leaf Fibers (RTS PALF) were analyzed across five key categories: Climate Change (6.83 kg CO<sub>2</sub>-eq), Freshwater Ecotoxicity (305 CTUe), Particulate Matter (2.84×10<sup>-7</sup> Disease Inc), Water Use (5.99 m<sup>3</sup> depriv.), and Freshwater Eutrophication (3.65×10<sup>-3</sup> kg P-eq). This data was extracted from the Thailand supply chain and evaluated in accordance with EU PEF guidelines.

This study aims to demonstrate the viability of PALF as a sustainable alternative to conventional fibers in denim fabric production. Experimental results show that PALF integration enhances fabric performance while contributing to environmental sustainability. The research seeks to lead the wider adoption of sustainable materials in the textile industry and promote a more environmentally conscious manufacturing approach.

The findings indicate that PALF is not only an ecological alternative but also a competitive raw material in high-performance textile production. With the addition of elastomeric components, the elasticity and strength properties of PALF-based fabrics were significantly improved. This demonstrates that PALF can be successfully used in performance-demanding textile applications such as denim.

The research also addresses the growing demand for sustainable textiles within the context of circular economy principles. By utilizing agricultural by-products that would otherwise be discarded, PALF represents an exemplary model of resource efficiency and waste reduction in textile manufacturing. This approach aligns with global sustainability goals while offering technical solutions that meet the demanding requirements of modern textile applications.

## 2. EXPERIMENTAL STUDY

In this study, The Pineapple Leaf Fibers used in this study were extracted from the leaves of the pineapple plant (*Ananas comosus*). PALF with 11.4 dtex fineness and 38-60 mm length. three different weft yarn compositions were utilized for the production of Pineapple Leaf Fiber (PALF) based sustainable denim fabrics. Ne 12/1 RSAN267 (100% Organic Cotton) was used as the standard warp yarn for all denim fabric samples. The weft yarns used in the study are presented in detail in Table 1..

**Table 1.** Properties of weft yarns used in the study.

| YARN CODE     | WEFT YARNS                                  |
|---------------|---------------------------------------------|
| <b>GNS-10</b> | Ne 10/1 Siro Spun Yarn (85%Cotton/15% PALF) |
| <b>GNS-12</b> | Ne 12/1 Ring Spun Yarn (85%Cotton/15% PALF) |
| <b>GNS-20</b> | Ne 20/1 Siro Spun Yarn (85%Cotton/15% PALF) |

## 3. RESULTS

Fabric samples were conditioned for 24 hours under standard atmospheric conditions after finishing processes and subjected to the following tests. Weigth (ASTM D3776), Stiffness (ASTM D4032), Ph (MORAPEX-A), Tensile (ASTM D5034), Tear (ASTM D1424), Shringkage (AATCC 135).

This report presents a comprehensive analysis of the physical and mechanical properties of three distinct weft fabric samples composed of different yarn structures and fiber compositions.

**Table 2.** Fabric Test Results

| YARN CODE     |                                               | WEIGHT                    |                            | STIFFNESS<br>( kg ) | pH   | TENSILE<br>( kgf ) |      | TEAR<br>( grf ) |      | SHRINKAGE<br>( % ) |      |
|---------------|-----------------------------------------------|---------------------------|----------------------------|---------------------|------|--------------------|------|-----------------|------|--------------------|------|
|               |                                               | DRY<br>oz/yd <sup>2</sup> | WASH<br>oz/yd <sup>2</sup> |                     |      | WARP               | WEFT | WARP            | WEFT | WARP               | WEFT |
| <b>GNS-10</b> | Ne 10/1 Siro Spun Yarn<br>(85%Cotton/15%PALF) | 9,8                       | 9,9                        | 1,04                | 4,38 | 65                 | 53   | 5545            | 5219 | -2,4               | -1,4 |
| <b>GNS-12</b> | Ne 12/1 Ring Spun Yarn<br>(85%Cotton/15%PALF) | 9,2                       | 9,5                        | 0,8                 | 4,19 | 80                 | 53   | 5741            | 5872 | -3,6               | -0,8 |
| <b>GNS-20</b> | Ne 20/1 Siro Spun Yarn<br>(85%Cotton/15%PALF) | 7,7                       | 7,7                        | 0,66                | 4,02 | 73                 | 26   | 6002            | 3588 | -1,2               | -0,4 |

All three yarns are composed of an 85% cotton and 15% PALF. GNS-10 offers a more rigid structure with the highest weight and stiffness values, while GNS-12, produced with the ring spun technique, exhibits the highest tensile strength in the warp direction. GNS-20, with the lowest weight and stiffness values, promises a lighter and softer texture, and demonstrates the highest dimensional stability. However, the low weft-direction tensile and tear strengths of GNS-20 necessitate careful consideration in its application. The pH values of all yarns fall within the acceptable range for textile products.

#### 4. CONCLUSION

This research comprehensively evaluated the performance of yarns and denim fabrics incorporating Pineapple Leaf Fiber (PALF) as a sustainable alternative to conventional textile fibers. The study successfully demonstrated the technical viability of using PALF in denim production, highlighting its potential to contribute to a more environmentally conscious textile industry.

Yarn selection should be guided by the specific requirements of the end product (weight, softness, durability, dimensional stability). GNS-12 is suitable for high-strength applications, whereas GNS-20 is ideal for designs prioritizing lightness and dimensional stability, though its weft-direction weakness must not be overlooked.

From an environmental perspective, the Life Cycle Assessment results underscore the sustainability benefits of PALF. The analysis of producing 1kg of Ready-to-Spin PALF demonstrated considerably lower environmental impacts across key categories like Climate Change, Freshwater Ecotoxicity, Particulate Matter, Water Use, and Freshwater Eutrophication when compared to conventional fibers. Utilizing agricultural waste like pineapple leaves aligns strongly with circular economy principles, offering a valuable pathway for resource efficiency and waste reduction in textile manufacturing.

#### ACKNOWLEDGMENT

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## SINGLE-STEP DEVELOPMENT OF MULTIFUNCTIONAL COTTON FABRICS USING BORON-BASED NANOCOMPOSITE FOR ENHANCED FLAME RETARDANCY AND ANTIBACTERIAL PERFORMANCE

Dilara Sevindik<sup>1\*</sup>, Esra Örüm Dayı<sup>1</sup>, Hatice Coşkun<sup>1</sup>, Necip Atar<sup>2</sup>

<sup>1</sup>Ağaoğlu Textile R&D Center, Uşak, Turkey

<sup>2</sup>Pamukkale University, Department of Chemical Engineering, Denizli, Turkey

\* d.sevindik@agaoglu.com

### ABSTRACT

Cotton fabrics are widely preferred in home textiles for their exceptional comfort, although they have some disadvantages concerning fire safety and hygiene, related to their low limiting oxygen index and vulnerability to bacterial growth. These drawbacks emphasize the necessity to simultaneously enhance multiple functional properties of cotton fabrics. This study aims to provide cotton woven fabrics both flame retardant and antibacterial properties in a single process, using a sustainable approach. Formulations containing five different boron compounds were applied to the fabric utilizing rotary screen printing, followed by a fixation step at 150 °C. The treated samples were subsequently evaluated for their physical, antibacterial, and flammability properties in accordance with relevant standards. The results indicated no significant negative impacts on the mechanical properties of the fabrics, and a high antibacterial activity of 99.9% was achieved in accordance with the AATCC 100-2019 standard. In flame retardancy tests, charring occurred in all samples; however, the formulation containing 5% boron concentration markedly restricted flame propagation. The findings show that boron compounds provide an efficient and sustainable option for enhancing multifunctional properties in cotton textiles.

**Keywords:** *Boron, flame retardancy, antibacterial, multifunctional, cotton*

### 1. INTRODUCTION

Cotton fabrics are widely used in home textiles for their superior comfort properties. However, they provide considerable fire safety risk owing to their low limiting oxygen index (LOI) and poor thermal stability [1–4]. Moreover, their hygroscopic structure and fiber morphology facilitate bacterial growth, posing a significant hygiene concern [5]. Halogen and phosphorus-based flame retardant chemicals, intended to reduce these dangers, face many limitations due to their toxicity and environmental impacts [2, 4, 6]. As a result, there is a growing demand for eco-friendly and multifunctional textile alternatives that meet both fire safety and hygiene standards. Despite these efforts, most current applications require multi-step processes, leading to high consumption of water, energy, and chemicals, hence causing restrictions on sustainability [5, 7]. Consequently, the advancement of eco-friendly and industrially viable solutions that can be executed in a single step is becoming increasingly significant. Boron compounds have been recognized as sustainable and multifunctional alternatives in textile applications owing to their low toxicity and minimal environmental impact. Boron compounds alter combustion behavior by boosting dehydration in the cellulose structure, enhancing charring, generating a protective barrier during thermal decomposition and also imparting antimicrobial properties [8–10]. This research aims to impart flame retardant and antibacterial properties to 100% cotton woven fabrics in a single step by integrating boron based nanocomposite materials into a pigment printing paste and applying them using rotary printing technology. Taking into account Turkey’s strong textile production capabilities and high boron reserves, it is assessed that integrating these systems into finishing processes will offer significant environmental and economic advantages [11]. This approach is expected to contribute to the development of home textile products with a low carbon footprint, multifunctionality and high safety standards.

## 2. EXPERIMENTAL STUDY

### 2.1 Materials

In this study, 100% cotton plain woven fabrics, having a weft density of 25 picks/cm, a warp density of 31 ends/cm and an areal density of 120 g/m<sup>2</sup>, were used. In the pretreatment, desizing was performed using  $\alpha$ -amylase enzyme (Genkim, Turkey) and a nonionic wetting agent (ER-SA, Turkey). This was followed by a bleaching using NaOH (32 Bé)(Borkim Chemical, Turkey), H<sub>2</sub>O<sub>2</sub> (Tempo Chemical, Turkey), an anionic stabilizer (Ecopol, Turkey) a wetting agent (ER-SA, Turkey) and a sequestering agent (ECOPOL, Turkey). During the rotary printing, a styrene acrylic-based binder (ER-SA Chemical, Turkey), a nonionic softener and emulsifier (İDEA Chemical, Turkey), a silicone-based defoamer (İBER Chemical, Turkey), ammonia (İGSAŞ, Turkey) and a synthetic polymer-based thickener (MYD Chemical, Turkey) were employed. In the finishing stage, a nonionic wax (AKKİM, Turkey), silicone (AKKİM, Turkey) and polyethylene-based softener (MYD Chemical, Turkey) was applied. Boron based nanocomposite was prepared using amine groups including boron compounds.

### 2.2 Methods

A pigment printing paste was initially prepared. The boron-based nanocomposite used in this study was synthesized at the Department of Chemical Engineering, Pamukkale University, and incorporated into the printing paste at two different concentrations (1% and 5%). The prepared printing paste was applied to the fabric by rotary printing. A reference sample (R0) was prepared using a blank printing paste without the boron-based nanocomposite for comparison with samples R1 and R2. The composition of the printing pastes for all samples is presented in Table 1.

**Table 1.** Composition of printing paste.

| Samples        | Boron-based nanocomposite (%) | Conventional pigment printing paste (%) |
|----------------|-------------------------------|-----------------------------------------|
| R0 (Reference) | 0                             | 100                                     |
| R1             | 1                             | 99                                      |
| R2             | 5                             | 95                                      |

After the printing process, the fabric samples were fixed at 150 °C for 4–5 minutes (Figure 1). Subsequently, a softening finishing treatment was applied to the fabrics using a stenter machine. In this stage, 20 g/L wax, 20 g/L silicone, and 3 g/L polyethylene were used.

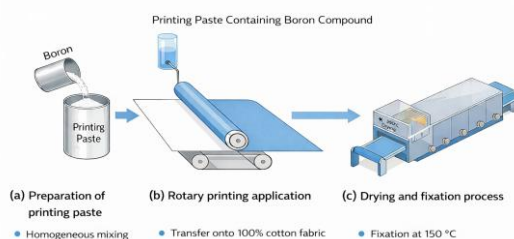


**Figure 1.** Printing and finishing process flow diagram.

Flame retardancy tests were conducted in accordance with BS 5852-0 and BS 5852-1. Antibacterial activity was evaluated against *Staphylococcus aureus* (ATCC 6538) and *Klebsiella pneumoniae* (ATCC 4352) following AATCC 100-2019. Furthermore, pilling performance, abrasion resistance, and tear strength were determined in accordance with TS EN ISO 12945-2, TS EN ISO 12947-3, and TS EN ISO 13937-2, respectively. Fourier Transform Infrared (FTIR) spectroscopy was performed to investigate the chemical structure of reference and boron nanocomposite treated samples.



### 3. RESULTS

#### 3.1 Flame Retardancy Test Results

Flame retardancy was evaluated using two ignition sources to represent smoldering and flaming combustion. The Cigarette test (Source 0) used a low energy ignition source to simulate smoldering [12, 14], while the Match test (Source 1) used a higher-energy source to simulate flaming combustion. The results are shown in Tables 2 and 3.

**Table 2.** Cigarette test (BS 5852 Source 0) results.

|                                                                      | Sample   |          |          |
|----------------------------------------------------------------------|----------|----------|----------|
| <b>Ignitability of upholstery fabrics cigarette test (BS 5852-0)</b> | R0       | R1       | R2       |
| <b>Sample behavior after flame</b>                                   | Charring | Charring | Charring |
| <b>Observing flaming after 60 min.?</b>                              | No       | No       | No       |
| <b>Conclusion</b>                                                    | Pass     | Pass     | Pass     |

Results from the cigarette test indicated that all samples had only localized charring; no flaming combustion or smoldering was observed after 60 minutes of exposure. The styrene-acrylic binder in the printing paste formed a layer on the fiber surface, thereby reducing air permeability and restricting the diffusion of oxygen [15]. Therefore, the combustion behavior in all samples was limited to localized charring, and due to the low energy nature of the cigarette test, performance differences between samples could not be clearly demonstrated. This situation is thought to be related to the low heat flux of smoldering combustion and the progression mechanism dependent on oxygen diffusion [12–14].

**Table 3.** Match test (BS 5852 Source 1) results.

|                                                                  | Sample    |           |           |
|------------------------------------------------------------------|-----------|-----------|-----------|
| <b>Ignitability of upholstery fabrics match test (BS 5852-1)</b> | R0        | R1        | R2        |
| <b>Flame application time</b>                                    | 20 second | 20 second | 20 second |
| <b>Sample behavior after flame</b>                               | Charring  | Charring  | Charring  |
| <b>Does the flame reach the top edge in 2 min.?</b>              | Yes       | Yes       | No        |
| <b>Conclusion</b>                                                | Fail      | Fail      | Pass      |

According to the results of the match flame test, the endothermic effect was limited in fabric samples coded R0 and R1, thus failing to meet the test criteria; sufficient charring and a surface barrier effect were achieved in R2 fabric samples, limiting flame spread and successfully passing the test. Therefore, the limitation of flame propagation and charring behavior can be attributed to the effect and concentration of boron-based nanocomposite. This phenomenon is associated with the formation of a glassy layer on the surface during thermal decomposition, which restricts oxygen transfer, promotes char formation, and reduces flame spread [15–17]. In addition, the endothermic decomposition of the water of hydration in boron-based nanocomposite provides a cooling effect via heat absorption and promotes dilution of the flammable environment through the release of water vapor [18].

#### 3.2 Antibacterial Activity Test Results

The antibacterial activity test results of the treated fabrics are shown in Table 4.

**Table 4.** Antibacterial activity test results.

|           | <b>Staphylococcus aureus (AATCC 6538)</b> | <b>Klebsiella pneumoniae (AATCC 4352)</b> |
|-----------|-------------------------------------------|-------------------------------------------|
| <b>R0</b> | 41.01%                                    | 37.87%                                    |
| <b>R1</b> | 99.99%                                    | 99.99%                                    |
| <b>R2</b> | 99.97%                                    | 99.97%                                    |

The antibacterial activity results show that all boron containing samples exhibited significant antibacterial activity against both gram positive *Staphylococcus aureus* and gram negative *Klebsiella pneumoniae*. In comparison, the control sample showed only limited bacterial reduction. However, the control sample demonstrated minimal bacterial decrease. This difference indicates that boron significantly contributes to antibacterial efficacy. This behavior may be linked to the impact of boron chemicals on cellular processes, specifically through changes in membrane permeability and the disruption of standard cellular functions [19, 20]. Furthermore, increasing the boron content did not result in a significant enhancement in antibacterial activity, as effective antibacterial performance was already achieved at a boron concentration of 1%. This suggests that sufficient antibacterial efficacy can be attained even at low boron levels, indicating that lower concentrations may be adequate for formulation purposes.

### 3.3 Pilling Degree and Abrasion Resistance Test Results

The results for pilling degree and abrasion resistance are presented in Table 5.

**Table 5.** Pilling and abrasion test results.

|    | Pilling degree | Mass loss after abrasion (%) |
|----|----------------|------------------------------|
| R0 | 4-5            | 1.57                         |
| R1 | 4-5            | 2.88                         |
| R2 | 4-5            | 2.92                         |

According to Table 5, all samples showed a pilling degree of 4–5, indicating high surface strength. In addition, boron application did not negatively affect the pilling tendency. The slight increase in weight loss after abrasion observed in R1 and R2 samples indicated increased material removal, suggesting a slight decrease in abrasion resistance due to the partial rigidity induced by the boron containing coating [21].

### 3.4 Tear Strength Test Results

The tear strength test results of the fabric samples are shown in Table 6.

**Table 6.** Tear strength test results.

|    | Warp (N) | Weft (N) |
|----|----------|----------|
| R0 | 6.34     | 5.24     |
| R1 | 6.07     | 4.72     |
| R2 | 5.07     | 3.55     |

Table 6 indicates that the tear strength of the R2 sample decreased by approximately 18% both directions compared to the R0 sample. This is thought to be the result from the application of the boron based nanocomposite, which enhances the rigidity of the fabric structure, thereby diminishing the mobility and deformability of the yarns. According to the literature, boron containing compounds increase the hardness and brittleness of the inter-fiber structure. In addition, mechanical properties tend to deteriorate with increasing boron concentration, with losses reaching up to approximately 30% at high concentrations [22]. Similar reductions in tear strength have been reported for different materials treated with boron compounds [23].

### 3.5. Fourier Transform Infrared (FTIR) Analysis

The confirmation of boron coating was investigated by FTIR analysis (Figure 2). FTIR analysis of boron coated fabrics typically reveals key absorption peaks, including out-of-plane B-N-B bending ( $900\text{--}950\text{ cm}^{-1}$ ) and B-N stretching ( $1050\text{--}1500\text{ cm}^{-1}$ ). These peaks confirm the successful coating of boron onto cotton fabrics [24].

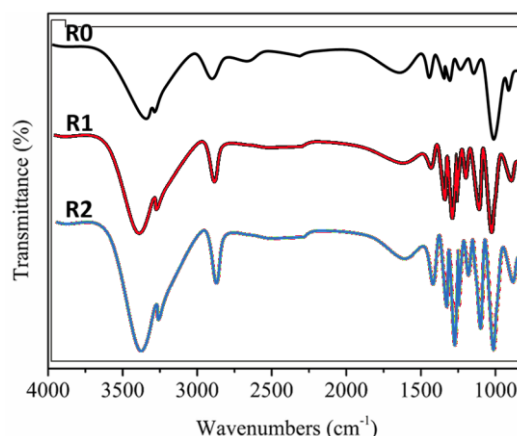


**Figure 2.** FTIR spectra of reference sample (R0) and boron treated (R1, R2) samples

#### 4. CONCLUSION

This study assessed the applicability of boron-based nanocomposites for 100% cotton woven fabrics by the rotary printing process and the multifunctional performance properties they provided. The results demonstrated that the developed system has multifunctional possibilities for antibacterial reduction and flame retardancy. Antibacterial test results demonstrated significant bacterial reduction even at low boron concentrations. Only the sample with 5% boron met the criteria in the flame ignition test, indicating that a specific threshold concentration is necessary for effective flame retardancy. Considering all results, a boron concentration of 5% provided a balanced and optimal performance for both antibacterial activity and flame retardancy. Accordingly, the developed system offers a multifunctional and sustainable solution for home textile applications where safety and hygiene are essential.

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## STUDENT ATTITUDES TOWARDS SUSTAINABILITY IN TEXTILES DURING THE TEXUNITE PROJECT

Mirela Blaga<sup>1</sup>, Mihaela Perdevară<sup>1</sup>, Ioana-Otilia Rusu<sup>1</sup>, Diana-Andreea Plăcintă<sup>1</sup>

Zlatin Zlatev<sup>2</sup>, Anne-Marie Grundmeier<sup>3</sup>

<sup>1</sup>“Gheorghe Asachi” Technical University, Iași, Romania, <sup>2</sup>Trakia University, Stara Zagora, Bulgaria,

<sup>3</sup>University of Education, Freiburg, Germany

\*mirela.blaga@academic.tuiasi.ro

### ABSTRACT

Service Learning (SL) is a pedagogical method that integrates academic education with community service to promote civic engagement, sustainability awareness, and practical skills among students. The European project, TexUnite – Service Learning on Sustainability in Textile and Fashion Education focuses on incorporating SL into textile and fashion seminars at six partner universities across five countries: Bulgaria, Germany, Romania, Slovenia, and Turkey. The online further education module, Sustainable Textile Lab (SusTexLab), offers training, methodological guidance, and teaching and learning materials as Open Educational Resources (OERs) to ensure wide dissemination.

This paper presents the SL project conducted by “Gheorghe Asachi” Technical University of Iași, Romania (TUIASI), as a best practice example. The study analyses changes in TUIASI students’ attitudes towards sustainability in the textile and fashion sector following their participation in the SL project and another educational activity, called virtual exchange (VE). By comparing pre- and post-test results based on a 5-point Likert scale, three thematic blocks were assessed: personal attitudes towards sustainability, potential for action, and the educational potential of VE. The analysis includes quantitative indicators and qualitative data from open-ended questions. Results show increased awareness, commitment, and preparedness for sustainable practices among students, with the most significant development in the block related to VE and intercultural learning.

**Keywords:** textiles sustainability, education for sustainable development (ESD), service learning, virtual exchange (VE).

### 1. INTRODUCTION

Service-Learning is a structured educational approach that combines community service with academic learning to enhance knowledge, promote civic responsibility, and create meaningful social impact. Recognised as a highly effective educational practice, it enables students to connect classroom theory with real-world applications, building valuable links between academic disciplines and community needs [1]. As the textile and fashion industry becomes more aware of its environmental impact, projects such as SL in fashion and textiles, when integrated into education, can help students develop practical problem-solving skills and greater self-efficacy, as highlighted by specialists [2]. As such, service learning was implemented within fashion courses, emphasising that students, together with faculty, identify community needs and address them through class projects [3]. The literature mentions a service-learning project in which students designed and created hospital gowns for premature infants. This initiative not only provided practical experience but also met a significant community need [4]. Other researchers explored the impact of a collaborative service learning (CSL) project on student learning experiences. They found that CSL projects positively influenced both cognitive and affective learning, with civic responsibility, enjoyment, and service-learning enhancing academic development. The study suggests a framework for integrating social responsibility initiatives into multi-class CSL projects [5]. Another example analyses how current research findings can be integrated into teachers' practice in schools while maintaining a high degree of relevance to everyday life. This is demonstrated by a service-learning project developed in Oldenburg and Bremen in 2019, which resulted in Slow Fashion teaching materials. These materials are a low-threshold resource for teachers who wish to work with pupils of all school types aged 9 to 16 in the field of Education for Sustainable Development (ESD) and textiles [6]. An existing study developed a problem-based service-learning project for a Trend Analysis and Forecasting course to enhance students' understanding and social responsibility. It explored the characteristics of problem-based service-learning, proposed a model for its implementation, and presented a case study of its outcomes. The project fostered civic responsibility, critical thinking, and discipline-specific learning, offering valuable insights for educators [7].



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These case studies demonstrate the diverse applications of SL in fashion and textile education, highlighting its role in community engagement, skills development, and practical experience. SL integrates community service with academic teaching, enriching students' educational experiences while benefiting the community. In fashion and textile education, this approach has already been applied in various ways, as shown by the selected studies [8-9].

## **2. SL PROJECT CONDUCTED BY TUIASI, ROMANIA**

Art therapy is a valuable approach for people with autism, offering various therapeutic benefits. Through creative activities, individuals with autism can explore their feelings, improve communication skills, and build social relationships. Art therapy employs creative techniques such as drawing, painting, and collage to help people with special needs explore the psychological and emotional nuances expressed in their art [10]. Knitted waste can be a reliable resource for creative activities for people with autism, due to its pleasant texture and the wide range of yarn colours, and the SL project has been inspired by this idea.

The SL project implemented by TUIASI, Romania, was carried out by students who developed creative projects for young people with autism from two partner organisations. While studying the design of knitted materials with various patterns on the automatic flat knitting machine, within the Computer Aided Design for Knitting course in the 7th semester of the Bachelor's degree in Knitting and Clothing Technology, the students produced materials that were recycled and upcycled to create decorative and functional objects together with partners with autism. Students also deepened their knowledge of knitting technology, EU sustainability regulations, ecological and social challenges in the textile industry, and were introduced to service-learning principles.

Special activities were organised for the Christmas holidays, such as decorating the Christmas tree and designing clothing for people with autism. The most notable event was participation in a charity concert to raise funds, where students and people with autism performed together on stage. Virtual exchange sessions were held with the University of Education, Freiburg, Germany, to enhance intercultural, linguistic, and digital skills. Pre- and post-assessments showed improved sustainability awareness among the students.

## **3. METHODOLOGICAL APPROACH**

This study analyses the change in attitudes of students from the TUIASI towards sustainability in the textile and fashion sector following their participation in the TexUnite project, which is based on virtual exchange VE and SL.

The methodology is based on pre- and post-intervention surveys administered to the participating students. The pre-tests were conducted immediately before the seminar introduction, and the post-tests were administered at the end of the semester. In addition to the pre- and post-tests, university teachers and stakeholders completed an online survey after the seminars to capture their views on the projects.

Seventeen students from the Knitting and Clothing Technology major at TUIASI, Romania, participated in the study and completed both tests, allowing for intrapersonal comparison of changes in attitudes. The age distribution shows that most participants were aged 21–23 years, followed by those aged 24–26 years. The data were analysed by calculating a weighted mean for each statement. Means and standard deviations were calculated for all variables, allowing assessment of the variation in responses. Due to the small sample size and the mixed design (partially dependent and partially independent observations), a test of statistical significance was not applied. The purpose of the study is primarily a descriptive assessment of changes in attitudes, and the reported increases in mean values indicate a clearly positive trend.

By comparing the results of the pre- and post-tests using a 5-point Likert scale, three thematic blocks were assessed: personal attitudes towards sustainability, potential for action, and the educational potential of virtual exchange. The analysis includes quantitative indicators (means and standard deviation) and qualitative data from open-ended questions. The weighted mean score was calculated as the sum of each response category multiplied by its assigned weight, divided by the total sum of weights, as indicated by Equation 1.

$$W_{mean} = \frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i} \quad \text{Eq.1}$$

where  $x_i$  is the value of category  $i$ ;  $w_i$  is the weight (frequency) assigned to category  $i$ ;  $n$  is the number of response categories.

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Table 1 shows the 30 questions from the pre- and post-tests for students, for which a 5-point Likert scale, ranging from “strongly disagree” to “strongly agree”, was established.

**Table 1.** Questions in pre- and post-tests.

| No.   | Question                                                                                                                                                    |
|-------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|
| I.A   | I think that sustainably produced textiles and clothing are a good thing.                                                                                   |
| I.B   | I am prepared to pay more for sustainably produced textiles and clothing.                                                                                   |
| I.C   | I prefer to buy eco-fair textiles and clothing.                                                                                                             |
| I.D   | Lack of transparency (greenwashing) prevents me from buying textiles and/or clothing labelled as eco-fair.                                                  |
| I.E   | I prefer to buy second-hand clothes.                                                                                                                        |
| I.F   | I pass on and/or donate textiles and clothing to social organisations.                                                                                      |
| I.G   | I take the opportunity to swap my textiles and clothing.                                                                                                    |
| I.H   | I take the opportunity to sell my textiles and clothing second-hand.                                                                                        |
| I.I   | By buying and producing sustainable textiles and clothing, I can counteract climate change.                                                                 |
| I.J   | The change towards more sustainability in the textile and fashion sector will only succeed if I become more involved.                                       |
| I.K   | When buying clothes, I check the labels.                                                                                                                    |
| II.A  | It is important to pass on and donate textiles and clothing if the textile and fashion sector is to be eco-fair.                                            |
| II.B  | It is important to take on social responsibility in the textile and fashion sector.                                                                         |
| II.C  | I see the opportunity to get involved in the local textile and fashion sector in a sustainable way.                                                         |
| II.D  | I see the opportunity to cooperate with sustainably orientated stakeholders in the textile and fashion sector.                                              |
| II.E  | I see the opportunity to promote a circular economy in the textile and fashion sector through cooperation between producers and consumers.                  |
| II.F  | I can minimise resource consumption through upcycling and/or recycling projects with stakeholders.                                                          |
| II.G  | I can minimise pre- and post-consumer waste through projects with stakeholders.                                                                             |
| II.H  | I see the opportunity to promote textile-related knowledge and/or practical textile skills through textile and fashion projects with stakeholders.          |
| II.I  | I see the opportunity to promote appreciation of textiles and clothing through textile and fashion projects with stakeholders.                              |
| II.J  | The project-oriented seminar is a good opportunity to make the sustainability potential of the textile and fashion sector publicly visible.                 |
| III.A | I find it important to exchange ideas about sustainability with students abroad to strengthen my professional orientation.                                  |
| III.B | I find it important to exchange ideas internationally to reflect on my knowledge, attitudes and actions regarding eco-fair textiles and fashion.            |
| III.C | I believe that VE (virtual exchange) is a good way to make sustainable approaches in the textile and fashion sector internationally visible and comparable. |
| III.D | I believe that my active participation in the seminar sharpens my awareness of the social responsibility of companies and consumers.                        |
| III.E | VE with students abroad expands my intercultural knowledge of sustainability.                                                                               |
| III.F | VE with students abroad changes my attitude towards sustainability in the textile and fashion sector.                                                       |
| III.G | VE with students abroad changes my decisions and actions in the textile and fashion sector in the long term.                                                |
| III.H | VE with students abroad sharpens my view of a common development towards a circular economy.                                                                |
| III.I | VE with students abroad makes me aware of my role and responsibility as a citizen in the EU.                                                                |

#### 4. RESULTS AND DISCUSSIONS

The results of the first group of questions (Figure 1) show an increase in personal attitudes towards sustainable practices after the training. While only the first indicator (I.A) starts at a high value and remains stable, all other statements show an increase – often from around 1.0–1.5 to over 3.8–4.1. This includes willingness to pay more for sustainable products (I.B), preference for eco-fair clothing (I.C), reduced impact of greenwashing (I.D), and increased approval of practices such as buying second-hand, donating, exchanging, and reselling (I.E–I.H). There is also an increase in the belief that sustainable consumption can counteract climate change (I.I) and that personal commitment is necessary for change in the sector (I.J). The project training leads to a significant strengthening of students’ personal attitudes towards sustainability.

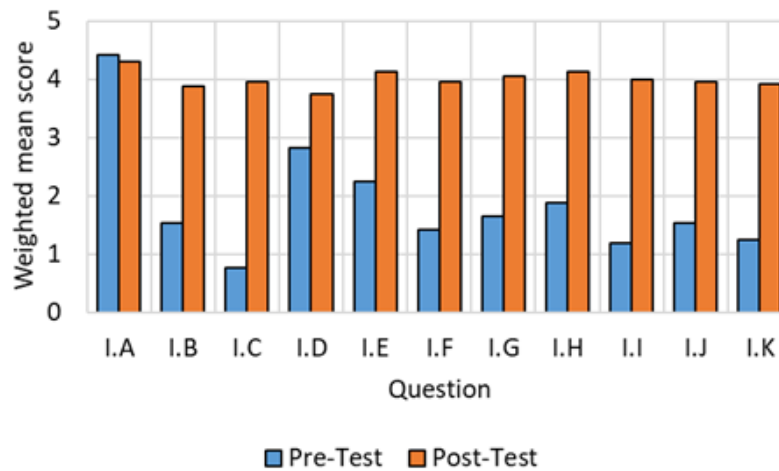


**Figure 1.** Weighted Mean Scores for Group I: Personal Attitudes.

The second group of questions (Figure 2) shows the relative progress in training outcomes, as the initial values in the Pre-Test were relatively low (0.88–2.65), and after the training all indicators increase to the range of 3.48–3.96. This means that participants not only develop more positive attitudes, but also begin to perceive real opportunities for action in the textile and fashion sector. The sense of the importance of social responsibility (II.B), the opportunities for cooperation with stakeholders (II.D–II. E), as well as the potential for waste reduction through recycling, upcycling and project work (II.F–II. G) is strengthened. Participants also begin to see more clearly the role of educational and project-oriented activities in increasing textile literacy and the public visibility of sustainability (II.H–II. J). The training significantly expands the perceived opportunities for practical participation.

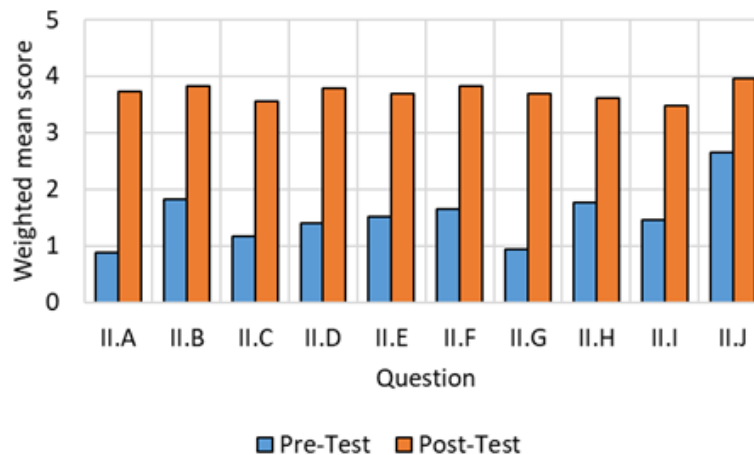


**Figure 2.** Weighted Mean Scores for Group II: Potential for Action.

The third group of questions (Figure 3) shows the impact of VE as an educational tool. All indicators increase significantly – from low initial values (0.76–3.12) to stable post-test scores between 3.78 and 4.17. Participants start to appreciate VE as an important mechanism for international exchange of ideas (III.A–III.C), for critical reflection on one’s own knowledge and attitudes (III.B), and for increasing awareness of social responsibility (III.D). The highest increase is observed in the intercultural understanding of sustainability (III.E), which reaches 4.17. Furthermore, participants show a change in their attitudes and behavior in the long term (III.F–III.G), as well as a clearer awareness of their role in the development towards a circular economy and European citizenship (III.H–III.I).

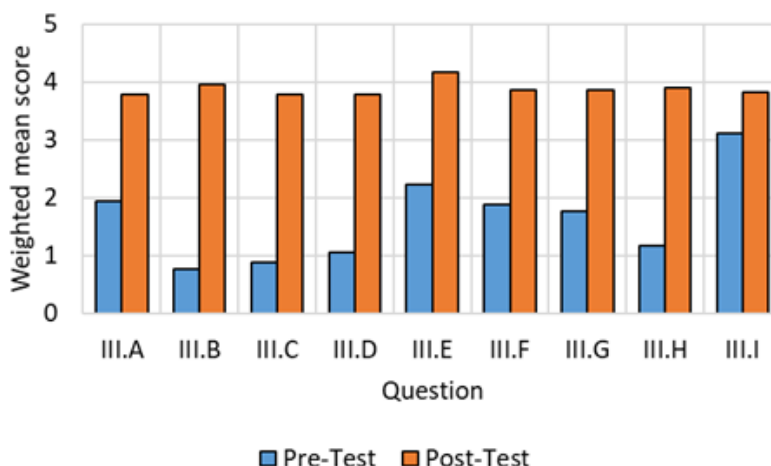


**Figure 3.** Weighted Mean Scores for Group III: Educational Potential through Virtual Exchange.

In conclusion, VE demonstrated a strong transformative effect on the educational and intercultural aspects of sustainability.

## 5. CONCLUSIONS

SL principles can be effectively integrated into fashion and textile sustainability curricula, encouraging students to reflect on waste generated after production and learn how to reduce the impact of textiles on the environment and climate change by recycling materials.

TUIASI students demonstrated creativity through sustainable practices and civic engagement by participating in activities with a group of people with special needs. They learned to communicate through artistic activities with the autistic partners and thus increased their empathy for others.

Students increased their self-confidence in design and communication, developed stronger teamwork, and slightly improved their English skills during virtual exchanges. Reflections emphasised that practical knowledge can be explored in a social context, and students became aware of options for recycling and upcycling waste materials.

The developed SL is an educational case study, featuring real-world examples that promote student learning and engagement in social causes, helping them become more responsible citizens. The partner organisations confirmed that the products created and the connections developed during joint sessions had a significant impact on teenagers and adults with autism.

Research results also indicate increased awareness, commitment, and preparedness for sustainable practices among students, with the most significant development observed in virtual exchange and intercultural learning.

## ACKNOWLEDGEMENTS

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## SUSTAINABLE APPROACHES WITH ODORLESS AMMONIA AND BENTONITE SUBSTITUTION IN PIGMENT PRINTING RECIPES

Özlem YARAR<sup>1\*</sup>, Ayca TEMREN<sup>2</sup>

<sup>1</sup> Harput Tekstil San. ve Tic. A.Ş – Ar-Ge Merkezi, 16140 Bursa, Türkiye

\*ozlem.yarar@kintekstekstil.com

### ABSTRACT

The chemicals used in pigment printing processes, particularly volatile bases and synthetic thickening agents, cause significant environmental and occupational safety problems. In this context, odorless ammonia and bentonite present different advantages and limitations when evaluated from a sustainability perspective. The primary aim of this study is to develop a sustainable and practically applicable pigment paste formulation that minimizes chemical consumption and environmental impacts. In this study, odorless ammonia substitution experiments were conducted based on a pigment paste formulation containing 7 g/l ammonia, commonly used in industrial applications. The results indicated that a pigment paste formulation containing 15 g/L of odorless ammonia fulfills the required technical specifications. In bentonite substitution studies, both the alkalinity and thickening effects of bentonite were examined. The results revealed that odorless ammonia could technically be an alternative to traditional ammonia, but the cost of the chemical outweighs its benefits. Bentonite acts as both a rheology modifier and an alkalizing agent, enabling a reduction of at least 80% in thickening agents and 70% in ammonia content, respectively, and allowing the development of a unique formulation. This study presents an innovative approach to the development of sustainable formulations in pigment printing chemistry and provides a scientific basis for the industrial applicability of environmentally friendly new-generation pigment printing formulations containing bentonite.

**Keywords:** *Pigment Printing, Bentonite, Odorless Ammonia, Rheology, Sustainability*

### 1. INTRODUCTION

Textile printing is a key surface coloration technique that enables the controlled application of color and patterns onto textile substrates. Pigment colorants are applied to the surface in a controlled and exact manner using specific techniques. Over time, printing techniques have evolved and the number of pigment colorant types that can be used has increased significantly [1-3].

Pigment printing not only stands out as one of the oldest printing methods but also offers ease of application [4-6]. More than 80% of printed products are preferred for pigment printing due to its ease of application, the ability of achieving a final appearance close to the final product during printing, applicability to almost any type of fiber or blend, and the fact that washing is required after the fixation process [4, 7-9].

Printing paste is the medium that carries colorants and enables their transfer onto the fabric surface prior to fixation. Printing pastes used in pigment printing typically contain components such as pigment colorants, emulsifiers, binders, softeners, thickening agents, foam inhibitors, and cross-linkers [4]. When preparing pigment pastes, the properties and usage conditions of each component must be considered.

A thickening agent is used to provide appropriate viscosity and rheological properties to the printing paste and, therefore, confines the pigments within the design area to prevent spreading beyond the pattern edges under high pressure [10]. A slightly alkaline pH stabilizes the thickener and prevents binder film formation. Pastes with a pH below 8 tend to dry quickly and clog printing screens and can be difficult to clean. Ammonia solution is commonly used to increase the pH [11].

Bentonite is an aluminosilicate consisting of an octahedrally coordinated aluminum oxide layer sandwiched between two tetrahedrally coordinated silica oxide layers and is widely found around the world [12]. Türkiye holds approximately 20% of the world's bentonite reserves. Bentonite forms a colloidal structure when in contact with water, swells, and exhibits high plasticity, making it widely used in many industrial fields. Therefore, increasing R&D and domestic production of bentonite is of great importance in Türkiye [13].

Bentonite can act as a thickening and rheology-modifying agent in various industries including textiles, food, and cosmetics. In addition, comprehensive research is being conducted on its use as a thickener, for wastewater color removal and during dyeing-coloring processes in the textile industry [14].

The textile industry is rapidly moving toward more environmentally friendly, biodegradable, and low-

emission alternative chemicals and production methods to meet strict environmental regulations such as the EU Green Deal and growing sustainability awareness. Odorless ammonia and bentonite offer sustainable alternatives to hazardous volatile bases and synthetic thickening agents in pigment printing.

In this context, our study investigates two chemical substitution strategies for pigment printing on cotton fabrics. As an alternative to traditional ammonia, the technical and economic performance of “odorless ammonia” was evaluated; additionally, due to its the alkali and thickening properties, bentonite was studied for integration into a more environmentally friendly pigment paste formulation.

## 2. EXPERIMENTAL STUDY

### 2.1 Materials and Methods

In this research, odorless ammonia was supplied by Alkemi Chemicals, while bentonite with an average particle size of 5  $\mu\text{m}$  was sourced from Eczacıbaşı. The 100% cotton fabrics, as well as the pigments and auxiliary chemicals used in the printing processes, were supplied by Harput Textile. Pre-treated cotton fabrics were printed in the dyehouse at the Kinteks site of Harput Textile. Pigment paste preparation was carried out using a laboratory-scale mixer at rotational speeds ranging from 750 to 2000 rpm for 10 minutes in a stepwise manner. Printing was performed using a 77-mesh flat screen with three passes. Subsequently, the printed fabrics were pre-dried at 100 °C for 3 minutes and then fixed at 160 °C for 5 minutes. In the odorless ammonia substitution studies, wet and dry rubbing tests were carried out on conditioned samples. In the bentonite substitution studies, pH of pigment pastes and fabric, fastness properties, and visual evaluations were conducted.

#### 2.1.1 Odorless Ammonia Substitution

Based on the conventional pigment paste formulation used in the plant, substitution studies were carried out using 7, 10, 12, and 15 g/L of odorless ammonia. pH measurements were conducted to determine the process suitability of the prepared pigment pastes. The formulations of the pigment pastes are presented in Table 1. Cotton fabric samples were printed using pigment pastes containing varying concentrations of odorless ammonia.

**Table 1.** Formulations of pigment pastes with ammonia and odorless ammonia

| Chemicals           | Recipe 1 (g) | Recipe 2 (g) | Recipe 3 (g) | Recipe 4 (g) | Recipe 5 (g) |
|---------------------|--------------|--------------|--------------|--------------|--------------|
| Binder              | 100          | 100          | 100          | 100          | 100          |
| Cross-linking agent | 7            | 7            | 7            | 7            | 7            |
| Thickener           | 16           | 16           | 16           | 16           | 16           |
| Water               | 870          | 870          | 870          | 870          | 870          |
| Ammonia             | 7            | -            | -            | -            | -            |
| Odorless Ammonia    | -            | 7            | 10           | 12           | 15           |

#### 2.1.2 Bentonite Substitution

In the following section, the effect of individual pigment paste components on pH was first investigated. Subsequently, bentonite-considered a potential alternative to ammonia due to its alkaline and thickening properties-was evaluated in terms of its influence on pH and rheological behavior.

**Table 2.** Formulations of pigment pastes with ammonia and bentonite

| Chemicals           | Recipe 1 (g) | Recipe 2 (g) | Recipe 3 (g) | Recipe 4 (g) | Recipe 5 (g) |
|---------------------|--------------|--------------|--------------|--------------|--------------|
| Binder              | 166          | 166          | 166          | 166          | 166          |
| Cross-linking agent | 10           | 10           | 10           | 10           | 10           |
| Water               | 799          | 746          | 760.4        | 771.5        | 757.5        |
| Thickener           | 18           | 14           | 1.60         | 0.85         | -            |
| Ammonia             | 7            | 4            | 2            | 1.65         | -            |
| Bentonite           | -            | 60           | 60           | 50           | 66.5         |

To achieve substitution, the amounts of ammonia and thickener in the pigment paste formulations were reduced and partially replaced with bentonite. The formulations developed within this context are presented in Table 2.

The behavior of bentonite in the prepared pigment pastes and the effect of ammonia addition on pH variation were monitored. Printing was then carried out under application conditions, followed by post-treatment processes. The pigment pastes were evaluated in terms of pre- and post-application behavior, printability, fabric handle, and color tone variations. Due to the non-Newtonian behavior of bentonite, linear flow characteristics could not be achieved, resulting in suboptimal print quality and foaming-related inconsistencies in paste's viscosity. Therefore, new formulations were developed and re-evaluated.

**Table 3.** Formulations of pigment pastes with anti-foaming agent

| Chemicals           | Recipe 1 (g) | Recipe 2 (g) | Recipe 3 (g) |
|---------------------|--------------|--------------|--------------|
| Binder              | 166          | 166          | 166          |
| Cross-linking agent | 10           | 10           | 10           |
| Water               | 798          | 754          | 768.3        |
| Foaming agent       | 1            | 3.5          | 2.5          |
| Thickener           | 18           | -            | 1.6          |
| Ammonia             | 7            | -            | 1.6          |
| Bentonite           | -            | 66.5         | 50           |

The updated pigment paste formulations are presented in Table 3. pH measurements were performed for all prepared pigment pastes. In addition, the effect of the foam-inhibiting agent on paste behavior was investigated prior to printing.

### 3. RESULTS AND DISCUSSION

#### 3.1. Effects of Different Ammonia Levels on Odorless Ammonia Substitution

Accordingly, pH values of around 9 and above were selected for optimal stability. Among the prepared pigment pastes, Recipe 5, containing 15 g/L of odorless ammonia substitution, was found to be the closest to the industrial paste formulation. The pH values obtained with different odorless ammonia concentrations are shown in Table 4.

**Table 4.** pH values of the prepared formulations

| Chemicals        | Recipe 1 (g) | Recipe 2 (g) | Recipe 3 (g) | Recipe 4 (g) | Recipe 5 (g) |
|------------------|--------------|--------------|--------------|--------------|--------------|
| Ammonia          | 7            | -            | -            | -            | -            |
| Odorless Ammonia | -            | 7            | 10           | 12           | 15           |
| pH               | 9.46         | 7.24         | 8.44         | 8.74         | 9.01         |

Aging and dry rubbing test results are shown in Table 5. After printing Recipe 1 and 5 subsequent processing, dry and wet rubbing tests were performed on conditioned fabrics, yielding identical results.

**Table 5.** Wet and dry rubbing fastness results

| Chemicals    | Ammonia | Odorless Ammonia | Wet rubbing | Dry rubbing |
|--------------|---------|------------------|-------------|-------------|
| Recipe 1 (g) | 7       | -                | 1           | 3-4         |
| Recipe 5 (g) | -       | 15               | 1           | 3-4         |

Amount used and unit costs are shown in Table 6. Results indicate that odorless ammonia can substitute for the ammonia-based plant recipe but is economically costly in terms of use and unit cost.

**Table 6.** Amount used and unit costs

| Chemicals        | Recipe 1 (g) | Recipe 5 (g) | Unit Cost (kg) |
|------------------|--------------|--------------|----------------|
| Ammonia          | 7            | -            | 40 cent        |
| Odorless Ammonia | -            | 15           | 1 Euro         |

#### 3.2 Effect of Bentonite Substitution on Pigment Paste Behavior

Furthermore, the pH effects of pigment paste components, compliance with processing conditions, and the behavior of bentonite substitutions in the pigment paste were investigated for textile applicability.

Details of the studies are as follows:

**Step 1:** The pH of formulations without thickener, containing 4, 5, and 6 g/L of ammonia, was measured as 10.00, 10.10, and 10.18, respectively.

**Step 2:** The pH of water was 7.60. Following the addition of binder and crosslinker, the pH values increased to 7.62 and 7.68, respectively.

**Step 3:** The pH of water after the addition of thickener alone was 5.70. Upon the subsequent addition of binder and crosslinker, the pH values decreased to 5.63 and 5.60, respectively. Ammonia increased the pH of the pigment paste, whereas the thickener decreased it.

**Step 4:** With the addition of 1.2, 2, 3, and 4.2 g/L of ammonia, the pH of the pigment paste was measured as 5.78, 6.35, 6.89, and 7.80, respectively. It was observed that ammonia loss during storage could lead to a decrease in pH; therefore, achieving a pH of 9 or higher was considered necessary for process stability.

**Step 5:** Ammonia and thickener contents in pigment paste formulations were reduced and partially replaced with bentonite. The pH and rheological properties of the pastes were evaluated.

The pH values of the pigment pastes are shown in Table 7.

**Table 7.** pH values of bentonite-based recipes

| Chemicals        | Recipe 1 | Recipe 2     | Recipe 3 | Recipe 4 | Recipe 5 |
|------------------|----------|--------------|----------|----------|----------|
| <b>Binder</b>    | 18       | 14           | 1.6      | 0.85     | -        |
| <b>Ammonia</b>   | 7        | 4            | 2        | 1.65     | -        |
| <b>Bentonite</b> | -        | 60           | 60       | 50       | 66.5     |
| <b>pH</b>        | 9.08     | Not measured | 9.29     | 10.13    | 9.11     |

Based on the results from Recipe 3, bentonite supports alkaline conditions. By reducing all three main components, these conditions can still support thickening, leading to Recipe 4. When the pH of Recipe 4 was measured, it rose to 10.13. In preparing Recipe 3, adding bentonite, binder, crosslinker, and water while mixing resulted in a paste with slightly lower viscosity than Recipe 1, and slightly higher viscosity when thickener and ammonia were added. Printing was performed on cotton fabric samples using the notably suitable viscosities of Recipes 1 and 3. Bentonite-containing pastes showed poor print transfer and produced a lighter shade. Images of printed fabrics after printing are shown in Figure 1.

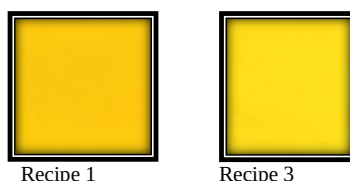


**Figure 1.** Printed fabrics obtained from Recipe 1 and Recipe 3

Recipe 4 produced a darker color tone, while Recipe 1 remained relatively lighter. Printed fabrics are shown in Figure 2.



**Figure 2.** Printed fabrics obtained from Recipe 1, Recipe 4, and Recipe 5

For Recipes 1, 4, and 5, removing the thickener from the plant recipe entirely and adding bentonite resulted in a pH above 9 as desired. However, bentonite, which provides non-Newtonian behavior and foaming in the pigment paste, hindered linear flow and reduced print transfer. Bentonite-containing pastes may be more suitable for flat-bed (film-druck) printing applications and require further optimization for rotary printing applications.

**6. Study:** Because foaming behavior was noted, new pastes were prepared with an anti-foaming additive. The pH values of the pigment pastes with anti-foaming agent are shown in Table 8.

**Table 8.** pH values of pigment pastes with anti-foaming agent

| Chemicals             | Recipe 1 (g) | Recipe 2 (g) | Recipe 3 (g) |
|-----------------------|--------------|--------------|--------------|
| <b>Thickener</b>      | 18           | -            | 1.6          |
| <b>Foam Inhibitor</b> | 1            | 3.5          | 2.5          |
| <b>Ammonia</b>        | 7            | -            | 1.6          |
| <b>Bentonite</b>      | -            | 66.5         | 50           |
| <b>pH</b>             | 8.99         | 9.15         | 9.61         |

Notably, the anti-foaming agent used in Recipe 2 reduced volumetric growth. Yet, the paste still had a foamy texture in Recipe 3, which was closer to the plant recipe. Printing with these pastes showed that Recipe 3's color tone was closer to Recipe 1's but still slightly light. Print images are shown in Figure 3.

After printing, the fabrics were fixed in the plant, and aged-wet rubbing, washing fastness, and fabric pH tests were performed. Test results are shown in Table 9.

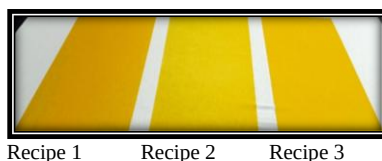


**Figure 3.** Prints for Recipe 1, 2, and 3

**Table 9.** Aged-wet rubbing, dry rubbing, and fabric pH test results

|                 | Aged rubbing | Dry rubbing | Fabric pH Recipe |
|-----------------|--------------|-------------|------------------|
| <b>Recipe 1</b> | 2-3          | 4           | 5.42             |
| <b>Recipe 2</b> | 2            | 3-4         | 7.74             |
| <b>Recipe 3</b> | 2            | 3           | 7.71             |

|                 | Wool | Acrylic | Polyester | Polyamide | Cotton | Acetate |
|-----------------|------|---------|-----------|-----------|--------|---------|
| <b>Recipe 1</b> | 4-5  | 4-5     | 4-5       | 4-5       | 4-5    | 4-5     |
| <b>Recipe 2</b> | 4-5  | 4-5     | 4-5       | 4-5       | 4-5    | 4-5     |
| <b>Recipe 3</b> | 4-5  | 4-5     | 4-5       | 4-5       | 4-5    | 4-5     |

Fabrics containing bentonite showed relatively high fabric pH values. Recipe 2, which contained odorless ammonia and bentonite but no thickener, did not have the required printability; screen transfer was weak. In this context, the applicability of Recipe 3 is more accurate. When using the plant recipe as a baseline, thickener can be reduced by at least 80%, and ammonia by at least 70%.

#### 4. CONCLUSION

The main findings of the study are as follows:

- Odorless ammonia is technically capable of substituting the current ammonia recipes, but cost is a limiting factor.
- Odorless ammonia, due to its lack of a strong odor, improves the working environment and could be considered an alternative chemical in potential regulatory scenarios.
- Bentonite can provide an effective substitute as both a pH regulator and thickener in pigment paste; however, it can cause flowability and printing uniformity issues in practice.
- Bentonite-containing recipes were found to be more suitable for flat-bed (film-druck) applications; additional optimization is required for rotary printing applications.
- This study provides a significant foundation for environmental and operational improvements in pigment paste printing, offering a scientific and practical approach toward developing chemical substitution strategies.
- Ammonia rapidly evaporates during printing and does not leave residues in the printed color. The alkaline residue in the printed color can cause color fastness problems [11]. Therefore, bentonite-containing pigment paste recipes, considering fabric pH after printing, may result in non-volatile bentonite leaving alkaline residues on the fabric and causing color fastness issues.
- Because of ammonia evaporation during storage of pigment pastes under plant conditions, pH decreases. Hence, preparing and using pigment pastes in the pH range of 9–9.5 in the short term appears ideal.
- Using bentonite as a powder in suspension form for practical use will improve mixing homogeneity and ease of handling.
- The bentonite-containing recipe approaches the plant recipe, but it did not fully achieve equivalent performance in important parameters such as paste viscosity, printability, fabric pH, color fastness, and handle.
- Using odorless ammonia and bentonite together in the same formulation could produce a more environmentally friendly and applicably feasible recipe.

#### ACKNOWLEDGMENTS

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## SUSTAINABLE CIRCULAR YARN DYEING: AN INNOVATIVE SINGLE-STAGE DYEING APPROACH TO REACTIVE DYEABLE COTTON/ACRYLIC BLEND YARNS

Neslihan OKYAY<sup>1</sup>, Fatih IŞIK<sup>1</sup>, Mücahid Yahya ŞEKER<sup>1</sup>

<sup>1</sup> Karacasu Tekstil, R&D Department, Kahramanmaraş, Türkiye

\*nes@karacasutekstil.com.tr

### ABSTRACT

Sustainable production approaches in the textile industry necessitate the reduction of energy, water, and chemical use, particularly in dyeing processes. In this context, the ability to dye acrylic fiber-containing yarns with reactive dyes in a single step offers significant environmental and process advantages compared to conventional double-bath systems. This study systematically investigated the dyeability of acrylic fiber-containing yarns with reactive dyes using a new generation circular yarn dyeing technology with a single-step reactive dyeing process that does not require caustic application. In the study, 16/1 Ne 100% cotton and 16/1 Ne cotton/standard acrylic (70/30%) yarns produced by ring spinning technology were determined as reference samples; and the effects of fiber composition and acrylic presence on dyeing performance were comparatively examined with 16/1 Ne cotton/acrylic (70/30%) yarns containing acrylic fibers that can be dyed with reactive dyes. During the dyeing process, the pH, as well as the salt and auxiliary chemicals, were carefully controlled, and homogeneous and repeatable dye distribution was ensured on the yarn surface and along the fiber cross-section. After dyeing, the color homogeneity of the yarns was determined by spectrophotometric measurements in the CIELAB color space; homogeneity was quantitatively evaluated by calculating the  $\Delta E^*_{ab}$  differences between the  $L^*$ ,  $a^*$ , and  $b^*$  values taken from different points along the yarn. In addition, the distribution of the dye along the fibers and dye uptake was quantitatively examined in the yarn cross-sections with a microscope, and the effect of acrylic fiber on color homogeneity in the yarn was observed in detail. The findings showed that cotton/reactive dyeable acrylic blended yarns, when compared to 100% cotton and cotton/standard acrylic yarns, could be successfully dyed in a single step with reactive dyes using the circular yarn dyeing system and exhibited high performance in terms of color homogeneity. Furthermore, the presence of acrylic fiber contributed to balanced color formation in the yarn structure without negatively affecting dye uptake. In conclusion, the study demonstrates that circular yarn dyeing technology significantly reduces resource consumption and environmental burden compared to traditional methods, enabling sustainable production, and serves as an important reference at both academic and industrial levels.

**Keywords:** *Circular Yarn Dyeing Technology, Cotton/Acrylic Yarn, Reactive Dyeing, Sustainable Textiles*

### 1. INTRODUCTION

In the textile industry, dyeing processes constitute one of the most critical and resource-intensive stages of the production chain due to the complex interaction of fiber-material properties, dye chemistry, and process parameters[1]. In particular, high liquor ratios, multi-stage process requirements, and intensive chemical use in conventional dyeing methods lead to significant environmental problems in terms of water consumption, energy demand, and waste load[2,3,4]. Therefore, sustainability-oriented process optimizations and the development of new generation technologies in textile dyeing have become priority research areas in recent years. Cellulosic fibers, especially cotton, have the ability to form covalent bonds with reactive dyes thanks to the hydroxyl (-OH) groups in their molecular structures[5]. This bonding

mechanism has made reactive dyes the most widely used class in cotton dyeing due to their high wet fastness and good color yield[6]. Nucleophilic substitution or elimination reactions occurring between the dye and the fiber in the reactive dyeing process are directly affected by parameters such as pH, temperature, electrolyte concentration, and time[7]. In contrast, acrylic fibers are primarily polyacrylonitrile-based and, due to their hydrophobic character and limited reactive functional groups, are classically dyed with cationic (basic) dyes[8]. This creates a significant process incompatibility in dyeing cotton/acrylic blended textile materials and generally necessitates the use of double-bath dyeing systems. Since different dyeing conditions are required for different fiber components in such systems, the process time is extended, water and energy consumption increases, and process efficiency decreases.

Recently developed reactive dyeable modified acrylic fibers can interact with reactive dyes thanks to anionic or reactive functional groups added to the fiber structure, thus offering the potential for single-bath dyeing together with cellulosic fibers. Such fibers enable process integration in multi-component yarn and fabric structures, providing significant advantages in terms of reducing both production costs and environmental burden. However, not only fiber modification but also advancements in dyeing equipment and process technologies play a critical role in sustainability. The circular yarn dyeing system used in this study is based on the principle of applying dye, alkali, and salt directly onto the yarn in specific proportions and in a controlled manner through an applicator unit during the transfer of yarn from bobbin to bobbin. Therefore, dye application is carried out by direct application onto the yarn surface rather than diffusion from a dye bath as in classical dyeing methods.

When studies on dyeing cotton/acrylic blends are examined in the literature, it is seen that they largely focus on traditional two-stage methods, while single-bath systems are discussed in a limited number of studies. In this context, in the study conducted by Islam et al. (2023), it was shown that cotton/acrylic blend fabrics can be dyed with indigo dye using a single-bath and single-stage method, and it was reported that this approach offers potential in terms of process simplification and reducing water/energy consumption[9]. Similarly, in a patent study based on the sequential application of direct and cationic dyes in a single bath, considering the different dye affinities of cotton and acrylic fibers, it was stated that both fiber components could be effectively dyed with stepwise temperature changes and that the process offered industrial applicability [10]. However, these studies mainly focused on conventional fabric dyeing systems and required either special dye classes or multi-step temperature-controlled applications.

In contrast to the existing literature, the present study investigates the single-stage dyeing behavior of cotton/reactive dyeable acrylic blended yarns in yarn form using reactive dyes and circular yarn dyeing technology. Unlike conventional exhaust dyeing methods, the circular dyeing system enables controlled direct application of dyes and auxiliaries onto the yarn surface without requiring a high liquor ratio or separate dye baths. Furthermore, while previous studies primarily focused on process feasibility, the present study systematically evaluates dye uptake, color development, and color homogeneity through both spectrophotometric and microscopic analyses. Therefore, this study contributes to the literature by demonstrating that reactive dyeable acrylic fibers can successfully participate in a single-stage reactive dyeing process together with cotton fibers under sustainable and industrially applicable process conditions.

## **2. EXPERIMENTAL STUDY**

In this study, Ne 16/1 100% cotton yarn was determined as the reference sample, and ring-spun yarns containing Ne 16/1 70% cotton / 30% standard acrylic and Ne 16/1 70% cotton / 30% reactive dyeable acrylic were used. As reactive dyeable acrylic fiber, a fiber with the ability to establish covalent or strong physical interactions with reactive dyes thanks to the functional groups added to its structure was used. The dyeing process was carried out using a circular yarn dyeing system, based on the principle of applying dyes and auxiliary chemicals to the yarn surface in a controlled manner through an applicator unit during continuous yarn transfer from bobbin to bobbin. After dyeing, the color homogeneity of the yarns was determined in the CIELAB color space by spectrophotometric measurements; homogeneity was quantitatively evaluated by calculating the  $\Delta E^*_{ab}$  differences between the  $L^*$ ,  $a^*$ , and  $b^*$  values taken from different points along the yarn. In addition, the distribution of the dye along the fibers and dye uptake was quantitatively examined in yarn cross-sections using a microscope.

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### 3. RESULTS AND DISCUSSION

Spectrophotometric analyses were conducted to quantitatively evaluate the color properties of yarns before and after dyeing. Based on the measurements obtained, the  $L^*$ ,  $a^*$ ,  $b^*$ , and color difference ( $\Delta E^*_{ab}$ ) values of the yarns within the CIELAB color space were determined, and the relevant results are presented in Table 1.

**Table 1.** The CIELAB color values and color difference ( $\Delta E^*_{ab}$ ) of the yarns used in the study before and after dyeing

| Sample                                       | $L^*$<br>(before) | $a^*$<br>(before) | $b^*$<br>(before) | $L^*$<br>(after) | $a^*$<br>(after) | $b^*$<br>(after) | $\Delta E^*_{ab}$ |
|----------------------------------------------|-------------------|-------------------|-------------------|------------------|------------------|------------------|-------------------|
| %100 Cotton                                  | 87.66             | 1.18              | 1.90              | 68.73            | 28.50            | 44.58            | 54.2              |
| %70 Cotton / %30<br>Standard Acrylic         | 89.15             | 0.37              | 10.10             | 75.20            | 20.10            | 19.68            | 26.0              |
| %70 Cotton / %30<br>Reactive Dyeable Acrylic | 86.74             | -0.01             | 13.03             | 61.10            | 21.35            | 30.25            | 37.6              |

The color characteristics of yarn samples before and after dyeing were evaluated using CIELAB color space values. Before dyeing, all samples were found to have high  $L^*$  values, indicating a light color character. After dyeing, a significant decrease in  $L^*$  values was observed in all samples, resulting in a darker appearance. Furthermore, a general increase in  $a^*$  values was observed, indicating a strengthening of the red tone component. The results show that, despite the controlled and repeatable process conditions provided by the circular dyeing system, fiber composition plays a decisive role in color formation. When the total color difference ( $\Delta E_{ab}$ ) results are examined, a significant color change is observed in all samples. The highest color change was obtained in the 100% cotton sample ( $\Delta E_{ab} = 54.2$ ). For the 70% cotton / 30% standard acrylic and 70% cotton / 30% reactive dyeable acrylic samples, values of 26.0 and 37.6 were calculated, respectively. The higher  $\Delta E$  value of the sample containing reactive dyeable acrylic indicates that this fiber participates more effectively in the single-step reactive dyeing process and has a stronger interaction with the dye. This reveals that the modified acrylic structure behaves compatibly with the reactive dye, enhancing color development.

When the findings are evaluated comparatively, the higher  $\Delta E_{ab}$  value of the sample containing reactive dyeable acrylic compared to the sample containing standard acrylic shows that this fiber has a stronger interaction with the dye and leads to a higher color change. However, the lower  $\Delta E_{ab}$  value of the sample containing standard acrylic reveals that this fiber structure limits dye uptake and provides lower color development. Overall, the results show that fiber type is a determining parameter in both color intensity and hue development and directly affects dyeing performance.

Furthermore, within the scope of the study, the distribution of dye along the fibers and dye uptake was quantitatively examined in the yarn cross-sections using a microscope, and the longitudinal cross-sectional images of the yarns are given in Figure 1.

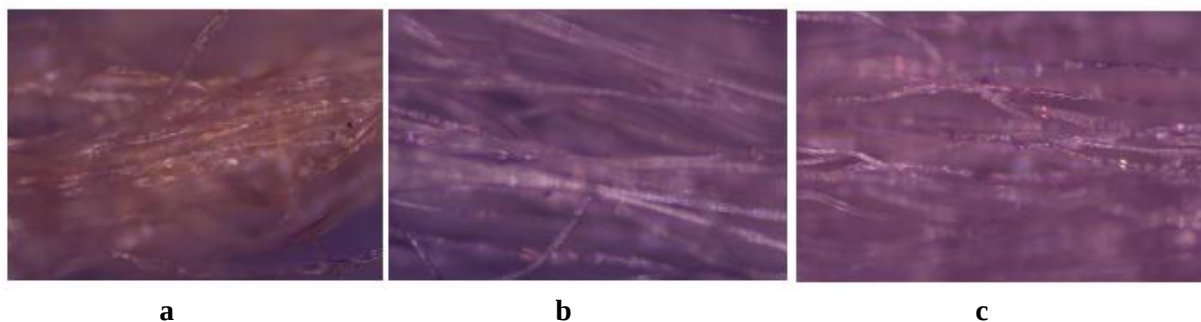


**Figure 1.** Microscopic longitudinal section images of the yarns used in the study: a) 100% Cotton b) 70% cotton / 30% standard acrylic c) 70% cotton / 30% reactive dyeable acrylic

Using microscopic images, the distribution and uptake of dye along the fibers in yarn cross-sections were evaluated both quantitatively and morphologically under single-stage and controlled process conditions achieved with circular yarn dyeing technology. In general, it was observed that the dye was distributed at different densities along the fiber cross-section in all samples, and this distribution varied depending on the fiber type.

In the 100% cotton sample, the dye was observed to be distributed more homogeneously and densely along the fiber, penetrating significantly into the fiber surface and inner regions. This is attributed to the high dye affinity of cotton fibers due to their cellulosic structure. The darker and more consistent color distribution observed in the fiber cross-section supports high dye uptake.

In the 70% cotton / 30% standard acrylic sample, the dye distribution was more heterogeneous, with limited dye uptake, especially towards the acrylic phase. Dye uptake was predominantly concentrated in the cotton phase, while lower dyeing intensity was observed in the acrylic fiber regions. This situation indicates that chemical differences between the fibers restrict dye diffusion.

In the 70% cotton / 30% reactive dyeable acrylic sample, it was determined that the dye showed a wider distribution throughout the fiber and that the acrylic phase also partially participated in the dyeing process. In this sample, it was observed that dye uptake occurred more evenly and the color intensity increased along the fiber cross-section.

In general, the findings reveal that fiber composition has a decisive effect on dye diffusion and retention behavior. In particular, it was concluded that structures containing modifiable acrylic exhibited higher dye uptake and more homogeneous distribution compared to structures containing standard acrylic.

#### **4. CONCLUSION**

In this study, the dyeability of cotton and cotton/acrylic blend yarns was systematically investigated using a single-stage reactive dyeing process developed with circular yarn dyeing technology. The findings demonstrated that the process provides a homogeneous, repeatable, and controlled dyeing environment. Spectrophotometric analyses in the CIELAB color space revealed that fiber composition plays a decisive role in color development and dyeing performance. In particular, the higher color change observed in the reactive dyeable acrylic-containing yarn confirmed that this modified fiber structure can effectively interact with reactive dyes within a single-stage dyeing process.

Compared with previous studies in the literature, which mainly focused on conventional fabric dyeing systems and multi-step dyeing approaches, the present study demonstrates that circular yarn dyeing technology can successfully achieve single-stage reactive dyeing in yarn form while maintaining satisfactory color homogeneity and dye distribution. Moreover, unlike traditional double-bath systems commonly used for cotton/acrylic blends, the developed approach offers significant reductions in process complexity, water consumption, chemical usage, and processing time.

The results indicate that circular yarn dyeing technology provides an environmentally friendly and economically advantageous alternative for sustainable textile production. Particularly for multi-component yarn structures, the method offers strong industrial applicability and contributes to the development of more sustainable dyeing technologies in the textile industry.

#### **ACKNOWLEDGMENT**

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## SUSTAINABLE DYEING OF DIFFERENT SYNTHETIC FABRICS WITH ALGAE-BASED DYESTUFFS

Ayşe Ceren Şen<sup>1,\*</sup>, Hülya Kıcık<sup>1</sup>

<sup>1</sup>Elyaf Tekstil San. Ve Tic. A.Ş., R&D Center, Bursa, Türkiye

\* [ceren.sen@elyaf.com](mailto:ceren.sen@elyaf.com)

### ABSTRACT

Synthetic dyes, which are widely used in the textile industry, pose serious environmental sustainability issues due to their high chemical loads and water consumption. In this study, the applicability of natural dyes derived from algae (a renewable and biodegradable resource) on synthetic fabric dyeing processes was investigated, and an eco-friendly alternative to conventional methods was developed. Experimental studies were conducted using algae-based natural dyes on polyester (PES), polyamide (PA), and acetate fabrics under laboratory- and pilot-scale conditions. Dyeing parameters including temperature (80–105 °C), duration (45–60 min), and dye concentration (10% and 20%) were optimized. Fastness properties, mechanical performance, and wastewater characteristics were evaluated. Results demonstrated homogeneous dyeing and acceptable fastness performance under optimized conditions, while no adverse effects on fabric mechanical integrity were observed. Wastewater analyses showed COD values of 1921–1946 mg O<sub>2</sub>/L depending on dye color. Overall, the findings confirmed the applicability of algae-based dyes on synthetic fabrics and highlighted their potential as a more sustainable alternative for textile dyeing.

**Keywords:** Algae-based dye, Natural dye, Sustainable textile, Synthetic fibers, Biodegradable material

### 1. INTRODUCTION

The textile industry is under increasing pressure to reduce its environmental footprint while maintaining production efficiency and material performance. This challenge has become more critical with the continuous growth of global fiber production, which reached 132 million tonnes in 2024, of which synthetic fibers accounted for approximately 69%, while polyester alone represented nearly 59% of total production [1]. Alongside this structural dependence on synthetic materials, textile coloration processes remain highly dependent on synthetic dyes, which are associated with intensive water and chemical consumption and environmentally harmful wastewater generation [1–3].

Textile dyeing and finishing are considered among the most environmentally impactful stages of textile production due to high water use, chemical loads, and wastewater generation. Dye-containing effluents may negatively affect aquatic ecosystems by reducing light penetration and increasing pollution parameters such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), and toxicity [2–4]. Therefore, the development of renewable and environmentally friendly alternatives to conventional dyes has gained increasing importance.

Natural dyes have attracted considerable attention because of their renewable and biodegradable nature. However, conventional plant- and animal-based dyes often suffer from limited color yield, low fastness properties, and seasonal availability [2,4]. In recent years, microorganism-derived pigments, particularly algae-based dyes, have emerged as promising alternatives because they offer controlled production, broader sustainability potential, and functional properties including antioxidant, antimicrobial, and UV-protective effects [5,6].

Despite increasing interest in algae-based pigments, studies focusing on their application in textile dyeing, especially for synthetic fibers, remain limited. The hydrophobic structure and high-temperature processing requirements of fibers such as polyester, polyamide, and acetate present additional challenges for natural

dye applications. Moreover, studies investigating pilot-scale applicability and industrial performance of algae-based dyes are scarce [2,6].

Accordingly, this study investigates the applicability of algae-based dyes for the dyeing of polyester (PES), polyamide (PA), and acetate (CA) fabrics under laboratory- and pilot-scale conditions. Process parameters were optimized and dyeing performance, color properties, fastness behavior, and mechanical performance were evaluated to assess the industrial applicability of the developed approach.

## 2. EXPERIMENTAL STUDY

### 2.1. Materials

In this study, woven fabrics composed of polyester (PES), polyamide (PA), and acetate (CA) were used for laboratory- and pilot-scale dyeing trials. Additionally, polyester single jersey knitted fabric was included in laboratory optimization studies. Fabric composition, structure, and weight details are presented in Table 1.

**Table 1.** Properties of the fabrics used in the experiments

| Number | Dyeing Scale                | Composition              | Weave Type                   | Fabric weight (gsm) |
|--------|-----------------------------|--------------------------|------------------------------|---------------------|
| 1      | Laboratory-scale            | 100% Polyamide           | Plain weave                  | 150.80              |
| 2      | Laboratory- and pilot-scale | 96% Acetate/ 4% Elastane | Plain weave                  | 197.85              |
| 3      | Pilot-scale                 | 100% Polyamide           | Twill weave                  | 102.24              |
| 4      | Pilot-scale                 | 100% Polyamide           | Plain weave                  | 165.51              |
| 5      | Pilot-scale                 | 100% Polyester           | Plain weave                  | 73.47               |
| 6      | Pilot-scale                 | 100% Polyester           | Plain weave                  | 82                  |
| 7      | Pilot-scale                 | 100% Polyester           | Plain weave                  | 26.54               |
| 8      | Laboratory-scale            | 100% Polyester           | Single jersey knitted fabric | 120                 |

Environmentally friendly algae-based natural pigments were used as dyestuffs in seven color variations, including green, pink, coral, yellow, blue, anthracite, and beige. Trade names and detailed structures of the dyes are not disclosed for proprietary reasons. Dyeing auxiliaries such as buffering, leveling, anti-creasing, defoaming, and washing agents were applied depending on fiber type and process requirements.

### 2.2. Method

The woven fabrics were dyed using algal-based dyes in seven different colors. The dyeing processes were optimized by considering different liquor ratios, temperature, and time parameters depending on the fabric type. Due to the low affinity of synthetic fibers toward natural dyes, the process conditions were rearranged to enhance dye–fiber interaction. For the phenolic yellowing problem in polyamide fabrics, a solution containing alkyl aryl sulfonate was applied.

#### 2.2.1. Laboratory-Scale Dyeing

Laboratory-scale dyeings were carried out on polyamide, acetate, and polyester fabrics using optimized acidic conditions (pH 4.0–5.0). Dye concentrations of 10% and 20% owf were evaluated for polyamide fabrics to determine the effect of concentration on color yield. Polyester dyeing experiments were additionally conducted at different temperatures (80, 100, and 130 °C) to determine suitable process conditions. Following dyeing, samples were rinsed and washed under standardized conditions to remove unfixed dye.

#### 2.2.2. Pilot-Scale Dyeing

Based on laboratory-scale optimization results, pilot-scale dyeing trials were conducted in a jet dyeing machine using optimized dyeing parameters. Algae-based dyes were applied at 10% owf concentration, and dyeing temperatures were adjusted according to fiber type. Detailed process conditions are summarized in Table 2.

**Table 2.** Pilot-scale dyeing process parameters

| Fabric number | Bath ratio | Anti-foaming | Surfactant-based chemical | Acid buffer | Anti-creasing | Leveling agent | Temperature (°C) | Time (min.) |
|---------------|------------|--------------|---------------------------|-------------|---------------|----------------|------------------|-------------|
| 2             | 1:10       | 2 g/L        | -                         | 0.9 g/L     | 2 g/L         | 2 g/L          | 105              | 45          |
| 3             | 1:20       | 2 g/L        | 2 g/L                     | 1 g/L       | -             | -              | 80               | 60          |
| 4             | 1:20       | 2 g/L        | 2 g/L                     | 1 g/L       | -             | -              | 80               | 60          |
| 5             | 1:20       | 2 g/L        | -                         | 0.9 g/L     | 2 g/L         | 2 g/L          | 100              | 45          |
| 6             | 1:20       | 2 g/L        | -                         | 0.9 g/L     | 2 g/L         | 2 g/L          | 100              | 45          |
| 7             | 1:20       | 2 g/L        | -                         | 0.9 g/L     | 2 g/L         | 2 g/L          | 100              | 45          |

### 2.2.3. Performance Evaluation

Color measurements were performed using a Datacolor 1050 spectrophotometer under D65 illumination and a 10° standard observer. CIELAB parameters (L\*, a\*, b\*, C\*, h°) and color strength (K/S) values were determined.

Fastness properties including washing, rubbing, water, perspiration, chlorine, oxidative bleaching, and light fastness were evaluated according to relevant ISO standards. Mechanical performance was assessed through tensile strength, tear strength, and seam slippage tests.

## 3. RESULTS AND DISCUSSION

### 3.1. Laboratory-Scale Results and Optimization

Laboratory-scale dyeing trials were performed to evaluate the applicability of algae-based dyes on synthetic fibers and to optimize process parameters.

For polyamide fabrics, dye concentrations of 10% and 20% owf were compared to assess their effect on color yield. As shown in Table 3, only minor differences in CIELAB and K/S values were observed between the two concentrations, indicating that increasing dye concentration did not significantly improve dye uptake. Therefore, 10% owf was considered sufficient, offering a more sustainable and economical process due to reduced dye consumption.

**Table 3.** Effect of dye concentration on color yield

| Color  | OWF | L     | a      | b      | C     | h      | K/S  |
|--------|-----|-------|--------|--------|-------|--------|------|
| Green  | 20% | 75.91 | -11.07 | 25.29  | 27.6  | 113.64 | 1.44 |
| Green  | 10% | 84.45 | -9.61  | 24.31  | 26.14 | 111.57 | 0.74 |
| Coral  | 20% | 86.28 | 8.21   | 13.87  | 16.12 | 59.37  | 0.33 |
| Coral  | 10% | 90.57 | 3.52   | 9.88   | 10.49 | 70.41  | 0.17 |
| Pink   | 20% | 84.28 | 18.21  | -2.91  | 18.45 | 350.92 | 0.12 |
| Pink   | 10% | 88.28 | 11.17  | -0.33  | 11.17 | 358.29 | 0.10 |
| Blue   | 20% | 79.84 | -7.27  | -15.81 | 17.41 | 245.30 | 0.12 |
| Blue   | 10% | 81.32 | -8.36  | -14.19 | 16.47 | 239.50 | 0.12 |
| Yellow | 20% | 94.45 | -5.03  | 16.94  | 17.67 | 106.54 | 0.17 |
| Yellow | 10% | 94.71 | -4.39  | 14.25  | 14.91 | 107.13 | 0.17 |

Polyester single jersey knitted fabrics were additionally dyed at 80, 100, and 130 °C to investigate the effect of temperature. Comparable dyeing performance was obtained at 100 and 130 °C, whereas lower color yield and residual dye in the bath were observed at 80 °C. Based on these findings, pilot-scale polyester dyeing was carried out at 100 °C.

### 3.2. Pilot-Scale Dyeing Results and Scale Comparison

The optimized laboratory-scale parameters were successfully transferred to pilot-scale dyeing trials. The CIELAB results of pilot-scale dyed fabrics are presented in Table 4.

**Table 4.** Color measurement values of fabrics dyed at pilot scale

| Fabric Number | Color  | L     | a     | b     | C     | h      | K/S  |
|---------------|--------|-------|-------|-------|-------|--------|------|
| 3             | Yellow | 94.76 | -5.43 | 16.95 | 17.80 | 107.76 | 0.18 |
| 4             |        | 94.65 | -5.39 | 16.03 | 16.91 | 108.58 | 0.15 |

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|---|------------|-------|-------|--------|-------|--------|------|
| 5 |            | 93.35 | -4.12 | 14.88  | 15.44 | 105.49 | 0.14 |
| 6 |            | 93.35 | -5.61 | 21.10  | 21.83 | 104.88 | 0.12 |
| 7 |            | 92.29 | -1.58 | 6.79   | 6.97  | 103.06 | 0.19 |
| 3 | Coral      | 88.71 | 5.49  | 11.06  | 12.35 | 63.60  | 0.19 |
| 4 |            | 89.51 | 4.60  | 11.26  | 12.17 | 67.78  | 0.21 |
| 5 |            | 90.58 | 3.60  | 10.80  | 11.38 | 71.56  | 0.14 |
| 6 |            | 87.17 | 9.95  | 11.99  | 15.58 | 50.31  | 0.11 |
| 7 |            | 92.29 | -0.80 | 6.33   | 6.38  | 97.22  | 0.20 |
| 3 | Blue       | 83.72 | -7.02 | -11.66 | 13.61 | 238.94 | 0.10 |
| 4 |            | 86.81 | -5.41 | -7.65  | 9.37  | 234.73 | 0.08 |
| 3 | Pink       | 85.65 | 16.13 | -2.60  | 16.34 | 350.84 | 0.09 |
| 4 |            | 84.68 | 17.67 | -3.70  | 18.06 | 348.16 | 0.10 |
| 3 | Green      | 83.00 | -8.60 | 24.39  | 25.86 | 109.42 | 0.75 |
| 4 |            | 82.33 | -8.42 | 23.77  | 25.22 | 109.49 | 0.73 |
| 5 | Anthracite | 43.43 | 1.86  | -5.01  | 5.35  | 290.33 | 1.18 |
| 6 |            | 32.20 | 3.03  | -9.14  | 9.63  | 288.37 | 1.81 |
| 7 |            | 70.39 | -2.17 | -1.75  | 2.79  | 218.79 | 0.38 |
| 2 |            | 46.81 | 9.81  | -6.45  | 11.74 | 326.68 | 0.82 |
| 5 | Beige      | 86.08 | 0.65  | 2.08   | 2.18  | 72.60  | 0.10 |
| 6 |            | 81.21 | 0.73  | 1.22   | 1.42  | 59.28  | 0.19 |
| 7 |            | 92.52 | -1.08 | 4.94   | 5.05  | 102.30 | 0.17 |

Overall, homogeneous and reproducible dyeing results were achieved on polyester, polyamide, and acetate fabrics using algae-based dyes. Color variations were observed depending on fiber type, which may be attributed to differences in dye–fiber interactions and surface morphology. Yellow and beige samples exhibited relatively high lightness ( $L^*$ ) values, whereas anthracite shades showed lower lightness and comparatively higher K/S values, indicating stronger dye uptake.

Green and anthracite colors generally exhibited higher color strength, while pink and blue shades showed relatively lower K/S values. Although slight visual and instrumental differences were observed among certain samples, the target color shades were generally achieved under pilot-scale conditions.

Comparative evaluations of laboratory- and pilot-scale dyeing showed only minor differences in color properties (Table 5), indicating that the optimized dyeing process can be successfully transferred to industrially relevant scales.

**Table 5.** Comparative color values of fabrics (fabric number 2) dyed at laboratory and pilot scale

| Color      | Dyeing Scale     | L     | a    | b     | C     | h      | K/S  |
|------------|------------------|-------|------|-------|-------|--------|------|
| Anthracite | Laboratory scale | 40.56 | 6.03 | -6.02 | 8.52  | 315.04 | 1.19 |
| Anthracite | Pilot scale      | 46.81 | 9.81 | -6.45 | 11.74 | 326.68 | 0.82 |

This indicates that the dyeing parameters determined at the laboratory scale can be successfully transferred to the pilot scale, and that the developed process is suitable for scale-up.

### 3.3. Process Optimization and pH Stability

pH stability was identified as an important parameter in algae-based dyeing processes. Preliminary trials showed that commercial buffering systems resulted in unstable pH values after dyeing, whereas acetic acid maintained a stable acidic environment (pH 4.4–4.5). Stable pH conditions contributed to improved process reproducibility and more controlled dyeing performance, supporting previous findings reported for natural dyeing systems [4].

### 3.4. Fastness and Mechanical Performance

Fastness and mechanical tests were conducted to evaluate the industrial applicability of algae-based dyes on synthetic fabrics. Washing, rubbing, perspiration, chlorine, oxidative bleaching, and light fastness generally showed values between 4 and 4/5, indicating satisfactory performance.



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Mechanical evaluations including tensile strength, tear strength, and seam slippage demonstrated that the applied dyeing conditions did not negatively affect fabric integrity. No significant deterioration in mechanical performance was observed after dyeing, indicating that the developed process preserved structural stability. In addition, phenolic yellowing observed in polyamide fabrics was successfully eliminated using an alkyl aryl sulfonate-based treatment during stentering, improving process reliability for industrial applications.

Overall, the results indicate that algae-based dyes can provide acceptable color performance, durability, and process applicability for synthetic textile dyeing under optimized conditions.

Wastewater samples obtained after dyeing were also analyzed in terms of chemical oxygen demand (COD). The measured COD values were 1921 mg O<sub>2</sub>/L for yellow dyeing and 1946 mg O<sub>2</sub>/L for blue dyeing. These results provide preliminary insight into the wastewater characteristics of algae-based dyeing processes.

#### 4. CONCLUSION

This study investigated the applicability of algae-based dyes for the dyeing of polyester (PES), polyamide (PA), and acetate (CA) fabrics under laboratory- and pilot-scale conditions. The results demonstrated that algae-based dyes can be successfully applied to synthetic fibers, achieving acceptable color performance and homogeneous dyeing under optimized conditions.

Process optimization showed that controlled acidic conditions and optimized dyeing parameters enabled satisfactory dyeing performance, while laboratory-scale parameters were successfully transferred to pilot-scale production. The dyed fabrics exhibited satisfactory fastness and mechanical performance, and process-related issues such as phenolic yellowing were effectively controlled.

Overall, the findings indicate that algae-based dyes offer a promising and more sustainable alternative for synthetic textile dyeing with potential industrial applicability. Further studies may focus on improving dye uptake and process reproducibility, particularly for hydrophobic fibers.

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## TECHNICAL PERFORMANCE AND ENVIRONMENTAL POTENTIAL OF TEXTILE-TO-TEXTILE RECYCLED PET YARNS IN AUTOMOTIVE SEAT COVER FABRICS

Semih Oylar<sup>1</sup>, Nur Ceyda Uyaniktir<sup>2,\*</sup>, Selenay Elif İşler<sup>3</sup>, Benamir FİDANCI<sup>4</sup>, Emir Baltacıoğlu<sup>5</sup>

<sup>1,2,3,4,5</sup> Martur Fompak International, Textile R&D Department, Bursa, Turkey

\* [ceyda.uyaniktir@marturfompak.com](mailto:ceyda.uyaniktir@marturfompak.com)

### ABSTRACT

Sustainability has become an essential focus in the automotive industry, particularly in the selection of materials used for interior components. Polyester fibers are widely used in automotive seat cover fabrics due to their durability, dimensional stability, and cost efficiency. Conventional recycling processes in the textile industry are often based on bottle-to-fiber recycling, where post-consumer polyethylene terephthalate (rPET) bottles are converted into textile-grade recycled polyester (rPES) fibers. However, this approach does not fully address the growing volume of textile waste generated by the apparel and technical textile sectors. Textile-to-textile (T2T) recycling represents a more circular solution by enabling the recovery and reuse of polyester fibers directly from textile waste. This study investigates the technical feasibility of replacing conventional recycled polyester yarn derived from bottle-based rPET with T2T recycled PES yarn in automotive seat cover fabrics. A reference fabric produced with bottle-based rPET-derived rPES yarn was reproduced using T2T recycled PES yarn while maintaining production parameters, including fabric construction, lamination structure, and finishing processes. The laminated structure consisted of a woven face fabric combined with foam and scrim layers. Both materials were evaluated according to automotive performance requirements such as thickness and grammage measurement, tensile elongation at break & tensile strength, surface abrasion and Taber abrasion tests specified by Toyota. Test results showed that the bottle-based recycled PET fabric exhibited better mechanical properties, with tensile strength values approximately 13–19% higher than the T2T-based fabric depending on the test direction. In terms of abrasion behavior, both samples achieved a grey scale rating of 4 in the Taber abrasion test, whereas the T2T-based fabric showed lower surface abrasion resistance, with grey scale ratings decreasing to 2 under 1 kg and 2 kg loading conditions in certain directions.

**Keywords:** *Automotive textiles, Textile-to-textile recycling, Recycled PET yarn, Automotive seat cover fabrics, Circular economy, Sustainable materials*

### 1. INTRODUCTION

The automotive industry has increasingly focused on sustainability and environmental responsibility in recent years, particularly in the selection of materials used for vehicle interior components. Automotive textiles are widely utilized in interior applications such as seat covers, headliners, carpets, and door panels. Among the different fiber types used in automotive textile applications, PET fibers are widely preferred because of their high mechanical strength, dimensional stability, chemical resistance, and cost efficiency. These properties make PET-based textiles particularly suitable for demanding applications such as automotive seating, where long-term durability and performance are essential [1]. Despite these advantages, the production of virgin polyester has significant environmental impacts. The manufacturing process of virgin PET fibers requires considerable energy consumption and relies heavily on petroleum-based raw materials, which contribute to greenhouse gas emissions and resource depletion. As a result, increasing attention has been directed toward developing more sustainable alternatives that can reduce the carbon footprint of polyester-based textile materials [2].

In response to these environmental concerns, recycling has become an important strategy within the textile industry. Recycled polyester has gained considerable attention as an alternative to virgin polyester in a wide range of textile applications. The most widely used method in the industry is bottle-to-fiber recycling, in which post-consumer PET bottles are collected, processed, and converted into polyester fibers suitable for textile production. This approach helps reduce plastic waste and lowers the demand for virgin raw materials [3]. In line with these developments, organizations such as Textile Exchange have actively promoted the adoption of recycled polyester; accordingly, the share of recycled polyester in total polyester production reached approximately 36% by 2019 and is projected to account for around 20% of total polyester production by 2030 [4].

Despite these advancements, bottle-to-fiber recycling does not directly address the increasing volume of textile waste generated during production and consumption processes. In recent years, the concept of textile-to-textile (T2T) recycling has emerged as a promising approach for establishing a more circular textile economy. Textile-to-textile recycling enables the recovery and reuse of fibers from textile waste, allowing materials to remain within the textile value chain rather than being downcycled or disposed of in landfills or incineration facilities [5]. This approach has the potential to significantly reduce environmental impacts of virgin materials and decreasing waste generation. Several studies have highlighted the environmental benefits of textile-to-textile recycling, including reduced energy consumption, lower carbon emissions, and improved resource efficiency within textile production systems [6].

Within this context, thermo-mechanical recycling represents one of the most feasible and industrially scalable method for implementing textile-to-textile recycling, particularly for polyester-based materials. In this method, post-consumer textile waste is collected and sorted according to fiber composition, followed by the removal of non-textile components. The sorted materials are then mechanically processed through shredding into fibers or flakes and cleaned to remove contaminants and finishing chemicals. After drying, the polyester is melted and reprocessed extrusion and melt-spinning to produce new fibers suitable for textile applications. This approach avoids complex chemical depolymerization steps, offering advantages in terms of lower energy consumption, reduced processing time, and cost efficiency [7,8].

Although thermo-mechanical textile-to-textile recycling offers a promising solution for circular material utilization, the performance of recycled fibers, yarns, and fabrics remains a critical concern, particularly for demanding applications such as automotive interiors. Repeated thermal and mechanical stresses during processing can lead to polymer chain degradation, reduced molecular weight, and deterioration of fiber morphology. These changes result in decreased tensile strength, increased brittleness, and higher variability compared to virgin materials. At the yarn and fabric levels, this is reflected in increased irregularity, higher hairiness, reduced abrasion resistance, and a greater tendency for pilling [9,10]. To overcome these limitations, strategies such as blending recycled fibers with virgin materials and optimizing processing parameters have been proposed. In parallel, advancements in recycling technologies and material engineering, particularly in melt processing, filtration, and spinning, have demonstrated significant potential to improve fiber uniformity and mechanical performance. Under optimized conditions, these developments enable recycled polyester fibers to achieve properties suitable for a wide range of textile applications, including those with relatively high performance requirements [11]. This study evaluated the technical performance of textile-to-textile (T2T) recycled polyester yarns in comparison with conventional bottle-to-fiber recycled PET yarns for automotive seat cover fabric applications by performing elongation, strength, and abrasion resistance tests according to Toyota specifications.

## **EXPERIMENTAL STUDY**

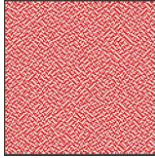
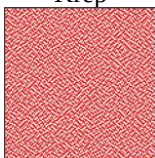
### **2.1 Materials**

In this study, two laminated automotive seat cover fabric structures were produced, with face fabrics obtained from different recycled sources. For Sample 1, the face fabric was produced using yarns produced from post-consumer PET bottles, supplied by Antex company. For Sample 2, the face fabric was produced using T2T recycled yarns obtained from post-consumer polyester textile waste, supplied by Re&Up company. Since only the effect of the recycled source was investigated between these two samples, the properties of the lamination materials and the finishing parameters were kept constant. Each samples face fabric was subjected to 90°C open width washing, 150 °C tumbling and 170°C stentering processes under the same conditions. Then, the produced fabrics were laminated with 30 dens 2.8 mm polyurethane (PU)

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foam and 32 g/m<sup>2</sup> PES circular knitted scrim using the flame lamination technique. The weaving of the fabrics, finishing processes, and the lamination of the produced face fabrics with PU foam and PES scrim were all carried out at Martur Sünger ve Koltuk Tesisleri A.Ş.

**Table 1.** Used Materials and Production Details of the Woven Face Fabrics

| Samples  | Yarn content                                 | Yarn Type             | Design Type                                                                                | Warp density (ends/cm) | Weft density (picks/cm) |
|----------|----------------------------------------------|-----------------------|--------------------------------------------------------------------------------------------|------------------------|-------------------------|
| Sample 1 | 90% PET bottle Recycled<br>PES 5% Virgin PES | 450 den/ 144 F<br>IMG | Krep<br> | 18                     | 23                      |
| Sample 2 | 100% T2T Recycled PES                        | 450 den/ 144 F<br>IMG | Krep<br> | 18                     | 23                      |

## 2.2. Method

### 2.2.1. Thickness and Grammage Measurement

Thickness and grammage values were measured of the produced samples with material specifications in accordance with TSL 2104G (4.16) and TSL 2104G (4.1). Fabric thickness (mm) was determined using a textile thickness gauge, while the mass per unit area (g/m<sup>2</sup>) was measured using a precision balance. For both parameters, the average values were calculated from five specimens.

### 2.2.2. Tensile Elongation at Break& Tensile Strength

This test was performed in accordance with the TSL 2105G (4.1.3) standard. Tensile elongation at break defines the elongation behavior of upholstery fabrics under tensile loading up to the point of rupture, and evaluates their resistance to deformation during use in automotive interiors. In this method, specimens prepared in both warp and weft directions are mounted on a tensile testing device with a 100 mm gauge length and tested at a speed of 200 mm/min after applying the specified preload (1.96 N for woven fabrics).

In addition to elongation at break, the tensile strength (break force) of the fabric is also determined within the same test. The force applied to the specimen at the moment of rupture is recorded in Newtons (N) and reported as the tensile strength. This value represents the maximum load the fabric can withstand before failure. The elongation percentage at the moment of rupture is also recorded and reported as the tensile elongation at break value.

### 2.2.3. Surface Abrasion

This test was conducted in accordance with the TSL 2105G (4.7) standard. Surface abrasion refers to the wear and deformation that occur when two surfaces are rubbed against each other. Automotive upholstery fabrics are continuously exposed to friction from various materials worn by users during vehicle use, making abrasion resistance testing essential. In this study, the test was performed by rubbing an abrasion fabric against the sample surface for 10,000 cycles under a 1 kg load.



**Figure 1.** Surface Abrasion Test Device

#### 2.2.4. Surface Abrasion at High Load

This test is performed according to the TSL 2105G (4.7.3) test standard. Surface abrasion at high load evaluates the resistance of upholstery fabrics against severe surface wear under higher mechanical stress conditions that may occur during vehicle usage. In this method, fabric specimens prepared in different directions are mounted on the surface abrasion tester with a polyurethane foam support layer, and an abrasive canvas is applied onto the fabric surface under a 2 kg load (19.6 N). The test is performed with a 140 mm abrasion stroke length at a speed of  $60 \pm 10$  cycles/min for 10,000 cycles. After testing, the surface condition of the fabric is visually evaluated according to the defined rating scale based on the observed surface damage.

#### 2.2.5. Taber Abrasion Test

This test is performed according to the TSL 2105G (4.8) test standard. Taber abrasion evaluates the surface wear resistance of upholstery fabrics against repeated rotational rubbing during vehicle usage. In this method, 120 mm diameter fabric specimens are mounted on the Taber abrasion tester and tested using CS-10 abrasive wheels under a 500 g load (4.9 N). The abrasion heads rotate on the fabric surface for 100 and 1000 cycles, and the surface condition is visually evaluated after testing. The abrasion performance is rated according to the defined evaluation scale based on surface damage observed on the fabric.



**Figure 2.** Taber Abrasion Test Device

## 2. RESULTS

The thickness values were measured at five different locations on each fabric sample. According to the thickness measurement results given in Table 2 below, both samples have similar average thickness values, with Sample 2 being slightly thicker. However, Sample 1 exhibits a lower coefficient of variation (CV%), indicating a more uniform and stable structure. In contrast, Sample 2 shows higher variability, which may be attributed to the heterogeneous nature of recycled textile waste fibers compared to recycled PET bottle-based fibers.

**Table 2.** Thickness measurement of the samples

| Measurement Type | Sample1       | Sample2 |
|------------------|---------------|---------|
| Thickness (mm)   | 1.79          | 1.85    |
|                  | 1.82          | 1.95    |
|                  | 1.80          | 1.98    |
|                  | 1.83          | 1.90    |
|                  | 1.81          | 1.92    |
|                  | Average value | 1.81    |
| CV%              | 0.87          | 2.58    |



The grammage values were measured at five different locations on each fabric sample. According to the thickness measurement results given in Table 3 below, Sample 1 has a slightly higher average grammage compared to Sample 2. Additionally, Sample 1 demonstrates lower variability (CV%), indicating a more uniform mass distribution. In contrast, Sample 2 exhibits higher variation, which may be related to the structural irregularities of fibers derived from recycled textile waste.

**Table 3.** Grammage measurement of the face fabric samples

| Measurement Type             | Sample1 | Sample2 |
|------------------------------|---------|---------|
| Grammage (g/m <sup>2</sup> ) | 268     | 252     |
|                              | 272     | 262     |
|                              | 270     | 265     |
|                              | 271     | 257     |
|                              | 269     | 258     |
| Average value                | 270     | 258     |
| CV%                          | 0.59    | 1.90    |

The tensile strength and tensile elongation at break results of both samples meet the minimum acceptance criteria, which are 500 N for tensile strength and 10% for elongation in all directions (L, T, and Bias). According to the measurement results given in Table 4 below, sample 1 exhibits higher tensile strength values in all directions compared to Sample 2, indicating better mechanical performance and structural integrity. Similarly, Sample 1 shows generally higher elongation values, except in the bias direction where both samples demonstrate comparable behavior. Although Sample 2 has lower tensile strength and more variability in elongation (especially in the transverse direction), all measured values remain well above the required limits. Therefore, both samples are considered acceptable in terms of tensile performance, with Sample 1 showing superior overall properties.

**Table 4.** Tensile strength and tensile elongation at break test result of the samples

| Samples  | Tensile elongation at break (%) | Tensile strength (N) |
|----------|---------------------------------|----------------------|
| Sample 1 | L:45.38                         | L:1799               |
|          | T:48.94                         | T:1860               |
|          | Bias:54.84                      | Bias:1141            |
| Sample 2 | L:41.7                          | L:1456               |
|          | T:35.5                          | T:1683               |
|          | Bias:56.15                      | Bias:1022            |

The Taber abrasion test results show that both samples achieved a grey scale rating of 4 under both 500 g load–100 cycles and 500 g load–1000 cycles conditions. Considering that the minimum acceptance criterion is 4 for both test conditions, all samples meet the required performance limits.

**Table 5.** Taber abrasion test result of the samples

| Samples  | Taber abrasion 500 g load,100 cycles (Grey scale) | Taber abrasion 500 g load,1000 cycles (Grey scale) |
|----------|---------------------------------------------------|----------------------------------------------------|
| Sample 1 | 4                                                 | 4                                                  |
| Sample 2 | 4                                                 | 4                                                  |

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The surface abrasion test results indicate that Sample 1 generally demonstrates better abrasion resistance compared to Sample 2. Under 1 kg load and 10,000 cycles, Sample 1 achieves a grey scale rating of 4 in all directions (L, T, Bias), fully meeting the minimum acceptance criterion of 3. In contrast, Sample 2 shows lower performance, with ratings of 2 in the longitudinal and bias directions and 3 in the transverse direction, meaning it does not fully meet the requirement under 1 kg load.

Under 2 kg load and 10,000 cycles, Sample 1 maintains acceptable performance in the transverse direction (4), while slightly decreasing to 3 in the longitudinal and bias directions, still meeting the minimum requirement. However, Sample 2 again shows insufficient performance in the longitudinal and bias directions (2), remaining below the acceptance limit, while only meeting the requirement in the transverse direction (3).

Overall, Sample 1 meets the acceptance criteria under all conditions and demonstrates more stable abrasion resistance. Sample 2, however, fails to meet the required performance in multiple directions, particularly under increased load, indicating lower surface durability.

**Table 6.** Surface abrasion test result of the samples

| Samples  | Surface abrasion<br>1kg load,10.000 cycles<br>(Grey scale) | Surface abrasion<br>2 kg load,10.000 cycles<br>(Grey scale) |
|----------|------------------------------------------------------------|-------------------------------------------------------------|
| Sample 1 | L:4<br>T:4<br>Bias:4                                       | L:3<br>T:4<br>Bias:3                                        |
| Sample 2 | L:2<br>T:3<br>Bias:2                                       | L:2<br>T:3<br>Bias:2                                        |

#### 4. CONCLUSION

This study evaluated the technical performance of textile T2T recycled polyester yarns in comparison with conventional bottle-to-fiber recycled PET yarns for automotive seat cover fabric applications. The results demonstrate that while T2T recycled yarns offer environmental advantages in terms of circular material utilization, certain performance limitations remain when compared to bottle-based recycled polyester.

In terms of physical properties, both samples showed comparable thickness and grammage values. However, the T2T-based fabric showed higher variability (CV%), indicating a less uniform structure. This can be attributed to the heterogeneous nature of post-consumer textile waste used in T2T recycling processes.

Mechanical performance results showed that both samples met minimum automotive requirements in terms of tensile strength and elongation at break. However, the fabric produced from bottle-based recycled PET yarns exhibited superior tensile strength and more consistent elongation behavior in all directions. But, the T2T-based sample still achieved acceptable performance levels, confirming its technical suitability for automotive applications under controlled conditions.

Abrasion resistance emerged as the most critical differentiating factor between the two samples. While both materials met the requirements in the Taber abrasion test, the T2T-based fabric exhibited significantly lower resistance in surface abrasion tests, particularly under higher load conditions. In several cases, it failed to meet the minimum acceptance criteria, indicating limitations in durability for demanding end-use conditions such as automotive seating.

Overall, the results suggest that T2T recycled polyester yarns can be considered an alternative for automotive textile applications where sustainability is a priority, provided that performance requirements are evaluated. However, to fully replace conventional recycled polyester, further improvements are necessary, particularly in enhancing fiber uniformity and abrasion resistance. Future study should focus on optimizing recycling processes, improving raw material sorting, and exploring blending strategies or advanced spinning technologies to enhance the performance consistency of T2T recycled fibers.

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## TECHNOLOGY TREND FORECASTING IN SUSTAINABLE TEXTILE INNOVATION THROUGH IPC-BASED PATENT ANALYSIS (2010–2025)

Büşra Bozyer<sup>1\*</sup>, Yunus Eroğlu<sup>2</sup>, Erkan Evran<sup>3</sup>

<sup>1</sup> Sanko Textile, Department of R&D, Gaziantep, Türkiye

<sup>2</sup> Gaziantep University, Department of Industrial Engineering, Gaziantep, Türkiye

<sup>3</sup> Sanko Textile, Department of R&D, Gaziantep, Türkiye

\*Corresponding author: [busra.bozyer@sanko.com.tr](mailto:busra.bozyer@sanko.com.tr)

### ABSTRACT

The global textile industry is experiencing rapid transformation driven by the demand for sustainability, digitalization, and innovation. This study aims to analyze technological development trends in the field of smart and sustainable textiles by utilizing patent data classified under International Patent Classification (IPC) codes. Focusing particularly on the main IPC groups D01F (chemical synthetic fibers), D01G (fiber preparation), and D01C (natural fiber processing), patent data between 2010 and 2025 were extracted from Espacenet and WIPO databases.

The yearly distribution of applications and applicant countries were examined to identify innovation hotspots. The analysis reveals a steady increase in patent activity in sustainable fiber technologies, especially after 2015, corresponding to rising environmental concerns and circular economy strategies. Additionally, subgroup-specific trends suggest a growing interest in bio-based polymers and fiber surface functionalization. By mapping these patterns, this study attempts to forecast which fiber-based innovations are likely to dominate the sector in the coming decade.

The research demonstrates that IPC-based patent analysis is a valuable approach for short-term technology forecasting and provides strategic insight for researchers and industry stakeholders aiming to align with emerging textile technologies.

**Keywords:** Patent Analysis, IPC Classification, Sustainable Fibers, Smart Textiles, Technology Forecasting

### 1. INTRODUCTION

The global textile industry is undergoing a significant transformation driven by sustainability concerns, rapid technological advancements, and increasing digitalization. Environmental challenges such as resource depletion, textile waste, and carbon emissions have accelerated the transition toward sustainable production systems and innovative material solutions. In this context, sustainable and smart textiles have emerged as key drivers of next-generation textile applications, integrating functionality, performance, and environmental responsibility [1-3].

Recent developments in smart textile technologies demonstrate the convergence of traditional textile manufacturing with advanced disciplines such as electronics, materials science, and information technologies. These innovations enable textiles to evolve from passive materials into interactive and multifunctional systems capable of sensing, communication, and adaptive responses. In particular, the integration of Internet of Things (IoT) technologies and intelligent materials has significantly expanded the application areas of textiles, ranging from healthcare and wearable systems to industrial and environmental applications [4-5].

Although smart textiles are commonly associated with electronic integration and sensor-based systems, their performance fundamentally depends on the properties and processing of the underlying fiber materials. Advanced fiber structures, such as synthetic high-performance fibers (D01F), optimized fiber preparation processes (D01G), and functionalized natural fibers (D01C) play a critical role in enabling key smart textile functionalities, including conductivity, flexibility, durability, and environmental responsiveness. Therefore,

innovation at the fiber level constitutes a foundational layer for the development of both smart and sustainable textile systems.

Parallel to these developments, patents have become one of the most reliable indicators for tracking technological innovation and industrial evolution. Patent data provide structured and standardized information reflecting technological progress, research and development activities, and innovation dynamics across industries. Accordingly, patent analysis is widely used to evaluate technological competitiveness, identify innovation patterns, and support strategic decision-making processes in both academic research and industrial applications [6-8].

In particular, the International Patent Classification (IPC) system enables a systematic and domain-independent analysis of technological developments. Compared to Keywords-based approaches, IPC-based analysis offers a more consistent and reliable framework by eliminating linguistic ambiguities and classifying technologies within a hierarchical structure. This approach has been extensively utilized in the literature to analyze technological trends and identify innovation hotspots across various sectors [9-11].

Furthermore, patent data have been increasingly employed in technology forecasting studies to explore future innovation trajectories. Due to their comprehensive and structured nature, patents serve as a valuable data source for forecasting methods, including time-series analysis, technology life cycle assessment, and statistical trend evaluation. These approaches enable researchers to anticipate technological evolution and identify emerging areas of innovation [12-14].

Despite the growing number of studies on patent-based technology analysis, limited research has specifically focused on sustainable textile innovations using IPC-based classification combined with time-series trend evaluation. In particular, existing studies often examine isolated technological domains, whereas comprehensive analyses covering chemical synthetic fibers, fiber preparation processes, and natural fiber processing within a unified framework remain scarce.

Therefore, this study aims to analyze technological development trends in sustainable textile innovations through IPC-based patent analysis. The study focuses on the main IPC groups D01F (chemical synthetic fibers), D01G (fiber preparation), and D01C (natural fiber processing), which represent the fundamental stages of fiber-based textile production. Patent data between 2010 and 2025 were collected from Espacenet and WIPO databases and analyzed using time-series trend analysis and comparative evaluation methods.

The findings are expected to provide valuable insights into the evolution of fiber-level technologies as a foundation for smart and sustainable textiles. Moreover, the study proposes a structured and replicable analytical framework that supports technology forecasting and strategic decision-making in the textile industry.

## **2. MATERIALS AND METHODS**

This study is based on patent data analysis rather than experimental investigation. Patent data were used as quantitative indicators to evaluate technological development trends in sustainable textile innovations, with a particular focus on fiber-level technologies that form the foundation of smart textile systems.

### **2.1 Data Source and Collection**

Patent data were collected from two major international patent databases: Espacenet (European Patent Office) and WIPO Patentscope. These databases provide comprehensive global coverage and standardized patent information, including publication dates, classification codes, applicants, and inventor details. To ensure data consistency and eliminate duplication, patent families were considered, and the “earliest priority date” was used as the reference criterion. The analysis was limited to the period between 2010 and 2025, allowing for the evaluation of long-term technological development trends.

### **2.2 IPC-Based Classification**

The International Patent Classification (IPC) system was used to categorize patent data into technological domains. IPC provides a hierarchical and standardized structure, enabling systematic and comparable analysis across different technology fields.



In this study, three main IPC groups were selected due to their relevance to fiber-based textile technologies and their indirect contribution to smart textile development:

D01F: Chemical synthetic fibers, including polymer-based fiber production, filament formation, and fiber modification processes

D01G: Fiber preparation processes, such as opening, cleaning, blending, and carding prior to spinning

D01C: Natural fiber processing, including chemical and mechanical treatments of fibers such as cotton, flax, and hemp

These IPC groups represent the fundamental stages of fiber production and processing, covering both synthetic and natural fiber technologies within a unified analytical framework. In addition, functional fibers and material-level innovations classified under these groups play a critical role in enabling smart textile functionalities such as conductivity, flexibility, and durability.

### **2.3 Data Processing and Analysis**

The collected patent data were analyzed using quantitative and comparative approaches. The analysis was structured into three main components:

#### **2.3.1 Yearly Trend Analysis**

The number of patent applications was calculated for each year to identify temporal changes in technological activity. The yearly distribution of patent data was used to generate trend curves and evaluate the growth patterns of innovation activities.

#### **2.3.2 Comparative IPC Analysis**

Patent counts for each IPC group (D01F, D01G, and D01C) were compared to determine differences in technological development levels. This analysis enables the identification of dominant and emerging technology areas within the textile sector.

#### **2.3.3 Country-Based Analysis**

The geographical distribution of patent applications was examined based on applicant countries. The leading countries were identified for each IPC group to evaluate global innovation dynamics and technological leadership patterns.

### **2.4 Research Framework**

The overall research framework of the study consists of the following stages:

- Collection of patent data from Espacenet and WIPO databases
- Classification of patents using selected IPC groups
- Analysis of yearly patent trends
- Comparative evaluation of IPC-based technological development
- Identification of country-based innovation patterns

This structured approach enables a systematic evaluation of technological trends and provides a reliable basis for short-term technology forecasting in the textile sector.

## **3. RESULTS**

This section presents the findings obtained from the analysis of patent data classified under the IPC groups D01F, D01G, and D01C for the period between 2010 and 2025. The results are evaluated in terms of overall patent trends, comparative technological development, and geographical distribution.

### 3.1 Overall Patent Trend

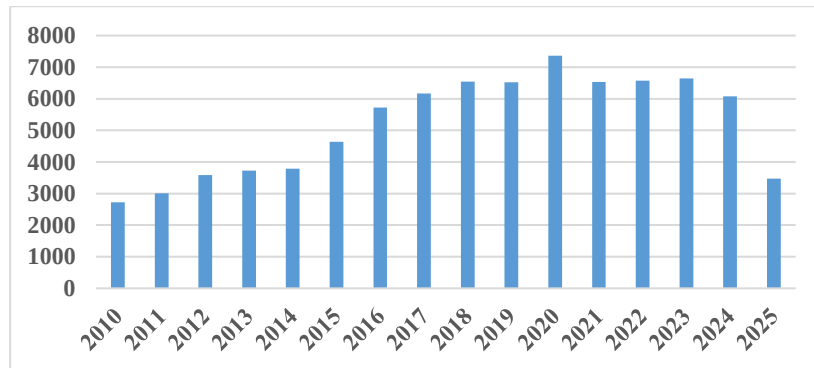


**Figure 1.** Total patent application trend in fiber-based textile technologies (2010–2025)

The analysis reveals a clear increasing trend in patent activity between 2010 and 2020, rising from 2,725 applications in 2010 to a peak of 7,358 in 2020. This growth reflects the increasing importance of innovation in fiber-based textile technologies, particularly in response to sustainability and performance requirements. After 2020, patent activity shows a stabilization phase with minor fluctuations between 2021 and 2024. The decrease observed in 2025 is attributed to incomplete patent publication data rather than an actual decline in innovation.

Overall, the results indicate that the analyzed technology domains remain in a growth-oriented phase.

### 3.2 Comparative IPC Analysis

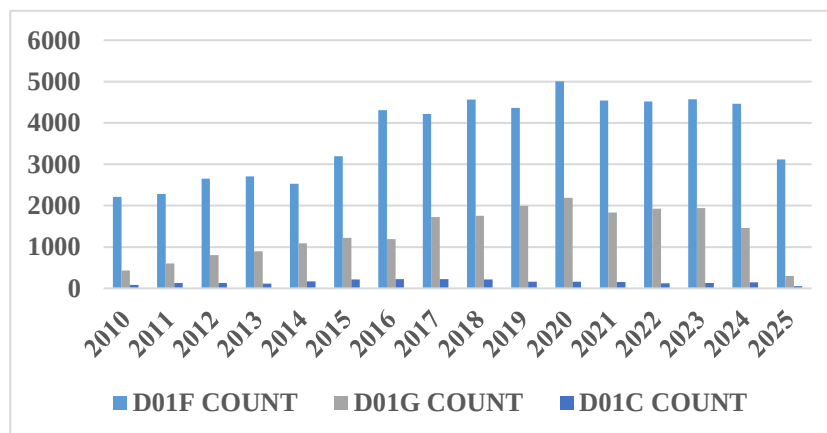


**Figure 2.** Comparative analysis of patent trends by IPC groups (D01F, D01G, D01C)

As shown in Figure 2, D01F exhibits the highest level of patent activity throughout the analysis period, followed by D01G, while D01C shows comparatively lower but stable levels.

D01F (chemical synthetic fibers) clearly dominates technological development, reflecting the strong industrial demand for high-performance fiber materials.

D01G (fiber preparation processes) demonstrates steady growth, particularly after 2015, indicating continuous efforts to improve production efficiency and process optimization.

D01C (natural fiber processing) shows relatively lower but stable patent activity, suggesting an emerging interest in sustainable and bio-based fiber technologies.

### 3.3 Country-Based Distribution

**Table 1.** Distribution of patent applications by leading countries across selected IPC groups

| IPC Group | Country | Patent Count |
|-----------|---------|--------------|
| D01F      | US      | 10,704       |
|           | JP      | 8,598        |
|           | KR      | 8,225        |
|           | DE      | 3,117        |
|           | CN      | 2,287        |
| D01C      | US      | 249          |
|           | KR      | 122          |
|           | CN      | 102          |
|           | JP      | 64           |
|           | GB      | 57           |
| D01G      | DE      | 1,439        |
|           | CH      | 808          |
|           | US      | 595          |
|           | KR      | 572          |
|           | JP      | 380          |

The geographical distribution indicates that patent activity is concentrated in technologically advanced regions. D01F is dominated by the United States, Japan, and South Korea, highlighting their leadership in synthetic fiber technologies. In contrast, D01G activity is largely concentrated in European countries, particularly Germany and Switzerland, reflecting their strength in textile machinery and processing technologies.

For D01C, patent activity is more evenly distributed across multiple countries, suggesting broader global participation in natural fiber processing and sustainability-driven innovation.

### 3.4 General Evaluation of Technological Trends

The combined analysis of patent trends and geographical distribution provides insights into the evolution of fiber-based textile technologies.

D01F remains the dominant innovation driver, reflecting the continued importance of synthetic fiber technologies. D01G shows steady development, emphasizing the role of process efficiency and production optimization. Meanwhile, D01C demonstrates growing but still limited activity, indicating increasing interest in sustainable and natural fiber solutions.

Overall, the results suggest a gradual transition toward a balanced innovation structure, where high-performance synthetic fibers coexist with sustainability-oriented natural fiber technologies.

## 4. DISCUSSION AND CONCLUSION

The findings of this study highlight the evolving structure of innovation in fiber-based textile technologies. Patent activity shows strong growth between 2010 and 2020, followed by a stabilization phase, indicating that these technologies are transitioning toward early maturity while maintaining innovation potential [1-3].

The dominance of D01F confirms that synthetic fibers remain the primary driver of technological development. However, the steady growth observed in D01G emphasizes the increasing importance of process optimization in textile production systems [13].

D01C, although characterized by lower patent intensity, shows stable development and a broader geographical distribution. This suggests a growing global interest in sustainable and bio-based materials [16-18].

From a technological perspective, the results indicate a shift toward a dual innovation structure, where performance-driven synthetic materials coexist with sustainability-oriented natural fiber solutions. This

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reflects the industry's effort to integrate performance and environmental considerations within a unified framework.

The study demonstrates that IPC-based patent analysis provides a reliable method for identifying technological trends and evaluating innovation dynamics [6-8]. By focusing on fiber-level technologies, the study also highlights the foundational role of material innovations in supporting the development of smart and sustainable textile systems.

However, the analysis is limited to selected IPC groups and relies solely on patent data, which may not fully capture all innovation activities. In addition, patent counts do not directly reflect technological quality or market adoption.

Future research may expand this approach by including additional IPC groups, incorporating citation-based analysis, or applying advanced forecasting models to improve predictive accuracy [12-14].

This study contributes to the literature by linking IPC-based patent analysis with fiber-level innovation in smart and sustainable textiles.

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## THE EFFECT OF GRAPHENE COATING ON THE THERMAL BEHAVIOR OF WOOL-BASED WOVEN FABRICS

Elif Altürk <sup>\*1-2</sup>, Nazlı Tatar<sup>3</sup>

1. İstanbul Okan University, Smart Infrastructures, Vocational High School, Tuzla, İstanbul/TURKEY
2. Warm Technology Company, TÜBİTAK TEKNOKENT, Gebze, Kocaeli/TURKEY
3. İstanbul Okan University, Electrical and Engineering Department, Tuzla, İstanbul/TURKEY

\* Corresponding Author, [elif.alturk@okan.edu.tr](mailto:elif.alturk@okan.edu.tr)

### ABSTRACT

This study comprehensively investigates the thermal properties of fabrics produced by weaving graphene-coated wool fibers. The results indicate that the addition of graphene significantly improves the thermal performance of the fabrics. Thermal conductivity values in the graphene-coated samples were measured in the range of 49.4–51.3 W/mK, with the highest value obtained in the goat wool-based fabric (51.3 W/mK). Thermal diffusivity values ranged from 0.103 to 0.115 mm<sup>2</sup>/s, while thermal absorption values ranged from 145.4 to 160 W·s<sup>1/2</sup>/m<sup>2</sup>K. Thermal resistance values ranged from 49.2 to 64.3 mK·m<sup>2</sup>/W depending on the fiber type, with the highest resistance determined in the goat wool-based sample. When compared to fabrics without graphene coating or those made with different fiber combinations, it is clearly evident that thermal conductivity values remained within the range of 46.1–49.35 W/mK, and that the graphene addition enhances performance. Additionally, the highest thermal resistance value of 93.4 mK·m<sup>2</sup>/W was obtained in the hybrid (sheep-goat) fiber structure. It is evident that the graphene coating not only increases thermal conductivity but also provides beneficial effects on thermal diffusivity, heat flux, and dynamic thermal behavior.

**Keywords:** Wool, graphene, smart textile, thermal fabric, double weaving

### INTRODUCTION

Thermophysiological comfort is the capacity of smart textile systems to preserve the human body's thermal equilibrium under varying environmental conditions. That is closely related to physiological mechanisms of the human body, the heat and moisture transfer characteristics of fabrics. A key element affecting thermophysiological performance is the air layer trapped between the skin and the fabric surface, referred to as the microclimate.

Graphene-based materials used in functional textiles, particularly graphene oxide (GO), reduced graphene oxide (rGO), and graphene nanoplatelets (GNP), exhibit significant differences in terms of surface chemistry, electrical conductivity, and interaction with fibers when compared. In this study, graphene nanoplatelets (GNP) were integrated into a wool-based textile structure via the dip-coating method to provide dual-functional performance enhancement. By forming a continuous and conductive percolation network on the fiber surface, the GNP coating ensured the homogeneous distribution of heat across the textile surface; thus, the formation of local hot spots was prevented, and the goal was to improve thermal comfort in wearable heating applications.

In addition, GNP's high surface area and edge-terminated morphology contribute to natural antibacterial activity by disrupting microbial membrane integrity and can reduce odor formation during prolonged skin contact. These combined effects demonstrate that the GNP dip-coating is not only an effective thermal management strategy in smart wearable systems but also provides additional hygienic functionality while preserving the fabric's natural texture and flexibility. This multifunctional enhancement clearly demonstrates the applicability of GNP-coated textiles in outdoor applications, medical support products, and auxiliary thermoregulation scenarios.



Graphene exhibits exceptional intrinsic properties such as outstanding thermal conductivity, remarkable mechanical strength, and superior electronic transport behavior. Thanks to these properties, graphene is attracting significant interest for integration into a wide range of advanced technologies.

In this study, the thermal properties of fabrics produced by weaving graphene-coated sheep and goat wool fibers—including thermal conductivity, thermal diffusivity, thermal resistance, and heat flux—were experimentally investigated.

## **2.EXPERIMENTAL STUDY**

### **2.1 Materials**

In this study, sheep wool and goat wool were used as the primary raw materials for fabric production. The fibers were blended in equal proportions, consisting of 50% sheep wool and 50% goat wool by weight.

Prior to weaving, the fibers were cleaned and prepared through standard carding and spinning processes to obtain uniform yarns suitable for weaving. The blended yarns were then produced and used in a traditional double-layer weaving machine.

### **2.2. Graphene coating by dip coating**

Experimental studies on graphene nanoplatelet (GNP) coating have been initiated in the project, and preliminary tests were conducted in the first phase using ready-made white wool fabrics. For this purpose, the 0.1% of GNPs were dispersed in a solvent system consisting of a mixture of isopropyl alcohol (IPA) and polyvinylpyrrolidone (PVP). It was observed that the resulting dispersion exhibited a very homogeneous distribution within the solution. Fabric samples cut to a size of 2 cm<sup>2</sup> were immersed in the prepared solution for varying durations to apply the coating; the samples were then dried at room temperature and subjected to a fixation process at 50 °C. Examinations revealed that the coating spread quite homogeneously over the fiber surface. Additionally, it was determined that the prepared GNP dispersion showed no signs of agglomeration during the 24-hour waiting period, indicating that the solution possesses high stability. These findings provide a strong foundation for the optimization and scaling-up studies to be conducted in subsequent stages.

In the second stage, the coating was applied to specially manufactured wool fabrics. First, to prepare the coating solution, 5 g of polyvinylpyrrolidone (PVP) was completely dissolved in 500 mL of isopropyl alcohol (IPA). Approximately 0.3 g of graphene nanoparticles was added to the resulting PVP solution, and a homogeneous dispersion was obtained using a magnetic stirrer.

The prepared graphene dispersion was applied to sheep-sheep, goat-sheep, and goat-goat woven fabric samples using the dip-coating method. The fabrics were immersed in the dispersion and left for 1–2 minutes to ensure their surfaces were coated with graphene nanoparticles. Following the coating process, the fabrics were laid out on a workbench at room temperature for pre-drying to remove excess solvent. The samples were then dried in an oven at 50 °C for 12 hours. Following the drying process, a 10-minute curing process at 70 °C was applied to enhance the adhesion of the coating to the surface.

As a result of these processes, the graphene nanoparticles were successfully coated onto the fabric surface, and the prepared samples were sent to the Textile Laboratory at Istanbul Technical University for testing and characterization.

### **2.3. Method**

In this article, Alambeta test (ISO 11092 standard test) was carried out that provides with the measurement of the following thermal parameters: thermal conductivity, thermal absorptivity, thermal resistance, and thermal diffusivity. This test simulates the human skin and its principle depends on the mathematical processing of time course of heat power passing through the tested fabric due to different temperatures of bottom measuring plate (22°C) and measuring head (32°C). When the sheep and goat fabrics are put, the

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measuring head drops down and touches the fabrics, the heat power levels are evaluated in the computer, and the thermophysical properties of the measured sample are evaluated, the measurement finishes very shortly. So, reliable measurements on wet fabrics are possible, since the sample moisture during the measurement keeps almost constant.

### 3.RESULTS AND DISCUSSION

#### 3. 1. Thermal properties of a Graphene-Coated Sheep-Goat Composite

In this study, fabrics made from sheep-sheep, goat-sheep, and goat-goat wool fibers were woven on a handloom using a multi-layer weaving structure. In particular, the thermal resistance of the sheep-goat wool fabric was found to be the highest. The use of different types of wool on the inner and outer surfaces creates natural micro-air pockets between the layers, and this structure provides significantly higher thermal resistance compared to conventional single-layer wool fabrics. Table 1 shows the thermal properties of the wool fabrics obtained.

**Table 1.** Thermal properties of fabrics produced by weaving different types of wool fibers

| Materials  | Thermal conductivity, mW/mK | Heat Resistance, R değeri, mK.m <sup>2</sup> /W | Heat Resistance, R değeri, K.m <sup>2</sup> /W |
|------------|-----------------------------|-------------------------------------------------|------------------------------------------------|
| Goat       | 49.35                       | 86.65                                           | 0.087                                          |
| Sheep      | 46.1                        | 52.6                                            | 0.053                                          |
| Sheep-Goat | 46.35                       | 93.4                                            | 0.093                                          |

In ISO 11092 tests, the thermal resistance of this double-layered wool composite reached a value of 0.08665–0.093 m<sup>2</sup>K/W, which exceeds the performance of polar fleece, softshell, and lightweight outdoor fabrics. These results demonstrate that the developed Warm fabrics offer advanced thermal resistance compared to traditional textile materials and can be classified as high-performance thermal textiles.

Experimental studies on graphene nanoplatelet (GNP) coating have been initiated in the project, and preliminary tests were conducted in the first phase using ready-made white wool fabrics. For this purpose, the GNPs were dispersed in a solvent system consisting of a mixture of 0.1% isopropyl alcohol (IPA) and polyvinylpyrrolidone (PVP). It was observed that the resulting dispersion exhibited a very homogeneous distribution within the solution. Fabric samples cut to a size of 2 cm<sup>2</sup> were immersed in the prepared solution for varying durations to apply the coating; the samples were then dried at room temperature and subjected to a fixation process at 50 °C. Examinations revealed that the coating spread quite homogeneously over the fiber surface. Additionally, it was determined that the prepared GNP dispersion showed no signs of agglomeration during the 24-hour waiting period, indicating that the solution possesses high stability. The collected samples were sent to the Textile Laboratory at Istanbul Technical University to complete the thermal tests. The results of these tests are summarized in Table 2.

**Table 2.** Thermal properties of fabrics produced by graphene-coated wool fibers

| Material   | La, Thermal Conductivity (mW/mK) | a, Thermal Diffusion, (mm <sup>2</sup> /s) | Thermal Absorbtion, b, W.s1/2/m2.K | Heat Resistance, r, mK.m2/W | Heat flux, qmax/qsteady,p | Heat Flow,qmax (W/m2) |
|------------|----------------------------------|--------------------------------------------|------------------------------------|-----------------------------|---------------------------|-----------------------|
| Goat-Sheep | 49.4                             | 0.115                                      | 145.4                              | 62.1                        | 2.307                     | 371                   |

|       |             |       |       |      |      |     |
|-------|-------------|-------|-------|------|------|-----|
| Goat  | <b>51.3</b> | 0.103 | 160   | 64.3 | 2.59 | 395 |
| Sheep | <b>50.0</b> | 0.11  | 150.6 | 49.2 | 2.42 | 460 |

The thermophysical properties of graphene-coated and uncoated sheep, goat, and sheep-goat composites were investigated in a comparative study. The thermal conductivity values of graphene-coated fabrics were measured as 49.4, 51.3, and 50.0 mW/mK for sheep-goat, goat, and sheep samples, respectively; in the graphene-free samples, these values were 46.35, 49.35, and 46.1 mW/mK. As shown in Table 2, the graphene coating increases thermal conductivity in all wool fabrics. Additionally, Table 2 indicates that thermal resistance values in graphene-coated samples (range of 62.1–64.3 mK·m<sup>2</sup>/W) are lower compared to those in graphene-free samples. This is an expected result because thermal conductivity and thermal resistance vary inversely with each other. Table 2 clearly demonstrates that the effect of graphene addition on the heat transfer mechanisms of the composite material. The high thermal diffusion and thermal absorption values observed in the graphene-coated wool samples indicate that the material can both conduct heat rapidly and respond more effectively to sudden temperature changes.

The fact that the goat-based sample achieved the highest thermal conductivity and thermal absorption values indicates that this material is particularly advantageous in applications where rapid heat transfer is critical (e.g., thermal balancing, heat dissipation, and energy-efficient systems). These results clearly demonstrate the effect of graphene addition on the heat transfer mechanisms of the composite material. In particular, the high thermal diffusion and thermal absorption values observed in the goat-based composite indicate that the material can both conduct heat rapidly and respond more effectively to sudden temperature changes. This result suggests that the goat fiber structure interacts more compatibly with graphene, thereby creating a positive effect on heat transfer.

The fact that the goat wool sample achieved the highest thermal conductivity and thermal absorption values suggests that this material may be particularly advantageous for heat diffusion and energy-efficient systems that rely on rapid heat transfer. On the other hand, the high heat flux value measured in the graphene-coated sheep sample demonstrates that the material can maximize the amount of heat passing through a unit area. This indicates that the sheep fabric sample may be advantageous in terms of facilitating effective heat transfer between surfaces.

#### 4.CONCLUSION

In conclusion, these findings indicated that the addition of graphene not only enhances thermal conductivity but also improves the material's dynamic thermal behaviour, and that performance can be optimized depending on the type of fiber. This offers a significant advantage in terms of application-specific material design. In conclusion, it has been determined that graphene coating enhances the thermal performance of fabrics developed using wool fibers and provides significant advantages, particularly in heat transfer and thermal management applications. This study highlights the potential for graphene-reinforced biocomposites to be used as sustainable and high-performance engineering materials.

#### ACKNOWLEDGMENT

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## THE RELATIONSHIP BETWEEN REGIONAL PRESSURE AND THERMOPHYSIOLOGICAL COMFORT IN TROUSERS

Özlem Tektaş Çelikkana<sup>1</sup>, Serap Piranoğlu<sup>1</sup>, Nursema Pala Avcı<sup>2</sup>, B. Cenkkut Gültekin<sup>2</sup>, E. Dilara Koçak<sup>2\*</sup>

<sup>1</sup>İpekyol Giyim Sanayi Pazarlama ve Ticaret A.Ş., İstanbul, Türkiye

<sup>2</sup>Marmara University, Technology Faculty, Textile Engineering Department, İstanbul, Türkiye

\* email address of corresponding author: [dkocak@marmara.edu.tr](mailto:dkocak@marmara.edu.tr)

### ABSTRACT

Comfort in clothing is achieved by balancing the heat, air, and moisture transfer processes between the human body and textile materials. In lower body garments, the high contact area between the body and the fabric directly affects microclimate formation by increasing regional pressure distributions. In this study, the comfort and mechanical performance of three different knitted fabric samples with different fiber compositions (80% Modal/15% Polyamide/5% Elastane, 96% Polyamide/4% Elastane, 81% Wool/14% Polyamide/5% Elastane) in leggings/pants applications were comparatively evaluated. The samples were produced with similar grammages (330–340 g/m<sup>2</sup>) and an interlock structure. To determine the performance of the fabrics, moisture management, bursting strength, pilling, and sweat/light fastness tests were performed; the data were interpreted together with numerical pressure mapping (gf/cm<sup>2</sup>) outputs obtained from CLO 3D software. As a result of vertical absorbency and drying time tests, it was determined that Sample 1, which has a high hydrophilic character, achieved the fastest moisture transfer at 18 seconds, Sample 2 remained at a moderate level at 28 seconds, and Sample 3, which contains wool, showed the highest moisture retention tendency, exceeding 60 seconds. In mechanical strength tests, Sample 2, with its high polyamide content, exhibited the highest burst strength at 417 kPa, followed by Sample 3 at 307 kPa and Sample 1 at 266 kPa. In pilling and linting tests, all samples showed medium-good performance thanks to their compact interlock structure, while matting resistance was excellent across all fabrics. In color fastness analyses, the light fastness value of all samples was 4, and the color change values in acidic and alkaline sweat environments were 4-5, meeting commercial standards. In CLO 3D simulation-supported pressure analyses, it was determined that Sample 2, with its high elastic recovery, provided more homogeneous and higher compression in the thigh and calf regions, while Sample 1, with its softer structure, offered a lower, comfort-oriented pressure profile. The findings reveal that achieving an optimum balance of comfort, durability, and compression in legging design requires a combination of fiber composition and structural knitting engineering tailored to regional anatomical needs.

**Keywords:** *Thermophysiological comfort, knitted fabric, fiber composition, leggings/trousers, fastness.*

### 1. INTRODUCTION

Maintaining the thermal balance between the human body and the environment is considered one of the fundamental functions of clothing systems. Garments are not merely passive layers providing protection against external factors; they serve as an active interface regulating the transfer of metabolic heat and moisture to the environment [1]. The primary function of clothing is to maintain comfort under various climatic conditions by creating a controlled microclimate between the person and the environment [2].

Thermophysiological comfort depends on achieving a balance between the conduction of heat produced by the body to the external environment and the removal of moisture formed on the skin surface through evaporation. It is stated that evaporation and convection mechanisms are decisive in the bidirectional heat and mass transfer processes occurring through clothing layers [3]. It is emphasized that heat and moisture transfer must be evaluated together in multilayer textile systems, as thermal insulation alone is insufficient

to explain comfort [4]. The comfort performance of a textile material is directly related to structural parameters such as fiber structure, porosity, air permeability, and surface wettability. Experimental studies have revealed that water vapor transmission varies depending on fabric porosity and the hydrophilic/hydrophobic character of the surface in contact with the skin [5]. It is reported that fiber morphology and yarn structure affect the moisture absorption–evaporation capacity of the fabric and, consequently, its microclimate behavior [6].

Recent research indicates that thermal comfort performance in textile and apparel materials should be evaluated using a holistic approach where thermal resistance, water vapor resistance, and air permeability are considered together [7]. Furthermore, experimental and numerical modeling studies demonstrate that the combination of porosity, environmental conditions, and air movement determines heat distribution and moisture transport, thereby confirming the critical role of fabric structure on thermophysiological performance [8].

The aim of this study is to compare the mechanical, surface, and thermophysiological comfort performance of knitted fabrics with different fiber compositions for use in leggings/trousers. The moisture transfer, bursting strength, pressure distribution, and color fastness properties of the fabrics were analyzed to examine their behavior under active use conditions. Based on the findings, the study aims to provide a basis for material selection that optimizes the comfort–durability–compression balance in the design of leggings.

## 2. EXPERIMENTAL STUDY

### 2.1. Material and Method

#### 2.1.1. Material

The properties of the materials used in the study and the process parameters for creating the knitted surfaces are given in **Table 1**. The knitted surfaces were provided by İpekyol A.Ş.

**Table 1.** Materials used and process specifications

| Parameter          | Sample 1                            | Sample 2                      | Sample 3                           |
|--------------------|-------------------------------------|-------------------------------|------------------------------------|
| Fiber Composition  | %80 Modal %15 Polyamide %5 Elastane | %96 Polyamide %4 Elastane     | %81 Wool %14 Polyamide %5 Elastane |
| Machine Type       | Double-bed circular knitting        | Double-bed circular knitting  | Double-bed circular knitting       |
| Construction       | Double Knit (Ponte)                 | Double Knit (Ponte)           | Double Knit (Ponte)                |
| Stitch Structure   | Double-faced interlock stitch       | Double-faced interlock stitch | Double-faced interlock stitch      |
| Elastane Placement | Plating (back bed)                  | Plating (back bed)            | Plating (back bed)                 |
| Main Yarn Count    | Ne 30/1                             | Ne 40/1                       | Ne 28/1                            |
| Elastane           | 40 Denier                           | 40 Denier                     | 40 Denier                          |
| Machine Gauge      | 18 GG                               | 20 GG                         | 18 GG                              |
| Weight             | 340 g/m <sup>2</sup>                | 330 g/m <sup>2</sup>          | 335 g/m <sup>2</sup>               |

#### 2.2. Method

Knitted fabrics with the specifications mentioned in Table 1 were produced on a SANTONI brand double-bed circular knitting machine in accordance with the Sartori system. A double knit (ponte) construction was used, where the front and back needle beds work together (Figure 1), and elastane yarn was integrated into the structure via the plating method from the back bed. By adjusting the stitch length and machine gauge, a full-bodied, stable, and recovery-oriented fabric was obtained at the target weight.



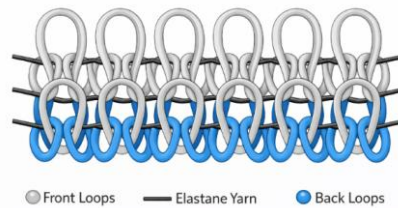


**Figure 1.** Schematic representation of knitted fabric structures

Standard laboratory tests were applied to determine the performance characteristics of the samples. Moisture transfer and vertical drying behavior were evaluated according to the ISO 17617 Annex A standard. Surface durability and pilling tendency were analyzed using the BS EN ISO 12945-1:2020 (Pilling Box method). The bursting strength of the fabrics was measured according to the BS EN ISO 13938-2:2019 pneumatic method. Light fastness performance was determined by the ISO 105 B02:2014 (Xenon Arc) standard, while color fastness in acidic and alkaline environments was tested according to ISO 105-E04. Perspiration fastness and staining behavior on adjacent fibers were evaluated within the scope of the ISO 105 E04:2013 standard. Pressure analysis was performed in a virtual simulation environment by applying garment patterns onto a 3D body model created in CLO 3D (Marvelous Designer infrastructure) software and defining the mechanical properties of the fabric. Contact pressure values obtained from the simulation output were calculated using the software's "Pressure Map" module and evaluated as a color distribution map in  $\text{gf}/\text{cm}^2$ .

### 3. RESULTS

#### 3.1. Moisture Transfer Behavior

Moisture transfer results (vertical wicking/drying time) are a significant indicator of thermophysiological comfort in leggings applications. The findings show that Sample 1 achieved the fastest transfer at 18 s, followed by Sample 2 at a moderate level of 28 s, while Sample 3 exceeded 60 s. These results demonstrate that fiber composition is a decisive factor in moisture management. During active use, the rapid removal of sweat enhances comfort by maintaining the microclimate balance [9]. In the literature, it is reported that moisture transfer in knitted fabrics depends on fiber type, capillarity, and structural parameters; structures containing hydrophilic fibers shorten the drying time by absorbing and spreading the liquid more rapidly [10]. Furthermore, it has been shown that moisture diffusion in multilayer textile structures is directly related to porosity and fiber morphology [5]. Accordingly, while Sample 1 provides superior active comfort, the extended drying time of Sample 3 indicates a high tendency for moisture retention.

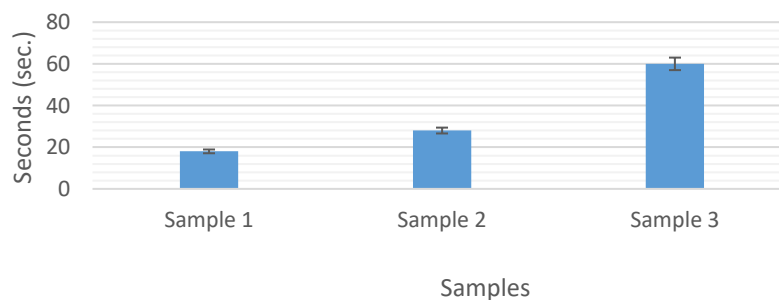


**Figure 2.** Moisture transfer results

#### 3.2. Bursting Strength

Bursting strength results indicate the resistance of fabrics against the multi-directional stresses encountered during the use of leggings. Sample 2 exhibited the highest strength (417 kPa), while Sample 3 showed a moderate level (307 kPa), and Sample 1 demonstrated the lowest strength (266 kPa). These findings suggest that fiber strength, loop density, and structural compactness are decisive factors. Since multi-axial loads

occur specifically in the knee and hip regions of form-fitting garments, high bursting strength is a critical parameter for service life and tear resistance [11]. In the literature, it has been reported that the bursting strength of knitted fabrics is directly related to fiber properties and fabric construction; more compact and double-knit structures enhance mechanical performance by distributing the load more homogeneously [12]. Accordingly, it can be stated that samples showing higher bursting strength are more suitable for garments subjected to high stress during movement, such as leggings.

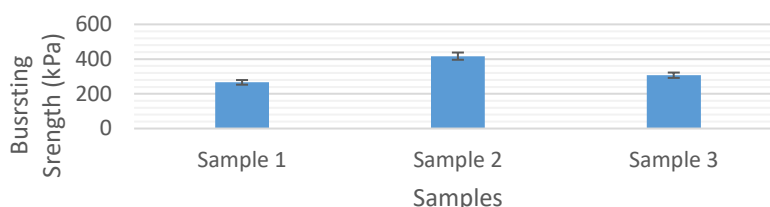


**Figure 3.** Bursting strength results

### 3.3. Surface Performance

According to the surface performance results presented in Table 2, all samples exhibited medium-to-good performance in pilling and fuzzing, while showing excellent performance in matting. The fact that all three fabrics were produced with the same double knit construction supports surface stability due to the compact structure. Double-knit structures offer higher elastic recovery and deformation resistance compared to single-knit fabrics, owing to the interlocking loop formation; these characteristics make them preferable for form-fitting garments [13].

Fiber composition directly influences surface durability. While Sample 1, with its high modal content, provides a softer hand-feel and a sense of comfort, it is known that the synthetic fiber contribution in Sample 2, which has a high polyamide ratio, increases abrasion and pilling resistance [14]. Sample 3, containing wool, supports recovery behavior by providing natural elasticity and bulkiness. In the literature, it is stated that synthetic fiber additives enhance mechanical and surface durability, while natural fibers contribute to comfort and elastic recovery. This balance is noted as being crucial for performance continuity, particularly in slim-silhouette garments [15]. These results demonstrate that utilizing different fiber compositions within the same construction can optimize the comfort–durability–recovery balance in leggings design.

**Table 2.** Comparison of Surface Performance Properties

| Parametre | Sample 1 | Sample 2 | Sample 3 |
|-----------|----------|----------|----------|
| Pilling   | 3        | 3        | 4        |
| Fuzzing   | 3–4      | 3–4      | 4        |
| Matting   | 5        | 5        | 5        |

(Scale: 5 = Excellent, 1 = Very Poor)

### 3.4. Fastness

The light fastness results (Table 3) indicate that all three fabrics meet the required color resistance standards. For all samples, the color change value against light was 4, while values in acidic and alkaline perspiration environments ranged between 4–5. This demonstrates sufficient resistance against fading and color loss during use. In activewear products, fastness values of 4 and above are reported to be commercially acceptable performance levels [16]. It is consistent with the literature that the synthetic fiber content in Sample 2 supports color stability by strengthening the dye-fiber interaction; similarly, in Sample 3, comparable fastness values were maintained despite the natural fiber content, thanks to appropriate finishing processes [17]. Furthermore, it is stated that fiber composition and dyeing process parameters are decisive factors for light and perspiration fastness in knitted fabrics [18]. In this context, the fastness values

obtained at the 4 and 4–5 levels indicate that the aesthetic appearance of products such as leggings, which are frequently exposed to light, perspiration, and friction, will be preserved throughout their service life.

**Table 3.** Light fastness values

| Feature                           | Colour Change   | Sample 1 | Sample 2 | Sample 3 |
|-----------------------------------|-----------------|----------|----------|----------|
| Color change to light             | pH=5.5 Acid     | 4        | 4        | 4        |
| Acidic perspiration environment   | pH=8.0 Alkaline | 4–5      | 4–5      | 4–5      |
| Alkaline perspiration environment | pH=5.5 Acid     | 4–5      | 4–5      | 4–5      |

### 3.5. Perspiration Fastness

Perspiration fastness results (Table 4) indicate that all samples generally achieved values at the 4–5 level under both acidic (pH 5.5) and alkaline (pH 8.0) conditions, providing sufficient color stability for leggings applications. Although a slight decrease to level 4 was observed in the cotton adjacent fiber for Sample 1, the maintenance of the 4–5 range in other fibers suggests a low risk of significant color transfer during sweating. In Sample 2, the consistent attainment of 4–5 values across all adjacent fibers indicates more balanced dye fixation and stable performance. In Sample 3, despite a decline to level 4 in some measurements for cotton and nylon fibers, the overall performance remains within the "good" fastness class.

In the literature, perspiration fastness values of 4 and above are considered sufficient for active sports and form-fitting garments, as this level minimizes the risk of color transfer and supports the product's service life [18]. In this context, all three samples are evaluated as being resistant to color change under perspiration conditions and exhibit suitable performance for leggings applications.

**Table 4.** Perspiration fastness results

| Sample   | Koşul             | Acetate | Cotton | Nylon | Polyester | Acrylic | Wool |
|----------|-------------------|---------|--------|-------|-----------|---------|------|
| Sample 1 | pH=5.5 (Acid)     | 4–5     | 4      | 4–5   | 4–5       | 4–5     | 4–5  |
|          | pH=8.0 (Alkaline) | 4–5     | 4      | 4–5   | 4–5       | 4–5     | 4–5  |
| Sample 2 | pH=5.5 (Acid)     | 4–5     | 4–5    | 4–5   | 4–5       | 4–5     | 4–5  |
|          | pH=8.0 (Alkaline) | 4–5     | 4–5    | 4–5   | 4–5       | 4–5     | 4–5  |
| Sample 3 | pH=5.5 (Acid)     | 4–5     | 4      | 4–5   | 4–5       | 4–5     | 4–5  |
|          | pH=8.0 (Alkaline) | 4–5     | 4      | 4     | 4–5       | 4–5     | 4–5  |

### 3.6. Pressure Distribution Analysis

Pressure results indicate that all samples provide the necessary controlled compression for leggings; however, the pressure levels vary depending on the elastic properties of the fabrics. Due to its higher elastic recovery and structural stability, Sample 2 generated a more homogeneous and higher pressure in the thigh and calf regions. It is stated in the literature that compact knitted structures containing elastane provide a more controlled and balanced pressure distribution [19]. While Sample 1 offered lower, comfort-oriented pressure due to its softer structure, Sample 3 exhibited a balanced performance between support and movement comfort. It is reported that appropriate levels of compression can reduce muscle vibration and enhance garment-body fit [20]. These results demonstrate that the investigated fabrics are capable of simultaneously providing functional compression and wearing comfort.

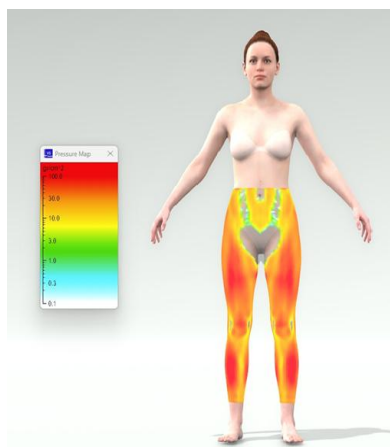


**Figure 4.** Pressure distribution analysis image

#### 4. DISCUSSION

The obtained results indicate that leggings performance depends on a multidimensional balance formed by the synergy of fiber composition, knitting construction, and elastic behavior, rather than a single parameter. In terms of moisture transfer, samples with a high ratio of hydrophilic fibers and suitable capillary structures provided better thermophysiological comfort during active use by ensuring shorter drying times. Conversely, the results for bursting strength and surface performance revealed that more compact structures with synthetic fiber additives enhanced mechanical durability and abrasion resistance. Pressure distribution analyses demonstrated that the elastic modulus and recovery behavior determine the compression level. Samples with higher elastic stability provided a muscle-supporting effect, whereas softer structures prioritized wearer comfort. To systematically clarify the individual contributions of the investigated raw materials, it is observed that the high modal ratio (80%) in Sample 1 directly governs the hydrophilic character, accelerating the moisture transfer rate to 18 s at the expense of mechanical strength. Conversely, the dominant polyamide ratio (96%) in Sample 2 acts as the primary contributor to structural compactness and multi-axial mechanical resistance, yielding the highest bursting strength (417 kPa) and an enhanced compression profile. Lastly, the high wool content (81%) in Sample 3 provides natural bulkiness and balanced motion comfort but shifts the behavior toward moisture retention (>60 s). Furthermore, the light and perspiration fastness results indicate that all fabrics possess sufficient color stability to maintain their aesthetic appearance under active-use conditions. Overall, it is concluded that the balance of comfort–durability–compression in leggings design must be optimized through precise fiber composition and structural engineering.

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## ULTRASOUND-ASSISTED CELLULOSE ISOLATION FROM LIGNOCELLULOSIC AGRICULTURAL WASTES: A COMPARATIVE STUDY OF BLEACHING METHODS

Nursema Pala Avcı<sup>1\*</sup>, Nebahat Aral Yılmaz<sup>2</sup>, E. Dilara Koçak<sup>1</sup>

<sup>1</sup>Marmara University, Textile Engineering Department, İstanbul, Türkiye

<sup>2</sup>Yeditepe University, Material Science Department, İstanbul, Türkiye

\* email address of corresponding author: nursema.pala@marmara.edu.tr

### ABSTRACT

Today, the rapid depletion of fossil fuel resources and increasing environmental concerns have made the search for sustainable, renewable, and biodegradable biomaterials crucial. This study investigates the isolation and characterization of pure cellulose from agricultural waste, namely banana (*Musa sapientum*) stalks and okra (*Abelmoschus esculentus*) stems. To effectively remove the amorphous matrix surrounding cellulose chains such as hemicellulose, lignin, and pectin, conventional magnetic stirring and ultrasound-assisted alkaline pretreatments were comparatively evaluated. After pretreatment, the fibers were subjected to bleaching with conventional sodium hypochlorite (NaOCl) and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), an environmentally friendly green alternative. The structural, morphological, and thermal properties of the resulting cellulose were characterized using FTIR, SEM, and TGA. FTIR results showed that the effect of pretreatment was dependent on the fiber morphology. Furthermore, it has been proven that NaOCl, being a highly oxidative chemical, is better at lignin degradation than H<sub>2</sub>O<sub>2</sub>, but it damages chain integrity. SEM images physically evidenced this purification, showing the stripping of amorphous protective layers and the emergence of highly fibrous, rough topographies triggered by acoustic cavitation. In addition, thermal analyses showed a remarkable improvement in the thermal stability of the isolated cellulose, as well as a significant decrease in water retention content. Overall, the findings demonstrate that ultrasound-assisted green chemistry approaches offer a highly efficient and sustainable way to convert banana and okra agricultural wastes into high-purity, thermally stable cellulose, making them excellent candidates for biopolymer composite reinforcements.

**Keywords:** Cellulose isolation, agricultural waste valorization, delignification, lignocellulosic biowaste, ultrasound pretreatment

### 1. INTRODUCTION

The rapid depletion of fossil resources and increasing environmental concerns have shifted industrial production towards sustainable models based on renewable and biodegradable raw materials [1]. In this context, the conversion of agricultural lignocellulosic waste into high value-added biomaterials has become a significant research area, particularly because it does not compete with food production [2]. Banana stalk fibers and okra stem fibers are promising sources for this conversion due to their high cellulose content, which is approximately 60–74% [3,4]. However, to obtain pure cellulose, removal of amorphous parts such as hemicellulose, lignin, and pectin is required. While traditional alkaline pretreatments are widely used, ultrasound-assisted methods generate microbubbles via acoustic cavitation, enabling more effective chemical penetration and increased process efficiency [5]. In the bleaching stage following alkaline treatment, sodium hypochlorite (NaOCl) stands out as a strong lignin remover, while hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) offers a more environmentally friendly alternative due to its lack of toxic byproduct formation [6]. This study investigates the isolation of cellulose from banana and okra fibers, comparatively evaluating conventional and ultrasound-assisted alkaline pretreatment methods with NaOCl and H<sub>2</sub>O<sub>2</sub> bleaching. The effect of these treatments on the chemical and morphological properties of the fibers is characterized by FTIR, TGA, and SEM analyses, which reveal the potential of ultrasound-assisted green chemistry approaches for converting agricultural wastes into high-value biopolymers.

## 2. EXPERIMENTAL STUDY

### 2.1 Materials

In this study, banana and okra fibers were used as lignocellulosic biomass sources. Sodium hydroxide (NaOH, analytical grade), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>, 35% concentration), and sodium hypochlorite (NaOCl), used in the pretreatment and delignification process of the fibers, were obtained from Sigma-Aldrich. Acetic acid (CH<sub>3</sub>COOH, 100%) was obtained from Merck. Pure distilled water was used in the preparation of solutions, reactions, and all rinsing processes.

### 2.2 Pretreatment and Isolation of Cellulose

Two alkaline pretreatment methods were applied to banana and okra fibers to remove hemicellulose, lignin, and other impurities. In the first method, fibers were conventionally treated in a 5 wt% NaOH solution at 50 °C for 45 minutes using magnetic stirring. In the second, ultrasound-assisted pretreatment was performed under the same conditions using an ultrasonic probe (50% amplitude, 50% duty cycle) to induce acoustic cavitation. After pretreatment, all fibers were washed to neutral pH and dried. Delignification was carried out using two bleaching agents, NaOCl and H<sub>2</sub>O<sub>2</sub>. For NaOCl bleaching, alkali-treated fibers were processed in an acidic medium (pH ~4) at 70 °C for 1 hour, then washed and dried. For H<sub>2</sub>O<sub>2</sub> bleaching, fibers were treated at 70 °C for 1 hour in an alkaline medium (pH 11–11.5) with a final peroxide concentration of 8%, followed by washing and drying under the same conditions.

Samples were coded based on biomass type (B: banana, O: okra), pretreatment method (U: ultrasonic, M: magnetic stirring), and bleaching agent (C: NaOCl, P: H<sub>2</sub>O<sub>2</sub>), as summarized in Table 1.

**Table 1:** Sample codes

| Sample Code | Fiber Type | Pretreatment      | Bleaching                     |
|-------------|------------|-------------------|-------------------------------|
| B           | BANANA     | -                 | -                             |
| BU          |            | Ultrasonic NaOH   | -                             |
| BUC         |            |                   | NaOCl                         |
| BUP         |            |                   | H <sub>2</sub> O <sub>2</sub> |
| BM          |            | Conventional NaOH | -                             |
| BMC         |            |                   | NaOCl                         |
| BMP         |            |                   | H <sub>2</sub> O <sub>2</sub> |
| O           | OKRA       | -                 | -                             |
| OU          |            | Ultrasonic NaOH   | -                             |
| OUC         |            |                   | NaOCl                         |
| OUP         |            |                   | H <sub>2</sub> O <sub>2</sub> |
| OM          |            | Conventional NaOH | -                             |
| OMC         |            |                   | NaOCl                         |
| OMP         |            |                   | H <sub>2</sub> O <sub>2</sub> |

### 2.3 Characterization Techniques

A Perkin Elmer brand FTIR spectrometer was used to examine the changes in the chemical composition and the removed functional groups of raw and chemically treated fibers. Measurements were performed in transmission/absorbance mode in the wavenumber range of 4000 to 400 cm<sup>-1</sup>.

Thermogravimetric Analysis (TGA) and Differential Thermogravimetry (DTG) measurements were performed using a PerkinElmer, Pyris 6 / TA Instrument to investigate the thermal degradation behavior and stability of raw and processed fibers. Samples in the range of approximately 5-10 mg were placed in alumina crucibles and tested under a controlled nitrogen (N<sub>2</sub>) atmosphere with a flow rate of 20 mL/min, heating from room temperature to 600 °C at a rate of 10 °C/min. A Zeiss-Evo MA10 Scanning Electron Microscope (SEM) was used to observe the physical changes in the surface morphology and

fibrillation degree of the fibers caused by different pretreatments and bleaching agents. Before measurements, the surface of the samples was coated with a thin conductive layer to prevent electron charging and obtain clear images.

### 3. RESULTS

#### 3.1 Fourier-Transform Infrared Spectroscopy (FTIR) Analysis Results

To determine the effects of chemical and physical pretreatments on fiber structure, the FTIR spectra of untreated and treated banana and okra fibers were examined. Figure 1a shows the structural difference between mechanical and ultrasonic-assisted pretreated banana fibers. Mechanical pretreatment (BM) of banana fibers provides a more homogeneous delignification compared to ultrasonic processing (BU) by physically stripping lignin and hemicellulose from the fiber surface, thanks to macroscopic frictional forces. Ultrasonic cavitation, on the other hand, remains more localized and microscopic, showing a more aggressive effect in breaking down p-hydroxyphenyl lignin units at  $830\text{ cm}^{-1}$  band but having a more limited effect in overall matrix removal [7]. After the pretreatment steps, the use of NaOCl (BUC, BMC) in the bleaching stage completely erases the lignin peak in the  $1512\text{ cm}^{-1}$  band, resulting in high-purity cellulose [6], while the application of  $\text{H}_2\text{O}_2$  (BUP, BMP) breaks the cross-links in the cellulose chains through the effect of alkalinity, exposing free hydroxyl groups and significantly increasing the intensity of the O-H peak in the  $3300\text{--}3400\text{ cm}^{-1}$  band [8].

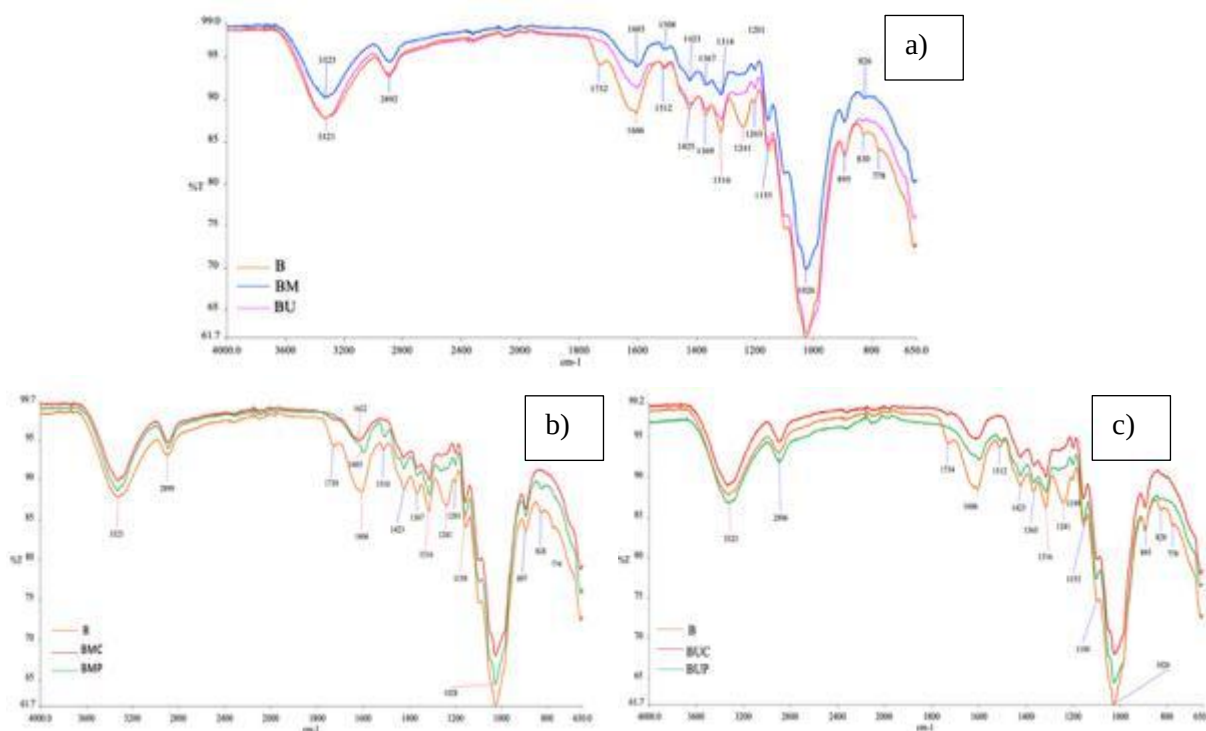


**Figure 1:** Structural characterization of banana fibers: (a) FTIR spectra of raw (B), mechanically pretreated (BM) and ultrasonically pretreated (BU) fibers; (b) comparison of fibers bleached with NaOCl (BUC) and  $\text{H}_2\text{O}_2$  (BUP) after ultrasonic pretreatment; (c) spectra of fibers bleached with NaOCl (BMC) and  $\text{H}_2\text{O}_2$  (BMP) after mechanical pretreatment.

In okra fibers, the peaks of  $1732\text{ cm}^{-1}$  hemicellulose and  $1240\text{ cm}^{-1}$  lignin, which are prominent in the raw fiber, are almost completely flattened, especially with ultrasonically assisted alkaline treatments (OU), proving the successful removal of hemicellulose, pectin, and lignin [9]. With the removal of impurities, the  $\beta$ -glycosidic bond peak of crystalline cellulose at  $897\text{ cm}^{-1}$  became more prominent in both pretreatments. As in banana fibers, sodium chloride bleaching (OUC, OMC) completely erases the lignin-derived  $1502\text{ cm}^{-1}$  peak in okra fibers, while after hydrogen peroxide treatment (OUP, OMP), lignin residues may remain as a small shoulder, but the O-H band intensifies with the increase in the amount of free hydroxyl on the surface [8].

In particular, chlorinated bleaching completely oxidizes the amorphous and hydrophilic components, reducing their water-holding capacity; this is a common mechanism that decreases the strength of the O-H band in both fiber types [10].

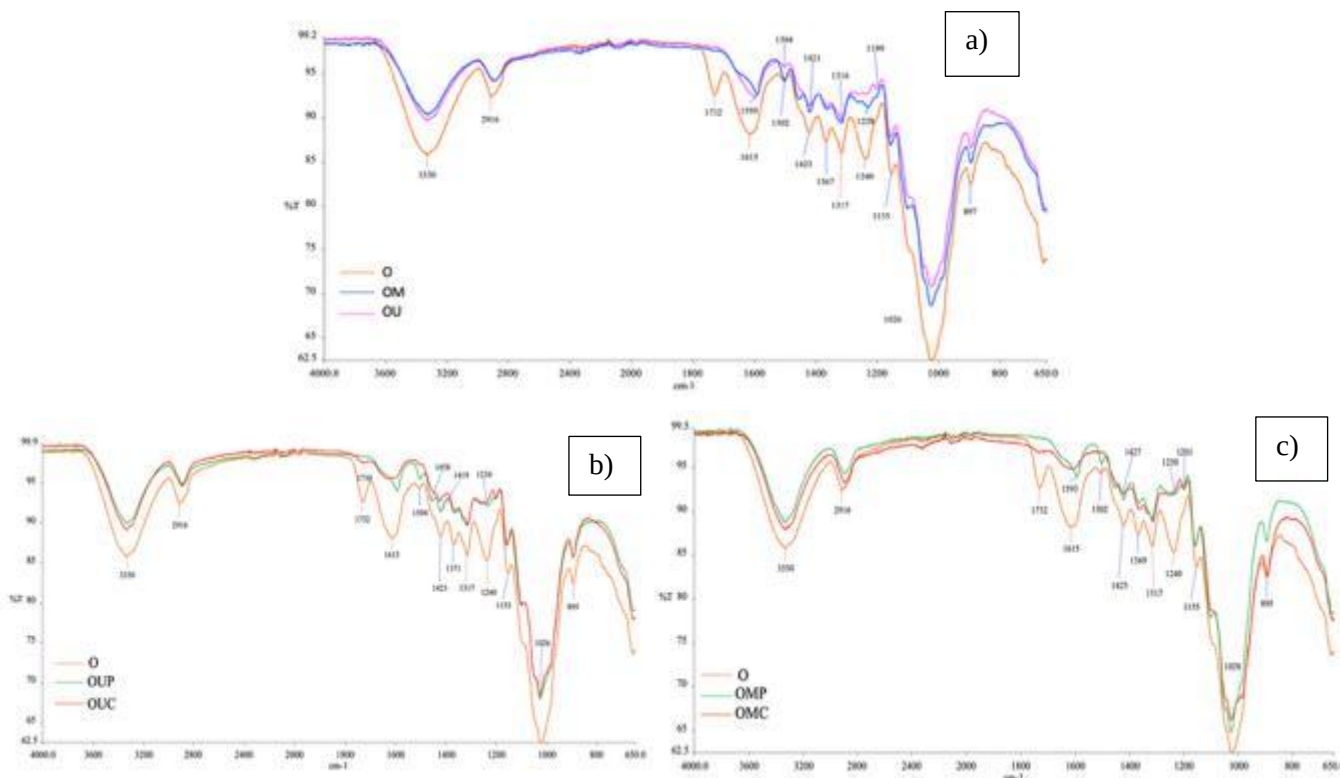


**Figure 2:** Structural characterization of banana fibers: (a) FTIR spectra of raw (O), mechanically pretreated (OM) and ultrasonically pretreated (OU) fibers; (b) comparison of fibers bleached with NaOCl (OUC) and H<sub>2</sub>O<sub>2</sub> (OUP) after ultrasonic pretreatment; (c) spectra of fibers bleached with NaOCl (OMC) and H<sub>2</sub>O<sub>2</sub> (OMP) after mechanical pretreatment.

### 3.2 TGA and DTG Analysis Results

TGA and DTG analyses shown in Figures 3 and 4 reveal the thermal effects of ultrasonic pretreatment and hydrogen peroxide bleaching on banana (B) and okra (O) fibers; in both fiber types, mass loss below 150°C is attributed to moisture evaporation, while the lower moisture loss in the OUP sample is associated with the efficient removal of hygroscopic components such as hemicellulose and pectin. The partial removal of hemicellulose in banana fiber is supported by attenuation in the 1734 cm<sup>-1</sup> and 1606 cm<sup>-1</sup> bands in the FTIR spectrum, but the main structural transformation is observed in okra fiber (OUP); indeed, the hemicellulose shoulder in the DTG curve of O is completely lost in OUP, and the cellulose degradation peak is sharper and shifted to higher temperatures (~355–360°C). In both samples after treatment (BUP: 18.14%; OUP: 22.03%), the increased residual mass was attributed to the preservation of the lignin structure (1512/1504 cm<sup>-1</sup> bands) and the removal of hemicellulose, while the results show that the applied treatment had a much more significant effect on the purification and improvement of the thermal stability of okra fiber compared to banana fiber [11,12].

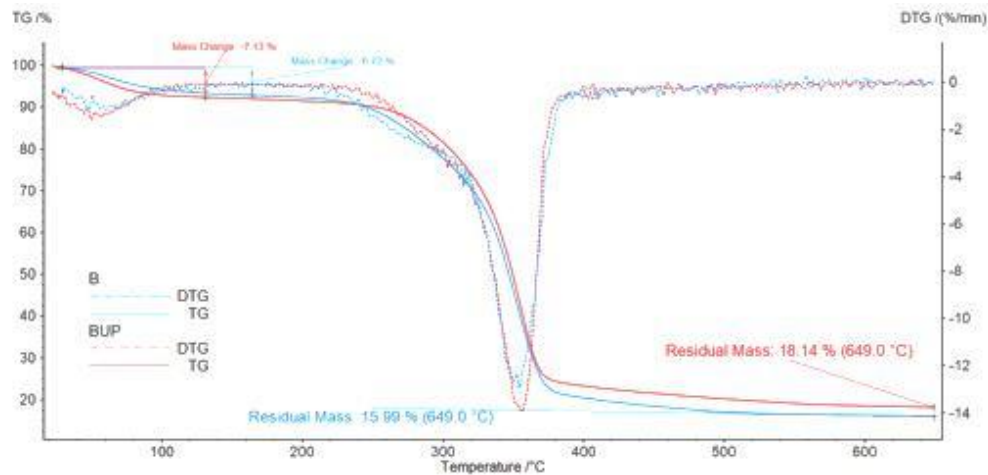


**Figure 3:** TGA and DTG graphs of raw banana fiber (B) and banana fiber with ultrasonic pretreatment and hydrogen peroxide bleaching (BUP).

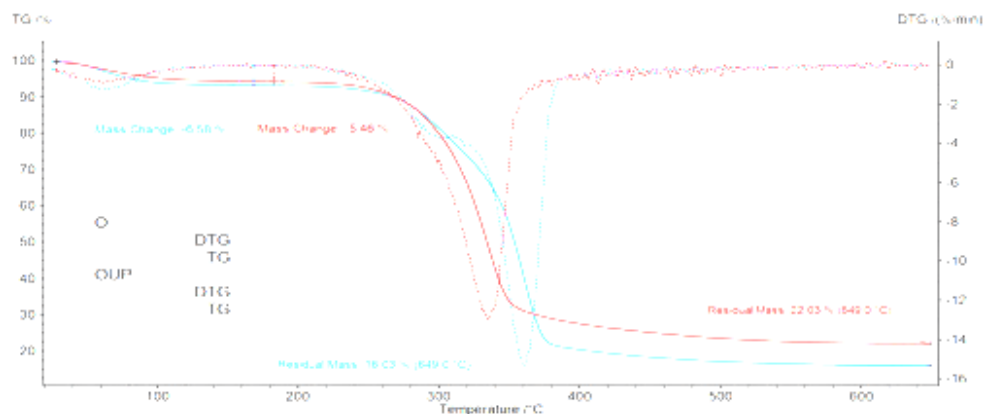


**Figure 4:** TGA and DTG graphs of raw okra fiber (O) and okra fiber with ultrasonic pretreatment and hydrogen peroxide bleaching (OUP).

### 3.3 SEM Analysis of Fiber Surface Morphology

The surface of raw fibers is coated with non-cellulosic amorphous components such as hemicellulose, lignin, pectin, waxes, and oils that tightly bind cellulose microfibrils together. These components form a protective layer around the fiber, filling cracks or microvoids on the surface and presenting a relatively homogeneous and thick layer [13]. Due to this protective amorphous matrix, the cellulose microfibrils, which are the actual load-bearing elements, are not clearly visible on the surface of the raw fibers, and the fibers appear as thick bundles of adhering fibers. Ultrasonic-assisted alkaline pretreatment followed by applied hydrogen peroxide ( $H_2O_2$ ) bleaching leads to dramatic changes in the physical architecture of the fibers [5]. When the amorphous hemicellulose and lignin layers and waxy impurities on the surface are removed through chemical dissolution, the outer wall of the fibers peels off, and a significant reduction in the average fiber diameter occurs. The fact that BUP and OUP fibers (See Figure 5) have a thinner profile compared to their raw versions is physical evidence of this mass loss. The most noticeable difference on the surface of the treated fibers is the clear visibility of the longitudinal grooves and cellulose microfibrils. The micro-explosions created by ultrasonic cavitation separate the cellulose bundles, increasing the surface area and creating a rough topography.



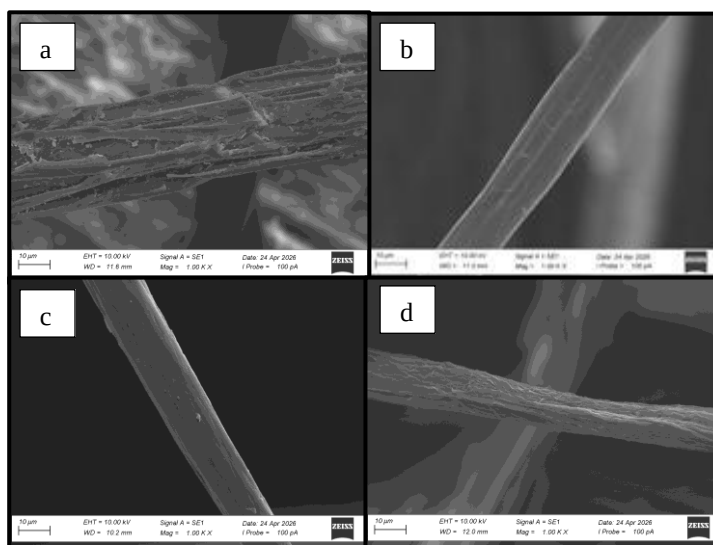


**Figure 5:** SEM images of treated and untreated fibers, respectively; a) B, b) BUP, c) O, d) OUP

#### 4. CONCLUSION

The isolation of high-purity cellulose from agricultural waste depends on the interplay between fiber morphology and chemical treatment methods. The results indicate that the effectiveness of ultrasonic pretreatment is influenced by the initial fiber morphology of the biomass. Ultrasound-assisted methods demonstrated greater efficiency in disrupting the rigid matrix of okra fibers, whereas conventional mechanical approaches were more effective for the distinct structural hierarchy of banana fibers.

The bleaching process revealed a clear distinction between traditional and sustainable agents. Sodium chloride (NaClO), although an effective lignin-removing agent, can cause cellulose chain degradation. In contrast, hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) was validated as a robust green alternative, enabling efficient bleaching and lignin removal while preserving the integrity and length of the cellulose polymer chains.

In conclusion, achieving an optimal balance between cellulose purity and structural integrity necessitates a raw material-specific approach. Future research will focus on optimizing peroxide bleaching parameters, including concentration, temperature, and duration, to maximize the degree of polymerization. These efforts aim to produce longer and purer cellulose chains and to further facilitate the conversion of lignocellulosic waste into high-value, sustainable biomaterials.

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## **POSTER PRESENTATIONS**

## ANALYSIS OF THERMO-OXIDATIVE DEGRADATION AND YELLOWING MECHANISMS IN PAN-BASED FIBERS

Semih Doğan<sup>1</sup>, Selin Gümrükçü<sup>1</sup>

<sup>1</sup>AKSA Akrilik Kimya Sanayii

### ABSTRACT

Heat setting is a critical thermal treatment for polyacrylonitrile (PAN)-based fibers and fabrics, as it largely determine the dimensional and visual stability of the final product. Under elevated temperatures and in the presence of oxygen, PAN chains undergo cyclization and crosslinking reactions, which initiate thermo-oxidative degradation. During heat-setting above 180 °C, the combined effects of temperature and oxygen induce chemical and physical changes in the polymer backbone, leading to undesirable visual defects such as yellowing and color shifts. This study aimed to elucidate the thermal and oxidative degradation mechanisms occurring during heat setting above 180 °C and to develop solving strategies to prevent or delay degradation. Degradation indicators were monitored using an integrated analytical approach combining colorimetric measurements, spectrophotometric analyses, and chemical characterization methods. A comparative examination was conducted using a standard acrylic fiber and a reference acrylic fiber exhibiting pronounced thermal yellowing. The resulting dataset was implied through root-cause analysis to identify key reaction pathways and critical triggers responsible for yellowing and color instability under high-temperature conditions. Therefore, the outcomes of this study enhances the suitability of PAN-based fibers for textile applications involving processing conditions at elevated temperatures and broadens their use in such demanding environments.

**Keywords:** color stability, fiber, heat setting, Polyacrylonitrile, thermal-oxidative degradation

## BIAXIAL MESH DEFORMATION OF KNITTED FABRICS FROM RECYCLED WOOL YARNS FOR THERMO-PHYSIOLOGICAL UNDERWEAR

Denise Lenk<sup>1</sup>, Holger Cebulla<sup>1</sup>,

<sup>1</sup> Chemnitz University of Technology, Faculty of Mechanical Engineering, Department of Textile Technology,  
Reichenhainer Straße 70, 09126 Chemnitz, Germany

\*denise.lenk@mb.tu-chemnitz.de

### ABSTRACT

Knitted fabrics made from recycled wool yarns represent a promising material class for functional underwear, combining the intrinsic hygroscopic and thermoregulatory properties of wool fibres with the high deformability of knitted structures. Beyond fibre-related characteristics, the thermos-physiological performance of underwear is strongly governed by structural parameters such as stitch geometry, mesh size, and their deformation behaviour under mechanical load. During wear, underwear is predominantly subjected to biaxial strain, resulting in pronounced changes in pore geometry that directly influence air permeability, thermal insulation, and moisture transport. A quantitative understanding of mesh size variation under biaxial deformation is therefore essential for the function-oriented and predictive design of knitted underwear fabrics. This study systematically investigates the deformation behaviour and mesh geometry evolution of knitted fabrics produced from recycled wool yarns under defined biaxial strain states. Particular attention is given to the influence of recycled fibre characteristics, including short fibre lengths, increased yarn irregularity, and reduced fibre cohesion, which lead to less clearly defined loop structures and a higher variability of mesh geometry compared to virgin wool yarns. These material-specific features significantly complicate the reproducible control and modelling of stitch formation and deformation behaviour. Pore size variations under controlled biaxial deformation were quantified using a newly developed biaxial testing device combined with digital image processing. The methodology enabled the simultaneous evaluation of local and global mesh geometry, allowing for a spatially resolved analysis of structural heterogeneity and characteristic deformation patterns. The results reveal mesh size variations that strongly depend on yarn inhomogeneity and applied strain, providing a mechanistic basis for interpreting strain-dependent variations in thermos-physiologically relevant transport properties. Observed changes in pore geometry correlate directly with expected variations in airflow, heat transfer, and moisture management under wear conditions, highlighting the importance of accurate structural characterisation for functional textile design. Overall, the study establishes a methodological framework for linking biaxial deformation, mesh geometry, and functional performance of knitted fabrics made from recycled wool yarns. The findings contribute to calculation-based design strategies for thermos-physiologically optimised underwear, while promoting the integration of sustainable recycled fibre materials into high-performance textile applications.

**Keywords:** *Recycled wool fibres, Knitted fabrics, Biaxial deformation, Thermo-physiological comfort*



## 1. INTRODUCTION

The present work constitutes an exploratory experimental study investigating the influence of a newly developed recycling process on yarn structure as well as the deformation behaviour of knitted fabrics made from recycled wool-silk fibers. Wool and wool-blend materials represent a particularly valuable resource for textile recycling processes. As a renewable and biodegradable fiber, wool exhibits favourable mechanical and thermos-physiological properties, making it highly suitable for high-quality reuse. However, a key prerequisite for successful recycling is the preservation of fiber integrity during mechanical processing. A major challenge in the recycling of wool fibers is the reduction in staple length. Mechanical shredding and opening processes lead to fiber breakage and, consequently, to a significant decrease in average fiber length. This directly affects both the spinnability and the mechanical properties of the resulting yarns [1, 2].

At the same time, structural modifications induced by recycling may also provide functional advantages. Shortened fibers increase the specific fiber surface area within the yarn structure and may thereby enhance moisture and heat exchange in textile fabrics. In knitted structures in particular, variations in yarn surface characteristics and states of extension lead to changes in loop geometry and pore size (Fig. 1), which in turn influence the drape behaviour on the human body [3].

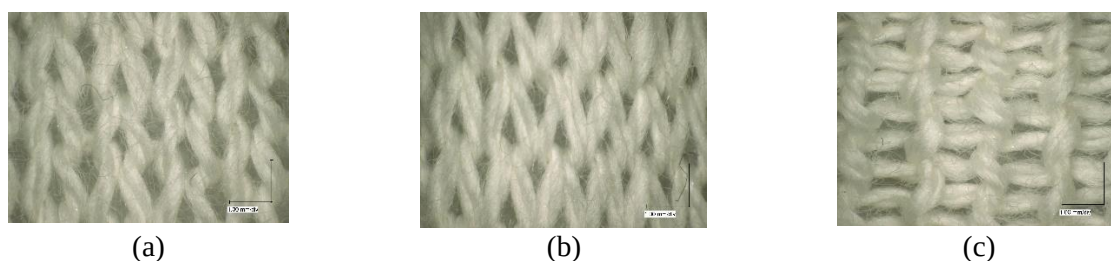


**Figure 1.** Images of knitted wool samples: (a) in relaxed state; (b) after being stretched wale wise; (c) after being stretched course wise [author’s own images]

The resulting changes in porosity and deformability have a direct impact on thermophysiological properties, especially in garments worn close to the skin. During wear, knitted underwear is predominantly subjected to biaxial deformation, which alters loop openings and pore geometry. These structural changes directly affect air permeability, heat transfer, and moisture management. In addition, material-related parameters such as fiber length distribution and yarn irregularity further influence the deformation behavior and structural stability of the fabric. Despite the relevance of these interactions, a systematic understanding of how recycling-induced material changes affect the deformation behavior and pore geometry of knitted fabrics under biaxial loading remains limited. In particular, the relationship between yarn inhomogeneity and the variability of loop structure has not yet been quantitatively investigated.

Against this background, the aim of the present study is to analyze the influence of biaxial strain states on the loop geometry of knitted fabrics produced from wool-silk yarns with recycled fiber content. By combining controlled mechanical loading with image-based analysis, this work seeks to establish a quantitative link between material characteristics, structural deformation, and their potential impact on thermophysiological properties.

## 2. EXPERIMENTAL STUDY

The present study is divided into two main areas of investigation. The first focuses on the recycling process of textiles made from wool-silk blends. In this context, the entire process chain is considered, starting from an industrially produced yarn, followed by the manufacturing of a knitted fabric, the subsequent recycling process, and the re-spinning of yarn, up to the production of new knitted fabrics from recycled material. The objective is to systematically capture and evaluate structural changes along this process chain. The second area comprises the analysis of loop geometry and deformation behavior of knitted structures made from industrial yarns in comparison to those made from recycled wool-silk yarns. For this purpose, a newly

developed testing method for characterizing the biaxial deformation behavior of knitted fabrics is applied. In combination with an integrated image-based evaluation, this approach enables the detection and statistical analysis of structural changes under defined strain conditions. This methodological framework establishes the basis for a systematic investigation of knitted fabrics under varying mechanical loading conditions and allows for the derivation of relationships between deformation behavior, loop structure, and the resulting thermophysical properties.

## 2.1 Recycling Process

The starting material is a yarn composed of a 70% wool and 30% silk blend with a fineness of Nm 44/1. The fiber lengths within the yarn are verified to be approximately 80 mm. Due to their high hygroscopicity, good thermal insulation, and pleasant tactile properties, wool-silk blends exhibit particularly advantageous characteristics for garments worn close to the skin. Wool fibers, in particular, are capable of absorbing significant amounts of moisture without feeling wet, thereby supporting a stable microclimate between the skin and the textile. The initial yarn is processed into knitted fabrics using circular knitting technology in the structures interlock and double jersey. The applied recycling process is based on the controlled feeding of defined, cut textile surface geometries, whereby the geometry of the input material has a significant influence on the resulting fiber lengths. It has been demonstrated that geometrically defined knitted pieces with a cutting size of 10 cm × 10 cm provide the most favorable processing conditions for the subsequent spinning process. The cutting process and the underlying knit structure account for approximately 20% of the variation in fiber length distribution [1, 2].

The recycled fibers obtained in this manner are subsequently processed into new yarns using a conventional short-staple spinning process based on ring spinning. Due to the defined composition and characterization of the input fibers, the spinning process can be specifically controlled and simplified. The objective of the present study is initially the production of a yarn with a fineness of Nm 44/1 from a 50/50 blend of virgin and recycled fibers. The systematic investigation and validation of suitable blending ratios remain subjects of future research. Furthermore, the production of knitted fabrics from both virgin and recycled yarns is intended to enable comparative analyses of thermophysical properties.

Yarns produced from recycled wool-silk fibers exhibit distinct structural characteristics as shown in Table 1. As a result of the mechanical processing during recycling, not only does fiber shortening occur, but also increased yarn irregularity and a more heterogeneous yarn surface.

**Table 1.** Mean fiber length parameters of recycled wool-silk fibers after 1, 2, and 3 carding passes (MK), measured by OFDA for Double Jersey (DJ) and Single Jersey (SJ) fabrics.

| Sample group | Diam (μm) | H (mm) | CvH (%) | B (mm) | CvB (%) | L (mm) | CvL (%) |
|--------------|-----------|--------|---------|--------|---------|--------|---------|
| DJ · 1 MK    | 14.5      | 18.6   | 51.6    | 23.9   | 55.2    | 15.7   | 53.7    |
| DJ · 2 MK    | 14.8      | 21.7   | 75.4    | 43.0   | 63.8    | 18.4   | 76.8    |
| DJ · 3 MK    | 14.6      | 19.6   | 43.1    | 23.2   | 47.0    | 17.2   | 46.0    |
| SJ · 1 MK    | 15.0      | 23.9   | 48.3    | 29.5   | 49.2    | 21.0   | 50.0    |
| SJ · 2 MK    | 14.5      | 25.1   | 113.1   | 57.8   | 123.9   | 22.0   | 118.9   |
| SJ · 3 MK    | 14.4      | 22.5   | 46.2    | 27.3   | 44.2    | 19.7   | 48.9    |

H = Hauteur; B = Barbe; L = true length; Cv = coefficient of variation.

Table 1 further reveals that the number of carding passages significantly affects both the mean fiber length and its variability. In particular, the second carding passage (2 MK) results in a pronounced increase in the coefficient of variation for all length parameters, especially in single jersey (SJ) samples, indicating a high degree of fiber inhomogeneity. While mean fiber lengths (H, B, and L) tend to increase after initial processing, a subsequent stabilization or slight reduction is observed after the third passage. Compared to double jersey (DJ), the SJ samples generally exhibit higher variability, suggesting a stronger sensitivity to mechanical processing. This increased fiber length variability and yarn inhomogeneity are expected to directly influence loop formation and structural stability in the knitted fabrics. In particular, heterogeneous fiber distributions can lead to irregular loop geometry and locally varying pore sizes, which become more pronounced under biaxial deformation. This provides a material-related explanation for the higher pore size variability and deformation sensitivity observed in the single jersey structures in the subsequent analysis.

Knitted structures in single jersey and double jersey constructions are produced on a circular knitting machine with a gauge of E20. The materials used include both virgin yarns and a yarn composed of 50% recycled wool-silk fibers and 50% virgin wool-silk, which was prototypically manufactured by ring spinning based on the recycling process described in Section 2.1. The resulting knitted fabrics are subsequently analyzed using microscopic methods in order to investigate loop deformation and the associated geometric changes under different strain conditions. For this purpose, a newly developed testing device is employed, which enables the fixation of defined deformation states in all directions of the knitted structure. In addition to uniaxial tensile loading in wale and course directions, biaxial strain states can also be realized, allowing precise measurement of the corresponding dimensional changes. Using appropriate image analysis techniques, the loop geometries are systematically quantified and evaluated in relation to the applied strain. The chosen experimental approach enables the representation of realistic deformation states, as they occur in knitted garments due to body movements. In this way, the relationship between macroscopic strain conditions and changes in loop geometry can be analyzed in detail. The resulting variations in pore size and pore distribution within the knitted structure directly affect the thermophysiological material properties, particularly air permeability, thermal insulation, and moisture transport (see Fig. 2).

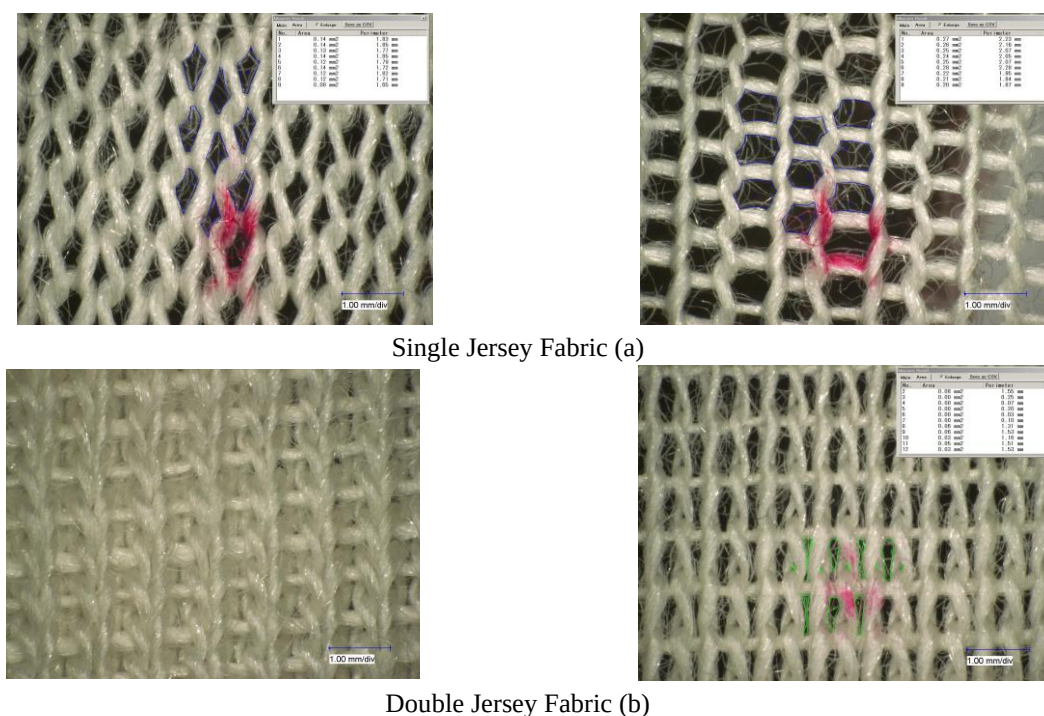


**Figure 2.** Images of knitted wool samples: (a) Single jersey fabric (left) relaxed state (right) maximum biaxial stretch; (b) Double jersey fabric (left) relaxed state (right) maximum biaxial stretch [author's own images]

The images presented represent preliminary trials; a comprehensive and in-depth analysis will be carried out in future work.

### 2.3 Image acquisition and analysis

First, the data obtained from knitted fabrics made of virgin yarns were analyzed to establish a reliable reference basis for comparison with fabrics produced from recycled yarns. A single jersey knit structure was examined both in its relaxed state (see Figure 3a) and under maximum biaxial loading (see Figure 3b), allowing the assessment of deformation-induced changes in pore geometry. The captured images were exported and processed using a Python-based image analysis workflow implemented in the PyCharm development environment, utilizing the Skimage library. Within this framework, pores in the knitted structure were automatically detected through image segmentation. Objects in contact with the image borders were systematically excluded to reduce noise and avoid incomplete feature representation. For each



detected pore, geometric parameters were determined, in particular the projected area and selected shape descriptors. The pore areas were converted from pixel units into square millimetres using a calibrated conversion factor, ensuring quantitative comparability. These parameters were used to evaluate both the characteristic pore size and the structural variability within the investigated knitted fabrics. In addition, statistical descriptors, including pore count, mean pore area, standard deviation, and coefficient of variation, were calculated to characterize the pore size distribution in both the relaxed and biaxially deformed states.

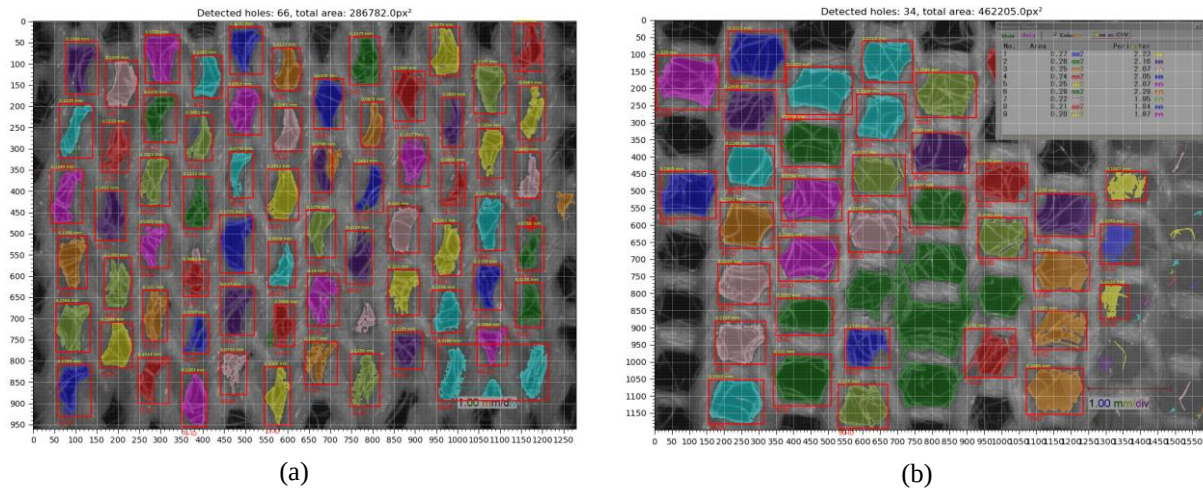


**Figure 3.** Pore size changes in wool-silk knitted fabric: (a) single jersey in the relaxed state; (b) single jersey under maximum biaxial deformation. [author's own images].

The resulting dataset provides the basis for subsequent statistical analyses aimed at identifying differences in the distribution of loops and pore openings between knitted fabrics made from recycled yarns and those made from virgin yarns.

### 3. RESULTS

Figure 4 presents the evaluation of pore size variability for single jersey and double jersey knitted fabrics in both the relaxed state and under maximum biaxial loading. The pore size distributions are compared for two defined deformation states: the unloaded condition and the maximum biaxially stretched condition.

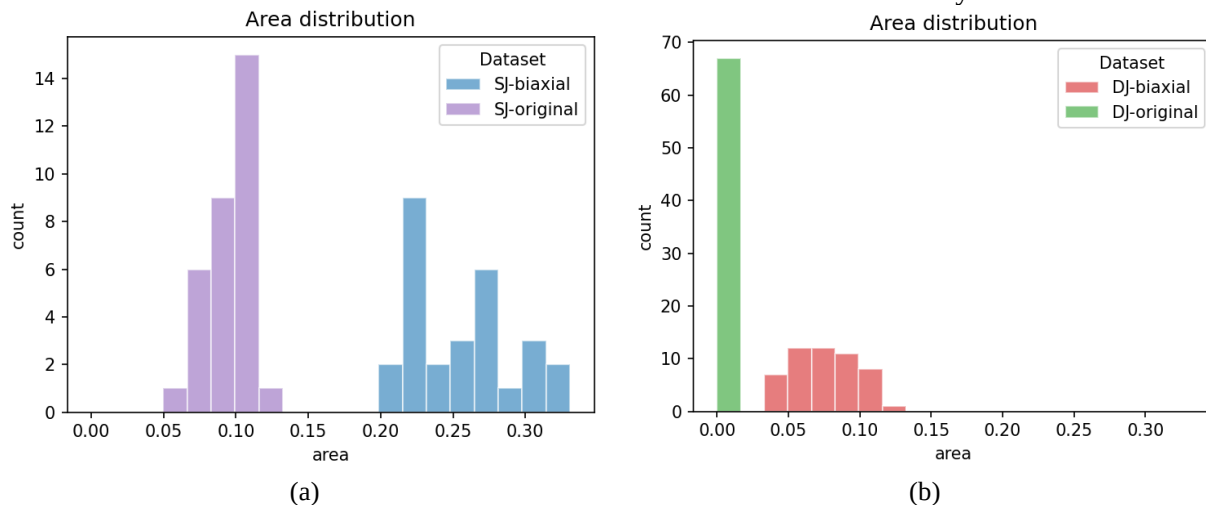


**Figure 4.** Comparison of single jersey and double jersey knitted structures in the relaxed state and under maximum biaxial deformation: (a) single jersey; (b) double jersey.

The single jersey fabric exhibits a significantly higher variability in pore size compared to the double jersey structure. As shown in Figure 4a, a broad distribution of pore sizes is observed already in the relaxed state, which becomes even more pronounced under biaxial deformation. This indicates a high structural sensitivity to mechanical loading. The increased scatter in pore size can be attributed to the asymmetric

loop configuration and the greater mobility of individual loops within the single jersey structure. In contrast, the double jersey fabric demonstrates a more compact and stable behaviour. As illustrated in Figure 4b, no significant pore openings are detected in the relaxed state, confirming the dense character of the structure. Under biaxial loading, pore formation becomes evident; however, both the absolute pore size and its variability remain considerably lower than in the single jersey fabric. This reflects the more balanced and interlocked loop configuration of double jersey fabrics, which restricts deformation and limits structural heterogeneity.

These differences in deformation behaviour have direct implications for thermos-physiological performance. The larger and more variable pore structure of single jersey fabrics is likely to enhance air permeability and moisture transport, while potentially reducing thermal stability. In contrast, the more uniform and compact structure of double jersey fabrics suggests more consistent insulation properties with reduced permeability. A detailed quantitative evaluation of pore size distribution and its dependence on strain level will be addressed in future work.

#### **4. CONCLUSION**

This study demonstrates that knitted fabrics produced from recycled wool-silk yarns can be successfully manufactured and analyzed despite fiber shortening induced by the recycling process. The results show that yarn inhomogeneity leads to increased variability in loop geometry, particularly under biaxial deformation. Significant differences between knit structures were identified. Single jersey fabrics exhibit larger and more variable pore sizes under mechanical loading, whereas double jersey fabrics show a more stable and homogeneous deformation behavior. These structural differences are expected to directly influence thermophysiological properties such as air permeability and thermal insulation. The applied combination of biaxial testing and image-based analysis provides a robust framework for the quantitative characterization of deformation-induced changes in knitted structures. This approach enables a deeper understanding of the relationship between recycled material characteristics, fabric structure, and functional performance. Future work will focus on the quantitative modeling of pore deformation and the extension of the analysis to different yarn finenesses and fiber blends.

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## BIODEGRADABLE NONWOVEN MULCHES AS AGRO-FOIL ALTERNATIVES: IMPACTS ON SOIL AND CROP

Paula Stampalija\*, Dragana Kopitar

University of Zagreb Faculty of Textile Technology, Department of Textile Design and Management, Zagreb, Croatia

\* paula.marasovic@tff.unizg.hr

### ABSTRACT

Conventional plastic agrofoils negatively impact soil health and pose environmental concerns, prompting the search for sustainable alternatives. While most studies on nonwoven mulches focus on extrusion-based nonwoven fabrics that resemble films, few have investigated mechanically produced needle-punched nonwoven mulches. In this study, nonwoven mulches ( $300 \text{ g m}^{-2}$ ) made from jute, hemp, and viscose (CV) fibres were produced on a carding machine and bonded by needle-punching. A two-year field experiment in Croatia (November 2022–May 2023 and October 2023–May 2024) was conducted to evaluate the performance of biodegradable mulches compared with conventional agrofoil for spring onion cultivation. The experiment assessed the effects of different mulch types on weed suppression, soil microclimate beneath mulches (temperature and moisture) and spring onion yield.

Winter conditions caused notable structural changes in the mulches, specifically mulch shrinkage, leading to increased mass per unit area and thickness. Weed suppression in plots covered with biodegradable mulch, compared to the control plot, and in the plot covered with agrofoil was successful.

Soils under jute and hemp mulches retained higher temperatures and moisture than those under viscose mulches. The correlation between changes in the nonwoven mulch structure due to biodegradation and the microclimate beneath mulches, as well as the influence of the microclimate on spring onion yields, was examined. Higher soil temperatures beneath jute and hemp mulches positively impact spring onion yield, whereas viscose mulch negatively affects it compared to conventional agrofoil. The findings suggest that warmer soil temperatures beneath mulches in late winter and early spring may have supported higher yields in 2023. In 2023, higher yields were also associated with appropriate moisture levels, which likely helped avoid drought stress during the critical developmental stages of spring onions. In 2024, excessive moisture may have caused waterlogging or poor root aeration beneath mulches, resulting in lower yields. The results suggest that using viscose mulch during the winter period can negatively affect onion yield due to excessive water absorption by the mulch. The results demonstrate that selecting appropriate biodegradable nonwoven mulch can replace conventional agrofoil, improving soil conditions and enhancing agricultural productivity.

**Keywords:** *cellulose-based fibres; nonwoven needle-punched mulches; soil temperature and moisture; weed control, spring onion yield*

### 1. INTRODUCTION

Biodegradable nonwoven mulches can improve the overwintering and plant growth by increasing soil temperature and creating a more favourable microclimate. Their effect, however, depends on the material and cultivation method. Some copolyester mulch types increase the leek yield and quality, while others reduce the onion bulb weight. The most favourable results are generally achieved when seedlings are grown under white nonwoven covers, highlighting the importance of proper material selection and planting method to achieve the greatest yields [1-4].

Mulch type strongly influences onion growth by affecting soil temperature and moisture. Plastic black polyethylene mulches provide high onion yields, but natural nonwoven mulches made from materials such as jute, reed, and viscose represent a more sustainable alternative. Biodegradable mulches can provide or even outperform conventional agrofoil with respect to growth metrics and plant yield. Reed mulch improved onion growth and even surpassed conventional agrofoil. Natural mulches can improve yield, moisture retention, and long-term soil quality, simultaneously suppressing weeds [5-11].

Bare soil can sometimes provide high yields of certain plants due to optimal nutrient availability. However, organic mulches may offer advantages by reducing soil temperatures in summer, consequently, lowering stress conditions for plants, protecting the soil and improving crop growth and yield [3, 4, 6, 9]. Overall, previous studies show that biodegradable nonwoven mulches positively affect soil conditions, reduce soil evaporation, and thus enhance crop growth and quality.

This study provides a comprehensive two-year evaluation of biodegradable nonwoven mulches under real field conditions, combining their performance and structural changes with spring onion yield. A comparison with conventional plastic agrofoil and bare soil is presented, highlighting the potential of sustainable mulches to improve the soil microclimate and yield. Additionally, the study enhances the understanding of the field performance and soil-related effects of biodegradable nonwoven mulches, which remain insufficiently investigated in the current literature.

## **2. EXPERIMENTAL STUDY**

### **2.1 Nonwoven mulches and field experiment**

The nonwoven fabrics were produced on cards and bonded with the needle-punching process. The fabrics were made from jute, hemp and viscose fibres with a nominal mass per unit area of  $300 \text{ g m}^{-2}$ . For comparison with conventional mulching materials, agrofoil with a mass per unit area of  $28 \text{ g m}^{-2}$  was selected as the reference material.

Two field experiments are conducted. The first field experiment investigating the behaviour of nonwoven mulches under field exposure started with the initial cycle on 17 November 2022, while the second cycle began on 25 October 2023, when nonwoven mulches and agrofoil ( $1.5 \text{ m} \times 1.1 \text{ m}$ ) were placed on the soil in randomly arranged blocks of three replication plots.

In the second field experiment, spring onions were planted following standard agronomic practices. The spring onion bulbs were planted in rows spaced 20 cm apart, with an in-row spacing of 10 cm, resulting in a dense plant population suitable for early harvest of green onions. Planting of spring onion in the first and second year was carried out on the same dates as the placement of nonwoven mulches on the field. Planting was conducted on prepared beds according to a randomised block design with three replications. Harvesting of spring onions took place on 19 May 2023 in the first year and on 20 May 2024 in the second year of the experiment.

### **2.2 Test methods**

Nonwoven fabric and agrofoil mulches were periodically collected from the field at two-month intervals until the spring onion harvest and subsequently tested to evaluate structural changes. Unexposed mulches were also analysed for comparison.

The mass per unit area and thickness (under an applied pressure of 1 kPa) were determined in accordance with ISO 9073-1:2023 and ISO 9073-2:1995, respectively. Air permeability was measured using a Mesdan Air Tronic Plus device according to the ISO 9073-15:2007, with a test area of  $10 \text{ cm}^2$  and a pressure drop of 100 Pa.

Soil temperature and moisture beneath the nonwoven mulches were monitored weekly throughout the two-year experimental period using the measuring probes. The yield of spring onion was assessed by determining the fresh mass of harvested plants using an analytical balance.

## **3. RESULTS AND DISCUSSION**

The results for nonwoven mulches, mass per unit area, thickness, and air permeability before exposure to field conditions (0) and every two months (I, II, III) in the two successive years (2022/2023 and 2023/2024) until spring onion harvesting (III), are shown in Table 1.

The mass per unit area of the jute nonwoven mulch mostly increased throughout the exposure period in both experimental years. Thickness increased after the initial two months of exposure and then mostly decreased until the end of field exposure. In the first experimental year, air permeability increased over the first four months and then decreased significantly during the final two months. On the contrary, after 2

months of exposure in the second year of the experiment, air permeability decreases and then increases until the end of the experiment.

Although jute and hemp are both bast fibres and might be expected to behave similarly under identical field conditions, this was not observed in this study. In the first experimental year, mass per unit area decreased slightly after two months of exposure, after which an increase until the end of the experiment was observed. In the second experimental year, a decrease in mass is noted, after which an increase follows until the end of the experiment. In the first year, the thickness follows the trend of mass per unit area change, until the last two months of exposure, when the thickness decreases while mass per unit area increases. In the second year of exposure, the opposite trend is visible. The thickness decreases until the last two months of the experiment, when it increases.

Although both jute and hemp are bast fibres, they differ in their structure, chemical composition, and degree of lignification, which directly affect their behaviour regarding fibre degradation. Also, differences in their fibre fineness (jute is 31.02 dtex and hemp is 58.54 dtex), rigidity and hydrophilicity influence their disorientation in mulches, consequently influencing structural mulch changes during field exposure. This can result in more pronounced, but less uniform changes in physical properties over time, particularly under fluctuating field conditions such as soil temperature and humidity. Additionally, environmental variability between the two experimental years (e.g. differences in rainfall, soil moisture, and temperatures) may have influenced “fibre to soil” interactions and microbial decomposition rates, further contributing to the observed contrasting trends.

**Table 1.** Properties of nonwoven mulches measured before field exposure (0) and at two-month intervals (I, II, III) during the experiments conducted in 2022/2023 and 2023/2024.

| Year of experiment |     | 2022/2023            |       |                                         | 2023/2024            |       |                                         |
|--------------------|-----|----------------------|-------|-----------------------------------------|----------------------|-------|-----------------------------------------|
| Mulch type         |     | M, g m <sup>-2</sup> | T, mm | AP, cm <sup>3</sup> /cm <sup>2</sup> /s | M, g m <sup>-2</sup> | T, mm | AP, cm <sup>3</sup> /cm <sup>2</sup> /s |
| Jute               | 0   | 277,7                | 3,65  | 186,24                                  | 277,7                | 3,65  | 186,24                                  |
|                    | I   | 290,6                | 4,05  | 205,79                                  | 332,9                | 3,82  | 174,48                                  |
|                    | II  | 293,8                | 4,03  | 240,15                                  | 303,8                | 3,70  | 183,76                                  |
|                    | III | 364,9                | 3,94  | 141,16                                  | 314,7                | 3,84  | 191,20                                  |
| Hemp               | 0   | 317,1                | 4,08  | 196,40                                  | 317,1                | 4,08  | 196,40                                  |
|                    | I   | 310,9                | 3,80  | 243,99                                  | 351,3                | 3,31  | 169,30                                  |
|                    | II  | 318,7                | 3,82  | 255,75                                  | 312,3                | 3,15  | 233,72                                  |
|                    | III | 348,8                | 3,67  | 197,89                                  | 296,8                | 3,57  | 166,48                                  |
| Viscose            | 0   | 289,8                | 4,65  | 52,50                                   | 289,8                | 4,65  | 52,50                                   |
|                    | I   | 335,9                | 3,77  | 38,49                                   | 335,7                | 3,49  | 39,00                                   |
|                    | II  | 351,8                | 3,98  | 48,64                                   | 395,6                | 3,49  | 35,82                                   |
|                    | III | 408,4                | 3,52  | 34,84                                   | 442,8                | 3,64  | 31,74                                   |
| Agrofoil           | 0   | 28,2                 | 0,07  | -                                       | 28,2                 | 0,07  | -                                       |
|                    | I   | 30,5                 | 0,14  | -                                       | 30,0                 | 0,05  | -                                       |
|                    | II  | 29,9                 | 0,07  | -                                       | 28,5                 | 0,07  | -                                       |
|                    | III | 30,9                 | 0,08  | -                                       | 29,3                 | 0,07  | -                                       |

M is mass per unit area in g m<sup>-2</sup>; T is thickness in mm, AP is air permeability in cm<sup>3</sup>/cm<sup>2</sup>/s

In both years of the experiment, the viscose nonwoven mulch showed an increase in mass per unit area during the exposure period. The thickness and air permeability of viscose mulches showed no clear overall trend in the first year of exposure. In the second year, air permeability decreased steadily throughout the exposure period, while thickness declined until the final two months of field exposure. The results suggest a densification of the fibrous structure over time, resulting in reduced pore connectivity and lower air flow through the exposed mulches. Visual inspection of the viscose mulches undoubtedly confirms densification of the viscose structures. Throughout the exposure period, the viscose mulches go from fluffy to more rigid and paper-like.

In both experimental years, the agrofoil mass and thickness slightly differ, and the trend is not clear.

**Table 2.** Soil temperature under nonwoven mulches, agrofoil and in the control field.

| Year            | 2022     |          |          |          | 2023     |       |       |      |
|-----------------|----------|----------|----------|----------|----------|-------|-------|------|
|                 | November | December | January  | February | March    | April | May   |      |
| <b>Jute</b>     | 10,2     | 4,7      | 4,0      | 3,0      | 8,8      | 10,6  | 14,7  |      |
| <b>Hemp</b>     | 10,0     | 4,7      | 5,2      | 3,2      | 9,0      | 10,7  | 14,8  |      |
| <b>Viscose</b>  | 9,6      | 4,4      | 3,8      | 2,9      | 8,7      | 10,3  | 14,8  |      |
| <b>Agrofoil</b> | 9,9      | 4,7      | 4,2      | 3,3      | 9,3      | 10,8  | 14,8  |      |
| <b>CF</b>       | 9,4      | 4,3      | 3,8      | 3,2      | 9,1      | 10,5  | 14,8  |      |
| Year            | 2023     |          |          |          | 2024     |       |       |      |
|                 | October  | November | December | January  | February | March | April | May  |
| <b>Jute</b>     | 16,0     | 12,3     | 5,3      | 4,6      | 3,6      | 10,6  | 13,0  | 17,2 |
| <b>Hemp</b>     | 16,0     | 17,5     | 5,3      | 5,8      | 3,8      | 10,8  | 13,2  | 17,3 |
| <b>Viscose</b>  | 15,5     | 11,8     | 5,0      | 4,4      | 3,5      | 10,3  | 12,6  | 16,7 |
| <b>Agrofoil</b> | 16,4     | 12,8     | 5,3      | 4,8      | 3,9      | 11,2  | 13,3  | 18,2 |
| <b>CF</b>       | 16,0     | 12,0     | 4,9      | 4,4      | 3,8      | 10,9  | 12,7  | 17,8 |

The differences in the behaviour of the same mulches between the two experimental years can be explained by variations in environmental conditions during field exposure. In the second year of the experiment, higher soil temperatures and increased soil moisture were recorded, which could have accelerated degradation processes and intensified interactions between the mulches and the soil.

Such conditions promote more significant structural changes of mulches and fibres, as well as faster microbial activity, resulting in different trends in mass per unit area, thickness, and air permeability compared with the first year.

**Table 3.** Soil moisture under nonwoven mulches, agrofoil and in the control field.

| Year            | 2022     |          |          |          | 2023     |       |       |      |
|-----------------|----------|----------|----------|----------|----------|-------|-------|------|
|                 | November | December | January  | February | March    | April | May   |      |
| <b>Jute</b>     | 22,3     | 20,3     | 19,6     | 17,2     | 19,9     | 21,6  | 22,9  |      |
| <b>Hemp</b>     | 23,5     | 20,6     | 19,1     | 16,6     | 20,3     | 21,6  | 23,6  |      |
| <b>Viscose</b>  | 23,0     | 20,7     | 18,6     | 16,2     | 19,8     | 21,5  | 23,9  |      |
| <b>Agrofoil</b> | 23,4     | 20,2     | 19,0     | 17,2     | 20,8     | 22,2  | 23,0  |      |
| <b>CF</b>       | 23,5     | 20,5     | 17,2     | 15,4     | 19,7     | 20,6  | 22,9  |      |
| Year            | 2023     |          |          |          | 2024     |       |       |      |
|                 | October  | November | December | January  | February | March | April | May  |
| <b>Jute</b>     | 26,3     | 25,3     | 19,1     | 20,4     | 24,2     | 25,8  | 24,7  | 25,1 |
| <b>Hemp</b>     | 25,4     | 25,6     | 19,6     | 20,4     | 24,5     | 24,4  | 24,0  | 24,0 |
| <b>Viscose</b>  | 31,4     | 26,0     | 19,1     | 20,2     | 24,9     | 24,7  | 25,5  | 26,3 |
| <b>Agrofoil</b> | 22,1     | 23,0     | 20,1     | 21,1     | 24,4     | 23,3  | 23,1  | 22,9 |
| <b>CF</b>       | 23,2     | 23,3     | 18,6     | 19,6     | 24,0     | 23,0  | 22,0  | 23,4 |

Seasonal variations in soil temperature and soil moisture under different mulch types, agrofoil, and bare soil (control field, CF) highlight the influence of soil cover types. Across both experimental years (2022/2023 and 2023/2024), consistent seasonal patterns were observed for both parameters.

During the winter period, soil beneath most biodegradable mulches and agrofoil maintains slightly higher temperatures compared to the control field, suggesting a buffering effect. The soil temperatures were lower only beneath viscose mulches during most of the winter months. Bare soil exhibited greater temperature variability, reflecting its exposure to field conditions.

Soil moisture exhibited a clear decrease during the winter months (December–February), followed by an increase in spring (March–May). In contrast, soil temperature followed the expected seasonal trend, with the lowest values recorded in winter and the highest in late spring and early autumn. These trends were consistent across all treatments.

Covering the soil with biodegradable mulches and agrofoil resulted in higher soil moisture compared to bare soil throughout both experimental years. The control treatment (CF) consistently showed the lowest moisture values, indicating increased water loss due to direct exposure. Among the mulching materials, viscose mulch demonstrated the highest capacity for moisture retention. Agrofoil improved soil moisture conservation, although its effect was moderate compared to viscose mulch. During the second year of experiment (2023/2024), the differences in soil moisture between treatments became more pronounced, especially for viscose mulch.

In terms of soil temperature, differences among treatments were less pronounced than for moisture, but still evident.

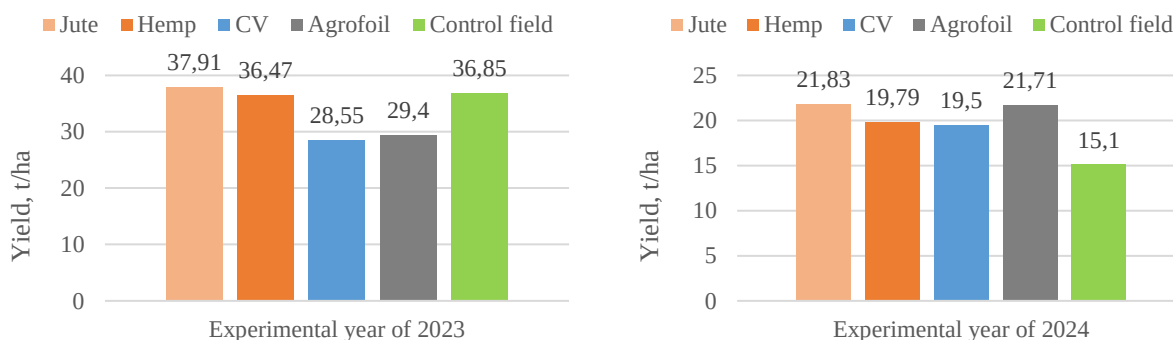


**Figure 1.** Spring onion yield in 2023 and 2024.

The yield results indicate a clear influence of mulches on spring onion productivity, with notable differences observed between the two growing seasons (2023 and 2024). Overall, the application of biodegradable mulches and agrofoil on spring onion yields is influenced by environmental conditions. In 2023, the highest yield was recorded under jute mulch (37.91 t/ha), followed by the control field (36.85 t/ha) and hemp mulch (36.47 t/ha). The relatively high yield in the control field during 2023, suggests that environmental conditions were favourable for spring onion cultivation, reducing the advantage of soil mulch treatments. Compared to the control field, in 2023, agrofoil (29.4 t/ha) and viscose mulch (28.55 t/ha) showed lower yields. Under environmental conditions in the year 2023, the benefits of mulching, such as improved moisture conservation, may be less pronounced, allowing bare soil to perform similarly to covered treatments.

On the contrary, in 2024, overall yields were lower across all treatments, indicating less favourable growing conditions. In 2024, the positive effects of soil mulches became more evident. Jute mulch again achieved the highest yield (21.83 t/ha), closely followed by agrofoil (21.71 t/ha), while hemp (19.79 t/ha) and viscose (19.5 t/ha) showed moderate performance. The control field exhibited significantly lower yield than all covered treatments (15.1 t/ha). This suggests that under stressful conditions, like reduced water availability or greater environmental variability, soil cover plays a critical role in maintaining crop productivity.

The superior performance of jute mulch across both experimental years may be attributed to its balanced effect on soil moisture retention and temperature regulation, creating favourable conditions for plant growth. Hemp mulch demonstrated stable but slightly lower yields, which may reflect its moderate influence on soil conditions. Agrofoil showed improved performance in the second year, likely due to its capacity to increase soil temperature. Conversely, viscose mulch, despite its high capacity for soil moisture retention observed in previous analyses, did not result in higher yields. This may indicate that excessive moisture levels negatively affected plant yield. These findings suggest that the use of viscose mulch may be less suitable under winter conditions, when already elevated soil moisture levels can further constrain optimal crop growth. The pronounced yield reduction in the control field in 2024 highlights the vulnerability of bare soil to adverse environmental conditions. Without protective mulches, increased evaporation and temperature fluctuations likely contributed to plant stress and reduced productivity.

#### 4. CONCLUSION

Biodegradable nonwoven mulches and agrofoil significantly affect soil conditions and crop yield. During field exposure, biodegradable nonwoven mulches underwent structural changes influenced by fibre characteristics and environmental conditions, with notable differences between the two experimental years. Yield results depended strongly on environmental conditions. In favourable conditions (2023), differences among treatments were small, while in less favourable conditions (2024), mulches and agrofoil clearly outperformed bare soil. Jute mulch achieved the most consistent and highest yields, indicating a balanced effect on soil temperature and moisture.

In contrast, viscose mulch did not improve yield despite high moisture retention, suggesting limited suitability under winter conditions. Biodegradable mulches, particularly jute, have potential for improving soil conditions and yield, but their effectiveness depends on environmental factors.



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## CHEMICAL COMPOSITION OF FLAX BAST FIBRES FOR SUSTAINABLE TEXTILE-BASED COMPOSITE MATERIALS

Ruzica Brunsek<sup>1,\*</sup>, Marijana Pavunc Samarzija<sup>1</sup>, Edita Vujasinovic<sup>1</sup>, Ivana Schwarz<sup>2</sup>

<sup>1</sup> University of Zagreb Faculty of Textile Technology, Department of Materials, Fibres and Textile Testing, Zagreb, Croatia

<sup>2</sup> University of Zagreb Faculty of Textile Technology, Department of Textile Design and Management, Zagreb, Croatia

\* [ruzica.brunsek@ttf.unizg.hr](mailto:ruzica.brunsek@ttf.unizg.hr)

### ABSTRACT

Flax fibres are increasingly recognised as promising renewable materials for sustainable textile-based composite systems due to their low density, favourable mechanical properties and biodegradability. The performance of natural fibre-reinforced composites strongly depends on fibre–matrix interactions and structural stability, which are influenced by the chemical composition of the reinforcing fibres. However, the chemical composition of flax fibres is complex and may vary with environmental factors and the analytical methods used to determine it.

In this study, the chemical composition of flax fibres was evaluated using two analytical approaches: a sequential method providing an overview of the complete chemical composition and individual methods focused on determining cellulose and lignin contents. The aim of applying two approaches was to examine how methodological differences influence the interpretation of fibre composition.

The results showed that lignin values from the two methods were similar, whereas the cellulose content determined by the Schulze method was considerably higher than that obtained by the sequential procedure. These findings demonstrate that the determination of cellulose content in flax fibres strongly depends on the analytical method used. Accurate chemical characterisation is therefore essential for reliable interpretation of flax fibre composition and for selecting fibres suitable for sustainable textile-based composite materials.

**Keywords:** *flax fibres, chemical composition, sustainable materials, textile-based composites*

### 1. INTRODUCTION

Due to their low density, favourable mechanical properties, renewability and biodegradability, flax fibres are increasingly recognised as promising materials for sustainable textiles, bio-based products and fibre-reinforced composites. As a leading bast fibre, flax has gained renewed attention for its high specific stiffness and strength, as well as its lower environmental impact compared with man-made fibres. Flax fibres, sourced from the outer stem tissues of plants, have been used in textiles for millennia [1–4]. This long history, together with the growing demand for lighter and more sustainable materials, has led to renewed scientific and industrial interest in flax. These properties make flax fibres particularly relevant in the context of circular economy strategies and European Union policies promoting the development of sustainable and bio-based materials. Although processing stages such as retting remain critical from a sustainability perspective, flax fibres can achieve strength and stiffness comparable to glass fibres in certain applications [1, 5, 6].

From a structural perspective, flax fibres belong to the group of bast fibres located in the phloem region of the plant stem. Individual elementary fibres are long, elongated cells that are naturally bonded into technical fibre bundles by pectic substances and other matrix components. During processing, particularly retting and mechanical separation, these bundles are partially separated into smaller fibre units. The hierarchical

structure of flax fibres, from the macroscopic fibre bundle down to cellulose microfibrils within the cell wall, plays an essential role in determining their mechanical behaviour [2].

The internal structure and chemical composition of flax fibres strongly influence their properties and performance. Flax fibres are biological composites composed primarily of cellulose, hemicellulose, lignin, pectin, waxes, and minor extractives. Cellulose, the predominant component, is a linear polysaccharide consisting of repeating anhydroglucose units linked by  $\beta$ -1,4-glycosidic bonds. Within the fibre cell wall, cellulose forms highly ordered crystalline microfibrils that provide high tensile strength and stiffness. Hemicellulose and pectin act as binding agents between cellulose microfibrils and fibre bundles, while lignin contributes to rigidity and resistance to degradation. The balance between these components determines fibre stiffness and moisture sensitivity [2, 6–8].

The proportions and distribution of these components are influenced by cultivar, climatic and soil conditions, agronomic practices, plant maturity, retting efficiency and anatomical heterogeneity along the stem. Consequently, the chemical composition of flax fibres is inherently complex and variable, which significantly affects their processing behaviour and compatibility with different matrices and end-use requirements [6, 7]. While high cellulose content contributes to favourable stiffness and strength, the hydrophilic nature of polysaccharides such as cellulose and hemicellulose can result in moisture absorption, affecting dimensional stability and fibre–matrix adhesion.

In addition to chemical variability, natural fibres also exhibit significant variability in their morphological and mechanical properties. Characteristics such as fibre diameter, cell wall thickness, microfibril angle and cellulose crystallinity continue to play a crucial role in determining tensile strength and elongation, which are increasingly important for modern material applications. This natural variability represents both a challenge and an opportunity: while it complicates standardisation and industrial processing, it also offers opportunities to tailor fibre properties through controlled cultivation and processing conditions. Understanding the relationship between fibre structure, chemical composition and performance is therefore essential for the efficient utilisation of flax fibres in modern materials engineering [1, 6].

Compared with conventional man-made reinforcements such as glass fibres, flax fibres offer several environmental and functional advantages. Their lower density enables the production of lightweight composite structures, while their renewable origin and biodegradability contribute to reduced environmental impact over the material life cycle. In addition, cultivating flax requires relatively modest agricultural inputs compared with some other industrial crops, further supporting its role in sustainable material systems. These characteristics have led to increased interest in flax-based composites across sectors such as automotive (for interior components), construction (for insulation panels), sports equipment (for bicycle frames and rackets), and consumer products (for furniture and packaging), where lightweight, environmentally responsible materials are in demand [1, 2, 6].

Despite these advantages, natural fibre composites also present certain limitations related to fibre variability, moisture sensitivity, and interfacial compatibility with hydrophobic polymer matrices. The hydrophilic nature of lignocellulosic fibres can lead to increased moisture uptake, which may affect the dimensional stability and long-term performance of composite materials. For this reason, detailed knowledge of fibre structure and chemical composition is essential for optimising fibre treatment, improving fibre–matrix adhesion, and ensuring reliable performance in engineering applications.

Reliable characterisation of flax fibre composition is therefore essential for understanding structure–property relationships and for selecting fibres suitable for sustainable composite materials. However, determining the chemical composition of bast fibres presents methodological challenges. Analytical methods differ in their selectivity and sensitivity, which can lead to variations in reported values of individual fibre components [4, 6]. Analytical approaches also differ in their principles and determination procedures, leading to variations in quantitative results, particularly for cellulose and lignin content. Careful methodological selection and transparent reporting of analytical procedures are therefore necessary for reliable interpretation and comparison of results.

Accurate determination of fibre composition is particularly critical when flax fibres are intended for high-performance applications such as bio-based composites. The relative proportions of cellulose, hemicellulose, lignin, and pectin influence fibre stiffness, interfacial adhesion with polymer matrices, and long-term durability under environmental exposure. For this reason, reliable analytical methodologies are required not only for fundamental fibre characterisation but also for guiding material selection and optimisation in sustainable engineering applications.

The aim of this study is to evaluate the chemical composition of flax fibres using two analytical approaches: a sequential method providing a comprehensive overview of fibre constituents and individual methods focused on determining cellulose and lignin content. By comparing these approaches, the study demonstrates how methodological differences influence the interpretation of fibre composition and its suitability for sustainable textile-reinforced composite applications.

## 2. EXPERIMENTAL STUDY

### 2.1 Testing samples

Technical flax fibres were used as the material for chemical composition analysis. The fibres were obtained from retted flax stems processed into technical fibres under laboratory conditions. The stems were subjected to biological maceration (retting) for 72 hours in hard hot water at 32 °C under controlled conditions. After retting, the stems were dried using a stream of warm air and manually separated into technical flax fibres.

### 2.2 Determining the chemical composition of flax fibres

#### 2.2.1 Determination of the complete chemical composition of fibres

The process of determining the chemical composition is based on the gradual removal of certain components from the fibres [9]. The share of each component is shown as the mean value of the measurement results for 6 parallel samples. The scheme of the determination of chemical composition is shown in Figure 1.

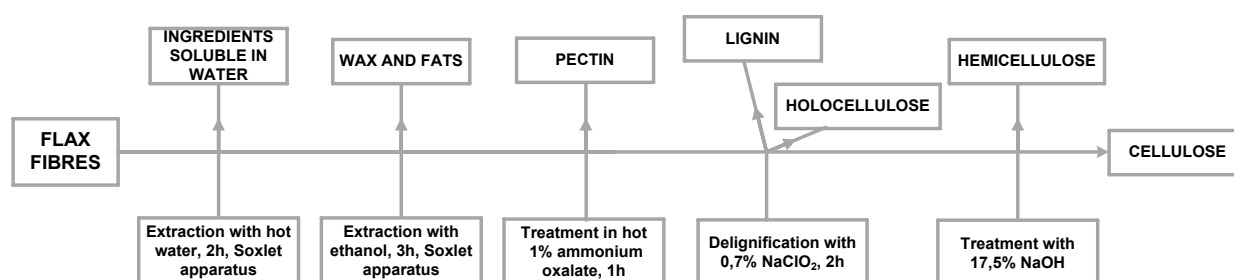


**Figure 1.** Schematic procedure of determining the chemical composition of flax fibers

#### 2.2.2 Determination of lignin and cellulose content of fibres

To compare the results obtained with the sequential method, cellulose and lignin contents were additionally determined using standard chemical analytical procedures. Lignin content was determined using the Richter method, which is based on acid hydrolysis and gravimetric determination of the insoluble residue. Cellulose content was determined using the Schulze method, which involves oxidative removal of non-cellulosic components followed by gravimetric determination of the remaining cellulose fraction [10].

## RESULTS AND DISCUSSION

The chemical composition of flax bast fibres determined by the sequential analytical method is presented in Table 1. As expected, cellulose represents the dominant structural component of the fibre, with a content of 77.34 %, forming highly ordered crystalline microfibrils responsible for the high strength and stiffness of flax fibres. This high cellulose content is consistent with the well-developed secondary cell wall of flax fibres, characterised by a high degree of cellulose deposition and orientation of microfibrils along the fibre axis.

**Table 1.** Chemical composition of flax fibres by sequential method.

| Component                                      | Content (%) |
|------------------------------------------------|-------------|
| <b>Ingredients soluble in water</b>            | 3.82        |
| <b>Wax and fats</b>                            | 0.39        |
| <b>Pectin</b>                                  | 3.62        |
| <b>Lignin</b>                                  | 3.19        |
| <b>Holocellulose (hemicellulose+cellulose)</b> | 88.98       |
| <b>Hemicellulose</b>                           | 11.64       |
| <b>Cellulose</b>                               | 77.34       |

The hemicellulose content is 11.64 %, while the total holocellulose content is 88.98 %, confirming that polysaccharides constitute the main fraction of the fibre structure. The obtained relation between holocellulose, cellulose and hemicellulose is consistent, indicating the reliability of the applied analytical procedure. The analysed fibres contain 3.62 % pectin, which plays a key role in binding fibre cells within bundles. Pectin content is closely related to retting efficiency, as pectic substances are progressively degraded during retting, enabling the separation of fibre bundles into elementary fibres. This value indicates effective retting, during which pectic substances are degraded, enabling the separation of fibres from the stem bark. Lignin content amounts is 3.19 %, which is typical for flax fibres and contributes to structural stability and resistance to degradation. The relatively low lignin content is characteristic of bast fibres and contributes to their flexibility and easier processing compared with more highly lignified fibres. The content of waxes and fats is very low (0.39 %), indicating a relatively clean fibre surface, which may favour fibre–matrix interactions in composite applications.

In addition to the sequential method, cellulose and lignin contents were determined using the Schulze and Richter methods. The results are presented in Table 2.

**Table 2.** Chemical composition of flax fibres by Schulze/Richter method.

| Component        | Content (%) |
|------------------|-------------|
| <b>Lignin</b>    | 3.89        |
| <b>Cellulose</b> | 93.13       |

The lignin content determined using the Richter method (3.89 %) was slightly higher than the value obtained by the sequential procedure (3.19 %). However, the difference between these values is relatively small and may be attributed to differences in the analytical procedures used for isolating lignin from the fibre structure. In contrast, the cellulose content determined using the Schulze method (93.13 %) was significantly higher than the value obtained by the sequential procedure (77.34 %). The difference between the two values amounts is approximately 15.8 %. This difference highlights the methodological sensitivity of cellulose determination. The Schulze method is based on the oxidative removal of non-cellulosic components prior to the gravimetric determination of cellulose. However, due to the complex hierarchical structure of flax fibres, complete removal of hemicellulose and other polysaccharides may be difficult to achieve. Consequently, remaining non-cellulosic polysaccharides may remain associated with the cellulose fraction, which can lead to an overestimation of cellulose content. These results demonstrate that the determination of cellulose in flax fibres strongly depends on the analytical procedure applied. Although instrumental techniques are increasingly used for determining the chemical composition of bast fibres, classical chemical methods remain essential for the quantitative determination of individual fibre components. Therefore, when reporting chemical composition data for bast fibres, the analytical method used should always be clearly specified.

The chemical composition of flax fibres reported in previous studies shows a relatively wide range of values, as presented in Table 3. According to the literature, cellulose content in flax fibres typically ranges from approximately 64 % to 85 %, while hemicellulose content generally ranges from 9 % to 19 %. Lignin is usually present in relatively small amounts, commonly between 2 % and 4 %.



**Table 3.** Chemical composition\* (%) of flax fibres by various authors [4].

| Cellulose       | Hemicellulose | Pectin      | Lignin      | Fat and waxes |
|-----------------|---------------|-------------|-------------|---------------|
| 85              | 9             | /           | 4           | /             |
| 73              | 10            | 15          | 9           | 5             |
| 71              | 19            | 2,0         | 2           | 1,7           |
| 65              | 16            | 3,0         | 3           | 1,5           |
| 64              | 17            | 1,8         | 2           | 1,5           |
| 71,0            | 18,6          | 2,3         | 2,2         | 1,7           |
| 64,1            | 16,7          | 1,8         | 2,0         | 1,5           |
| 66,14           | 16,24         | 2,14        | 2,0         | 1,09          |
| <b>**77.34</b>  | <b>11.64</b>  | <b>3.62</b> | <b>3.19</b> | <b>0.39</b>   |
| <b>***93.13</b> | /             | /           | <b>3.89</b> | /             |

\*In the table is not displayed numerical value of water, pigments, minerals and ash

\*\* Chemical composition of flax fibres by sequential method

\*\*\* Chemical composition of flax fibres by Schulze/Richter method

The cellulose (77.34 %) and lignin (3.19 %) contents obtained by the sequential method are consistent with the ranges reported in the literature. This agreement confirms that the results obtained by the sequential method are representative for typical flax fibre composition. In contrast, the cellulose content determined by the Schulze method (93.13 %) is higher than the range of values reported in the literature, indicating a methodological influence on the determination of cellulose content. The variability in cellulose content reported in the literature may be attributed not only to differences in raw material and cultivation conditions, but also to the analytical methods used for fibre characterisation

### 3. CONCLUSION

The chemical composition of flax fibres was analysed using two analytical approaches. The sequential method was used to determine the complete chemical composition, while the Schulze and Richter methods were used to determine cellulose and lignin contents.

The results from the sequential method indicate that flax bast fibres are mainly composed of polysaccharides. The holocellulose content is 88.98%, while the cellulose content is 77.34%. Such values are typical for flax fibres and contribute to favourable mechanical properties when used as reinforcement in textile-based composite materials.

The comparison of analytical methods highlights the impact of methodological choice on reported contents. The lignin contents determined by the sequential and Richter methods are similar. However, the cellulose content determined by the Schulze method is considerably higher than that obtained by the sequential method. This difference demonstrates that the analytical procedure used directly affects the determined cellulose content. Incomplete removal of non-cellulosic polysaccharides during cellulose determination can lead to increased calculated cellulose values, further emphasising the influence of method selection. The cellulose and lignin contents obtained by the sequential method are consistent with the ranges reported in the literature for flax fibres. The higher cellulose content obtained by the Schulze method confirms that differences in analytical procedures can influence the reported chemical composition of flax fibres. These results show that the interpretation of flax fibre composition depends on the analytical procedure used, and the applied method should therefore always be clearly specified when reporting chemical composition data. Reliable chemical characterisation is not only essential for understanding structure–property relationships but also for accurately and consistently selecting flax fibres for sustainable textile-based composite materials. Specifying the analytical procedures used ensures data comparability and underpins confidence in material performance, thereby facilitating progress in both research and application.

### ACKNOWLEDGMENT

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## DESIGN AND DEVELOPMENT OF AN ANTIBACTERIAL, SELF-HEALING, SMART HYDROGEL- CONTAINING CATHETER WOUND DRESSING

Burcu Yılmaz<sup>1,\*</sup>, Eda Akıncı<sup>2</sup>

<sup>1</sup> Su Biyomedikal Sistemler ve Sağlık Hizmetleri San. Ve Tic. A.Ş., R&D Center, Tekirdağ

<sup>2</sup> Su Biyomedikal Sistemler ve Sağlık Hizmetleri San. Ve Tic. A.Ş., R&D Center, Tekirdağ

\* burcu.yilmaz@submed.com.tr

### ABSTRACT

The treatment processes of hemodialysis patients who have lost 80–90% of their kidney function are based on the principle of cleansing blood withdrawn from the body through specialized machines and returning it to the patient. Since a high blood flow rate is required during this procedure, patients are treated through catheter, fistula, or graft applications. In these temporary or permanent catheter applications, protecting the insertion site from external environments and preventing infections are of great importance. For this purpose, catheter care and dressing procedures are performed at the beginning and end of dialysis sessions, and the catheter is covered with a protective dressing.

These dressings can be used for a maximum of 2–3 days in patients who undergo dialysis sessions on average three times per week, each lasting approximately four hours. In the developed catheter pouch design, it is aimed to achieve controlled release of chlorhexidine impregnated into a hydrogel structure to be applied to the catheter insertion site through the integrated wound dressing component. In this way, the frequency of dressing changes and manipulation of the insertion site during application will be reduced. This self-healing hydrogel wound dressing enables the product's usage period to be extended up to one week. These improvements will not only enhance patient comfort but also strengthen the product's competitive position in the sector.

**Keywords:** *Functional Wound Dressings, Hydrogel- Based Textile Structures, Medical Textiles, Antimicrobial Nonwoven Surfaces*

### 1. INTRODUCTION

Central venous catheters (CVC), which are widely used in hemodialysis treatment, pose a significant risk of infection due to the continuous exposure of the catheter insertion site to the external environment. In dressing and wound covering systems developed to reduce catheter-related infections, applications containing chlorhexidine have been shown to be particularly effective [1]. However, existing catheter dressings are generally structures that provide passive protection, have a limited usage period, and may lose their mechanical integrity during the patient's daily movements.

In modern wound dressings, not only the physical barrier property but also functional requirements such as moisture management, controlled drug release, antimicrobial activity, and user comfort have come to the forefront. The adjustable drug release properties of functional wound dressings and the ability of hydrogel-based structures to create a suitable healing environment around the wound have made these materials important in medical textile applications [2,3]. Furthermore, comprehensive reviews on wound dressings emphasize that an ideal dressing should not only provide protection but also maintain its integrity during use and offer ease of application [4].

However, in the literature, integrated catheter wound dressing solutions that provide antimicrobial agent release within a textile-compatible structure, exhibit self-healing properties, and aim for long-term use are limited. Based on this gap in the literature, in this study, a new catheter wound dressing containing chlorhexidine-loaded smart hydrogel, which is antibacterial and self-healing, has been designed and developed. The aim of the study is to present a wound dressing structure that reduces the risk of infection at the catheter insertion site while increasing patient comfort and offering innovative features from a medical textile perspective.

## **2. EXPERIMENTAL STUDY**

### **2.1 Material Selection**

Material selection was carried out by considering the criteria of biocompatibility, mechanical strength, and patient comfort. Nonwoven structures were preferred in the main structure of the wound dressing due to their advantages of flexibility and low particle release.

Since the product is intended to be used for one week, breathability and liquid barrier properties were determined as critical parameters. In this context, EVA-based films were found to be suitable.

For the hydrogel component, different polymer systems were investigated, and it was observed that PVP provided the most suitable performance. Alternatively, alginate, gelatin, carboxymethyl cellulose, and pectin-based hydrogels were also synthesized and evaluated comparatively.

### **2.2 Product Design**

The developed catheter wound dressing consists of a hydrogel layer, catheter pouch, opening-closing mechanism, and a carrier film layer.

The hydrogel layer provides an antimicrobial effect by directly contacting the catheter insertion site. While the catheter pouch protects the catheter from the external environment, the openable structure allows procedures to be performed without the need to completely remove the dressing.

With this design, it is aimed to extend the usage period and increase patient comfort compared to existing products.

The catheter pouch design is shown in Figure 1 and consists of the following parts:

- 1- Self-healing antibacterial hydrogel: The gel will contact the wound area at the catheter insertion site. With its controlled release feature, it applies medication to the wound area to provide antimicrobial activity and can self-heal against mechanical impacts.
- 2- Catheter pouch: At the end of the dialysis session, the patient's catheter is placed into this pouch, and the catheter is protected from external factors.
- 3- Opening-closing part: Thanks to the opening-closing section added to the pouch, it will not be necessary to open the catheter insertion site at every session. With the controlled release feature of the hydrogel, the wound area is disinfected by releasing an antibacterial solution for 7 days, and the catheter pouch can also be used during this period.
- 4- Pad: It is a support component that ensures the adhesion of the antimicrobial gel to the patient's skin.
- 5- Film: It is the main body that ensures the catheter pouch and pad parts remain together. Thanks to its hydrophilic structure, it prevents water penetration while allowing the catheter area to breathe.

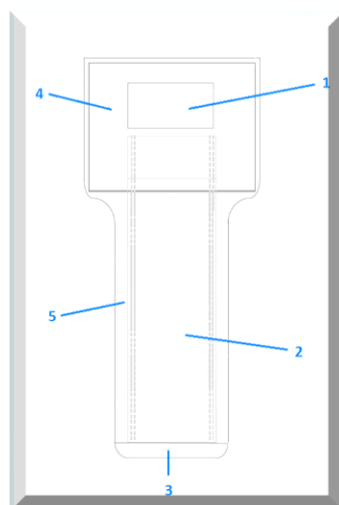


**Figure 1.** Catheter Pouch Design

### 2.3 Hydrogel Development Studies

Within the scope of the study, hydrogel structures were synthesized using different polymer systems and compared in terms of mechanical properties, swelling behavior, and controlled release performance. The obtained findings showed that the performance of hydrogels varies depending on the polymer composition and the degree of crosslinking. While an increase in crosslinking density led to an increase in mechanical strength, flexibility decreased; on the other hand, an increase in water content created a plasticizing effect, improving deformation capability. The optimum hydrogel formulation was determined by evaluating mechanical strength, flexibility, and controlled release criteria together.

Hydrogel dressings, developed as an alternative to absorbent dressings commonly used in the treatment of chronic wounds, can be customized for various wound types due to their high moisture content, controlled release, and permeability properties. Standard test methods were applied in the studies. The investigated parameters and their comparison with a commercial product (X product) are presented in Table 1 below. As a result of the comparisons, it was determined that PVP-based hydrogels coded as Formulation 5 and 6 exhibited higher mechanical strength and water absorption capacity compared to the commercial product.

**Table 1.** Study Results

|                                     | X PRODUCT | FORMULATION<br>1 | FORMULAITON<br>2 | FORMULATION<br>5 | FORMULATION<br>6 |
|-------------------------------------|-----------|------------------|------------------|------------------|------------------|
| THICKNESS (MM)                      | 1,9       | 2,1              | 2,0              | 2,8              | 3,1              |
| WEIGHT PER<br>UNIT AREA<br>(G/CM2)  | 1940 (38) | 1153             | 1025             | 3125 (89)        | 3342 (57)        |
| SWELLING IN<br>PURE WATER<br>(G/G)  | 15,4      | 11,0             | 11,2             | 18,7             | 30,7             |
| SWELLING IN<br>WOUND FLUID<br>(G/G) | 19,4      | 9,2              | 12,5             | 19,2             | 35,9             |
| MVTR                                | 0,22      | 0,55             | 0,49             | 1,03             | 1,13             |
| FHC (G/CM2)                         | 0,35      | -                | -                | 0,65             | 0,38             |
| DIRECT CHG<br>RELEASE (%)           | 71        | -                | -                | 73               | 81               |
|                                     | -         | -                | -                | 79               | 81               |



| FRANZ- TYPE<br>CELL CHG<br>RELEASE |          |          |        |           |           |
|------------------------------------|----------|----------|--------|-----------|-----------|
| E/kPa                              | 11(2)    | 10(2)    | 9(2)   | 33(3)     | 40(4)     |
| $\sigma_f$ / kPa                   | 88(1)    | 32(2)    | 17(2)  | 195(20)   | 101(9)    |
| $\epsilon_f\%$                     | 1232(60) | 500(100) | 419(5) | 1733(156) | 4408(235) |
| TOUGHNESS<br>(KJ.M3)               | 626(17)  | 80(8)    | 54(5)  | 1520(63)  | 238(78)   |
| SELF- HEALING<br>EFFICIENCY (%)    | -        | -        | -      | 55(4)     | 73(3)     |

### 3. RESULTS

#### 3.1 Controlled Release Test of Antimicrobial Agent

Hydrogel structures were designed to contain an antimicrobial agent and developed to provide controlled drug release. By optimizing the pore structure, it was aimed to ensure the long-term and controlled release of the active substance at the wound site. The release behavior was monitored over time under different environmental conditions and evaluated in detail using systems simulating physiological conditions. The analyses showed that the hydrogel structure provided effective and controlled drug release for approximately one week and reached its maximum release level within a few days.

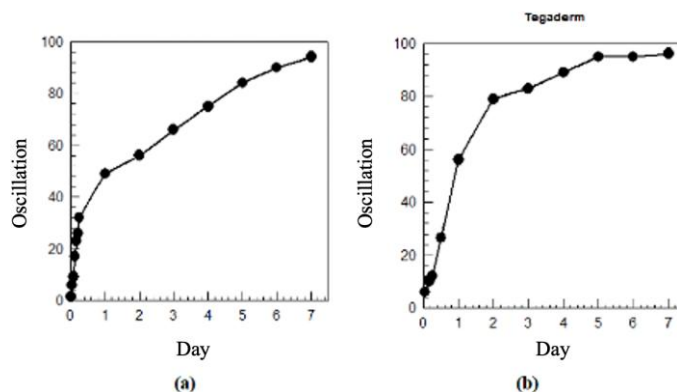


**Figure 2.** Drug release profiles of the modified formulation 6 hydrogel (a) and the commercial X product (b)

#### 3.2. Self- Healing Efficiency

For the self-healing tests, gel samples in the post-synthesis state were cut into two pieces from the middle. The two cut gel pieces were brought into contact at the cut surfaces and kept at 37 °C for 1 hour, after which the mechanical tests were repeated.

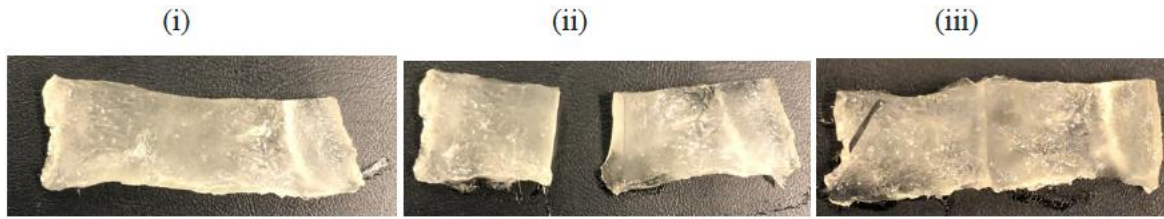


**Figure 3.** Images of the modified formulation 6 sample before cutting (i), after cutting into two pieces (ii), and after healing at room temperature for 1 hour (iii)



**Figure 4.** Tensile test images of the healed hydrogel sample

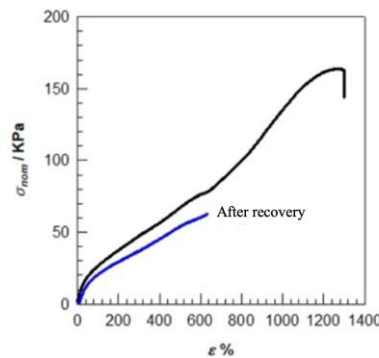


**Figure 5.** Stress- strain curves of the untreated hydrogel and the self- healed hydrogel at different healing times 37 °C

To determine the macroscopic healing performance of the hydrogel, whose healing efficiency was evaluated by rheological measurements, cut-and-heal tests were performed. After dividing the gel samples into two parts, the cut surfaces were brought together and mechanical tests were repeated after being kept at 37 °C for 1 hour. As a result of the analyses, the modulus-based healing efficiency was determined to be 88%, while the healing efficiency for fracture stress was calculated as 44% and the elongation (strain)-based healing efficiency as 48%. The findings showed that the developed hydrogel structure can regain its mechanical integrity to a certain extent and offers long-term use potential thanks to its self-healing property.

#### 4. CONCLUSION

In this study, a hydrogel-based wound dressing that is antibacterial, self-healing, and capable of controlled drug release was developed to reduce the risk of catheter-related infections. The obtained results showed that the developed system maintained its effectiveness for approximately one week and preserved its mechanical integrity. Compared to the limited number of multifunctional wound dressing approaches reported in the literature, this study presents an integrated solution that is textile-compatible and provides long-term use.

#### ACKNOWLEDGMENT

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## DESIGN OF A SMART GLOVE WITH HEATING FUNCTION BASED ON LIGNOCELLULOSIC WASTE

Pelin UZUNDERE<sup>1\*</sup>, Nil DOĞAN<sup>1</sup>, Selin Hanife ERYÜRÜK<sup>1</sup>, Özgür ATALAY<sup>1</sup>, Pelin ALTAY<sup>1</sup>, Marina TOETERS<sup>2</sup>

<sup>1</sup>Istanbul Technical University, Textile Engineering Department, Istanbul, Turkey

<sup>2</sup>Fashion Tech Farm, Eindhoven, Netherlands

[uzundere20@itu.edu.tr](mailto:uzundere20@itu.edu.tr), [dogann20@itu.edu.tr](mailto:dogann20@itu.edu.tr)

### ABSTRACT

The demand for sustainable personal thermal management systems has highlighted the environmental and ergonomic limitations of traditional electrically heated gloves (EHGs), which rely on non-recyclable synthetic materials and bulky insulation. This project focuses on the design of a smart, biodegradable heated glove for outdoor sports, utilizing lignocellulosic waste nonwoven fabric as a functional, conductive substrate. A critical physiological benchmark is maintaining hand skin temperature above the 15°C threshold to prevent the decline in manual dexterity associated with peripheral vasoconstriction. The research explores the integration of agricultural waste into a modular e-textile architecture by proposing a plasma-assisted electroplating protocol to functionalize okra fibre. This theoretical framework aims to create a robust 3D metallic network for efficient Joule heating while maintaining the fabric's sustainability. The methodology incorporates Design for Disassembly (DfD) principles, featuring a modular E-Block power unit and removable heating pads to ensure full circularity. Within the scope of the project, four conceptual designs were evaluated through a weighted decision matrix based on sustainability, dexterity, and thermal ergonomics. The evaluation identified the "Electro-Agile" Pro-Snowboarding Glove as the most promising configuration, offering an optimized balance between rapid thermal response and a 100% biodegradable profile. This work confirms the potential of replacing petroleum-based smart apparel with modular, bio-based conductive scaffolds that meet thermal needs.

**Keywords:** *Active Heating, Biodegradable Electronics, Design for Disassembly, Smart Textiles*

### 1. INTRODUCTION

Traditional smart apparel often utilizes petroleum-based synthetic fibers and permanently embedded electronic components, creating significant environmental waste. In cold environments, maintaining hand skin temperature above 15°C is critical; otherwise, manual dexterity can decline by up to 60% [1].

This study addresses these issues by developing a heated glove using lignocellulosic waste—an agricultural byproduct—as the core textile substrate. The primary goal is to achieve a fully circular product. By utilizing a modular design, the electronic heating elements can be easily separated from the glove. This ensures that the textile part, made from natural waste-based fibers, can biodegrade safely in nature without leaving microplastic residues, while the electronics are managed separately through a modular "insert-and-lock" system.

### 2. EXPERIMENTAL STUDY

#### 2.1 Materials

The experimental phase utilized a nonwoven fabric derived from lignocellulosic waste as the primary structural substrate. To optimize the glove's thermal architecture and functional performance, each layer was selected based on specific technical criteria. Poplar non-woven fabric integrated for its dual-functionality. In its natural state, it offers superior thermal insulation;

however, a key focus of this study was to functionalize poplar to provide electrical and thermal conductivity. Once functionalized, the Poplar fibers act as a textile-based resistor, enabling the circuit to operate and generate Joule heating. Lyocell selected for the inner layer due to its excellent biodegradability and high skin-contact comfort. Its moisture-management properties ensure an ergonomic and breathable interface for the user. Membrane incorporated as the outermost protective layer to provide essential wind and water resistance, ensuring the integrated electronic components and the user's hand are shielded from environmental factors while maintaining a 100% bio-based material profile.



**Figure 1.** Poplar Fabric



**Figure 2.** Lyocell Fabric



**Figure 3.** Membrane

## 2.2 Methods

The thermal comfort parameters were measured using the Alambeta device in accordance with ISO 11092 and ASTM D1518 standards. This instrument allowed for the objective determination of thermal conductivity, thermal resistance, and thermal absorptivity under a constant pressure of 200 Pa. Each sample was subjected to three independent measurements using the Alambeta device; the average of these sets was calculated to determine the final thermal parameters and reported as mean values standard deviation to ensure statistical reliability.

To transform the bio-based substrate into an active heating element, a conductive circuit was integrated using silver-based functionalization. As shown in **Figure 4**, a specific "meander" geometry was utilized to create a textile-based resistor. This pattern was engineered to optimize electrical resistance and ensure homogeneous heat distribution across the surface while maintaining the flexibility required for finger joint movements.



**Figure 4.** Textile Based Resistor

## 3. RESULTS

The thermal performance of the bio-based nonwoven fabrics was objectively characterized using the Alambeta device. The key parameters, including thermal conductivity, thermal resistance, and thermal absorptivity, are summarized in Table 1 as mean values  $\pm$  standard deviation.

The experimental results highlight the exceptional insulation capability of Poplar fibers within the modular glove architecture. Poplar demonstrated the highest thermal resistance ( $r = 113.4 \pm 1.7 \text{ W.s}^{1/2}/\text{m}^2.\text{K}$ ) which is significantly superior to the other bio-based layers tested. This high resistance, combined with the lowest thermal absorptivity ( $b = 58.3 \pm 4.3 \text{ W.s}^{1/2}/\text{m}^2.\text{K}$ ), indicates that the material provides a "warm" initial touch and acts as an efficient barrier against heat loss to the environment. In contrast, the Lyocell fabric exhibited the highest thermal conductivity ( $50.5 \pm 0.4 \text{ mW}/\text{m.K}$ ) and maximum heat flow ( $1090.8 \pm 26.1 \text{ W}/\text{m}^2$ ). While this makes Lyocell less effective as an insulator, it confirms its suitability for layers requiring rapid



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moisture management and heat dissipation from the skin. The integration of lignocellulosic waste as the primary substrate, reinforced by the insulating properties of Poplar, creates a stable microclimate essential for maintaining the hand skin temperature above the 15°C physiological threshold. Furthermore, the functionalization of Poplar fibers to enhance conductivity (as discussed in Section 2.1) aims to transform this natural insulator into an active heating element. These findings suggest that a carefully layered assembly of agricultural wastes can achieve thermal performance metrics comparable to synthetic e-textiles, while ensuring that the textile scaffold remains 100% biodegradable after the removal of modular electronic components.

**Table 1.** Alambeta Thermal Characterization Results (Mean  $\pm$  SD)

| Sample   | Thermal Conductivity<br>$\lambda_a$<br>(mW/m.K) | Thermal Diffusivity<br>$\alpha$<br>(mm <sup>2</sup> /s) | Thermal Absorptivity<br>$\beta$<br>(W.s <sup>1/2</sup> /m <sup>2</sup> .K) | Thermal Resistance<br>$r$<br>(mK.m <sup>2</sup> /W) | Thickness<br>$h$<br>(mm) | Max. Heat Flow<br>$q_{max}$<br>(W/m <sup>2</sup> ) | Heat Flow Ratio<br>$q_{max}/q_{steady}$<br>$P$ |
|----------|-------------------------------------------------|---------------------------------------------------------|----------------------------------------------------------------------------|-----------------------------------------------------|--------------------------|----------------------------------------------------|------------------------------------------------|
| Membrane | 34.5 $\pm$ 0.4                                  | 0.1 $\pm$ 0.06                                          | 115.9 $\pm$ 31.9                                                           | 13.9 $\pm$ 0.31                                     | 0.5 $\pm$ 0.01           | 622.03 $\pm$ 21.3                                  | 1.1 $\pm$ 0.04                                 |
| Lyocell  | 50.5 $\pm$ 0.4                                  | 0.05 $\pm$ 0.01                                         | 217.9 $\pm$ 16.3                                                           | 7.7 $\pm$ 0.06                                      | 0.4 $\pm$ 0.01           | 1090.8 $\pm$ 26.1                                  | 1.3 $\pm$ 0.02                                 |
| Poplar   | 40.9 $\pm$ 0.7                                  | 0.5 $\pm$ 0.06                                          | 58.3 $\pm$ 4.3                                                             | 113.4 $\pm$ 1.7                                     | 4.6 $\pm$ 0.05           | 239.3 $\pm$ 13.9                                   | 2.6 $\pm$ 0.1                                  |

#### 4. CONCLUSION

This research proves that high-performance smart textiles can be designed with a "zero-waste" vision. By using lignocellulosic waste and a modular DfD approach, we have created a heated glove that is functional and 100% biodegradable in its textile form. The separation of electronic hardware from the bio-based scaffold sets a new standard for circularity in the e-textile industry, proving that personal thermal management can be achieved within a fully sustainable framework.

#### ACKNOWLEDGMENT

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## DESIGN OF ALGINATE MICROCAPSULE-BASED WOUND DRESSING

Öykü Elmas<sup>1,\*</sup>, İsmet Ege Kalkan<sup>2</sup>, Umut Kıvanç Şahin<sup>3</sup>

<sup>1</sup> Istanbul Technical University, Textile Technologies and Design Faculty, Istanbul, Türkiye

<sup>2</sup> Istanbul Technical University, Textile Technologies and Design Faculty, Istanbul, Türkiye

<sup>3</sup> Istanbul Technical University, Textile Technologies and Design Faculty, Istanbul, Türkiye

\* oykuelmass@gmail.com

### ABSTRACT

Smart materials have attracted considerable attention in recent years due to their ability to exhibit responsive and functional behavior in advanced biomedical applications. Among these, biopolymer-based systems are regarded as promising candidates for next-generation wound dressing materials owing to their inherent biocompatibility, biodegradability, and structural adaptability. This study presents the design of an alginate-based encapsulated wound dressing system intended for biomedical applications. Sodium alginate was selected as the primary biopolymer due to its well-established ability to form stable hydrogel networks in the presence of divalent calcium ions ( $\text{Ca}^{2+}$ ). The encapsulation architecture was developed through ionic crosslinking, resulting in a three-dimensional polymeric matrix with improved structural cohesion and stability. The proposed encapsulated-based configuration is expected to provide superior performance compared to conventional hydrogel dressings by enhancing moisture retention capacity and improving the regulation of the wound microenvironment. The structural integrity of the system contributes to sustained dressing functionality, while its swelling behavior enables effective management of wound exudate over time. Overall, the alginate-based encapsulated system offers a simple yet highly effective and sustainable strategy for advanced wound dressing design. The study highlights the potential of engineered biopolymer architectures to improve functional performance in wound care applications. Future work will focus on optimizing mechanical properties and incorporating bioactive agents to further enhance the therapeutic efficiency of the system.

**Keywords:** *Alginate, Encapsulated wound dressing, Hydrogel systems, Biopolymers, Controlled release*

### 1. INTRODUCTION

A wound is defined as a disruption in the structural and functional integrity of epithelial tissue, which may extend to deeper layers such as the dermis, fascia, and muscle. Wound healing is a highly coordinated biological process involving sequential phases of hemostasis, inflammation, proliferation, and extracellular matrix remodeling, with the primary goal of restoring tissue integrity and re-establishing physiological homeostasis while minimizing infection risk [1,2]. In this context, wound dressings play a critical role by providing a protective barrier and maintaining an optimal microenvironment that supports tissue regeneration [3]. The increasing use of non-biodegradable polymeric materials in various sectors, including healthcare, has raised significant environmental concerns, driving research toward sustainable and biocompatible alternatives. In this regard, biopolymer-based systems have gained considerable attention due to their ability to form hydrogel networks with high water content and tissue-like structural characteristics, making them highly suitable for biomedical applications [4]. Among these materials, alginate is one of the most extensively studied natural polysaccharides for hydrogel formation owing to its excellent biocompatibility, biodegradability, and rapid ionic gelation behavior in the presence of  $\text{Ca}^{2+}$  ions [5].

Alginate-based systems are widely investigated in wound dressing and drug delivery applications; however, conventional hydrogel structures may still face limitations in terms of mechanical stability and

structural control under physiological conditions. To address these challenges, this study proposes the design of an alginate-based encapsulation wound dressing system aimed at enhancing structural stability and functional performance for advanced wound care applications. The proposed system is expected to enhance structural stability, maintain a moist wound environment, and improve overall wound dressing performance compared to conventional alginate-based hydrogel systems.

## **2. EXPERIMENTAL STUDY**

This study focuses on the design of an alginate-based encapsulation wound dressing system. Sodium alginate was selected as the primary biopolymer due to its biocompatibility, hydrophilic nature, and ability to form hydrogel structures. Calcium chloride ( $\text{CaCl}_2$ ) was considered as the ionic crosslinking agent responsible for hydrogel network formation through  $\text{Ca}^{2+}$ -mediated interactions.

In the proposed design, an aqueous sodium alginate solution is conceptually prepared and subsequently exposed to a divalent calcium ion environment. Upon contact, ionic diffusion of  $\text{Ca}^{2+}$  ions into the alginate matrix induces rapid gelation, leading to the formation of a three-dimensional crosslinked hydrogel network. This process results in structurally stable encapsulation units capable of retaining water and maintaining mechanical integrity.

The encapsulation architecture is designed to provide a controlled microstructured system in which alginate-based hydrogel domains act as protective carriers. These structures are intended to regulate moisture balance and create a favorable environment for wound healing by mimicking a hydrated extracellular matrix-like condition. Although no experimental validation was performed, the proposed system is conceptually expected to be evaluated based on swelling behavior, structural stability, moisture retention capacity, and suitability for wound dressing applications. These parameters are critical for assessing the performance of hydrogel-based biomaterials in biomedical contexts.

## **3. RESULTS**

The proposed alginate-based encapsulation system is expected to exhibit favorable properties for wound dressing applications due to the inherent characteristics of alginate hydrogels. The formation of a three-dimensional crosslinked network through ionic interactions with  $\text{Ca}^{2+}$  ions is anticipated to provide sufficient structural integrity while maintaining high water retention capacity. The hydrogel-based encapsulation structure is expected to create a moist wound environment, which is widely recognized as a critical factor in accelerating the wound healing process. In addition, the swelling behavior of the alginate matrix may contribute to effective absorption of wound exudate, thereby supporting fluid management and maintaining dressing functionality over time.

From a structural perspective, the encapsulation approach is anticipated to enhance the stability and organization of the hydrogel system compared to conventional bulk alginate dressings. The presence of defined hydrogel domains may allow improved control over material behavior and interaction with the wound surface. Furthermore, the biocompatibility and biodegradability of alginate are expected to support safe application in biomedical environments, minimizing adverse reactions and eliminating the need for secondary removal procedures. These characteristics make alginate-based systems particularly attractive for sustainable and patient-friendly wound care solutions.

Overall, the proposed system demonstrates strong potential as an advanced wound dressing material, combining structural stability, moisture management, and biocompatibility. The design also provides a suitable platform for future incorporation of bioactive agents, enabling further functionalization and enhancement of therapeutic performance.

## **4. CONCLUSION**

In this study, an alginate-based encapsulation wound dressing system was conceptually designed to address the limitations of conventional hydrogel structures. The proposed system highlights the potential of alginate as a biocompatible and biodegradable material capable of forming stable hydrogel networks suitable for wound healing applications. The encapsulation-based approach is expected to enhance structural stability, improve moisture management, and support a favorable wound microenvironment. These characteristics demonstrate the potential of the system as an effective alternative for advanced wound dressing design. Overall, this work provides a promising framework for the development of functional

biopolymer-based wound care materials, with future studies focusing on experimental validation and the incorporation of bioactive components to further improve therapeutic performance.

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## DESIGN OF SLEEP-ENHANCING TEXTILE PRODUCTS USING LAVENDER AND ACORN-BASED NATURAL COLORANTS

Sinem Cavdar<sup>1</sup> and Recep Karadag<sup>2</sup>

<sup>1</sup>EHM (English Home) Mağazacılık San. Tic. A.Ş., Burhaniye Nagihan Sokak No:2, 34676 Üsküdar, İstanbul, Turkey

<sup>2</sup>Faculty of Fine Arts, Department of Fashion and Textile Design, Istanbul Aydın University, Florya, İstanbul, Turkey

\* [sinem.cavdar@englishhome.com.tr](mailto:sinem.cavdar@englishhome.com.tr)

### ABSTRACT

This study focuses on the design of pillowcases dyed with lavender (*Lavandula angustifolia*) and acorn (*Quercus* spp.) extracts, within the scope of developing functional textile products aimed at naturally improving sleep quality. The calming volatile components of lavender (linalool, linalyl acetate) and the phenolic tannins in acorns that may support serotonin metabolism constitute the core bioactive elements of this research. These two plant sources were selected due to their dyeing potential as well as their positive effects on sleep. In the study, lavender flowers were extracted using an alcohol–water system, while acorn pellicles were extracted with aqueous solvents to prepare natural dye solutions. These extracts were then applied to cotton pillowcases under various dyeing conditions. The dyed samples were characterized in detail using color measurements (CIEL\*a\*b\*), chemical structure analysis (HPLC-DAD), surface morphology (SEM), and elemental composition (EDX). The slow-release potential of lavender’s aromatic volatiles and the binding behavior of acorn tannins on the textile surface were also evaluated. The findings demonstrate that lavender and acorn constituents were successfully integrated into the textile surface and that this application may offer a sense of relaxation, a soothing effect on the nervous system, and improvements in the sleep-initiation process. Overall, the study presents a sustainable approach to the development of sleep-friendly textile surfaces made entirely from natural and plant-based materials.

**Keywords:** Lavender; Acorn, Natural dyeing, Functional textiles, Sleep enhancement, Aromatherapy, Tannins, Sustainable home textiles

### INTRODUCTION

The increasing awareness of environmental sustainability and human well-being has led to a growing demand for functional home textiles that provide additional physiological benefits beyond conventional use. Natural dyes have gained renewed attention due to their biodegradability, low toxicity, and compatibility with sustainable production systems [1].

Lavender (*Lavandula angustifolia*) is widely known for its calming and sedative effects, attributed to its volatile compounds, such as linalool and linalyl acetate, which have been reported to improve sleep quality and reduce anxiety [2,3]. Integrating such compounds into textile structures provides a promising pathway for developing aromatherapeutic textiles. Acorn (*Quercus* spp.) is rich in hydrolysable tannins and phenolic compounds that exhibit a strong affinity toward textile fibers and contribute to dye fixation and functional performance [4,5]. In addition, tannins are associated with antioxidant and bioactive properties.

Despite increasing research on natural dyes, studies combining natural coloration with sleep-enhancing functionality remain limited. Therefore, this study focuses on the development of functional pillowcase textiles dyed with lavender and acorn extracts.



## 1. EXPERIMENTAL STUDY

### 2.1. Materials

100% cotton pillowcase fabrics were used as the substrate. Lavender (*Lavandula angustifolia*) and acorn (*Quercus ithaburensis*) were used as natural dye sources.

#### 2.1.1. Preparation of Natural Dye Extracts

Lavender (*Lavandula angustifolia*) flowers were extracted using an alcohol–water system to preserve volatile compounds. Acorn cups (*Quercus ithaburensis*) were extracted in an aqueous medium at elevated temperature (liquor ratio 1:20) to obtain tannin-rich solutions. In addition, dyeings were carried out using acorn extracts at concentrations of 10%, 15%, and 20%, and lavender extract at 5%.

#### 2.1.2. Dyeing Process

Cotton fabrics were dyed under controlled temperature and time conditions, followed by

washing with a nonionic detergent to remove unfixed dye molecules. The dyeing process is presented in Figure 1.

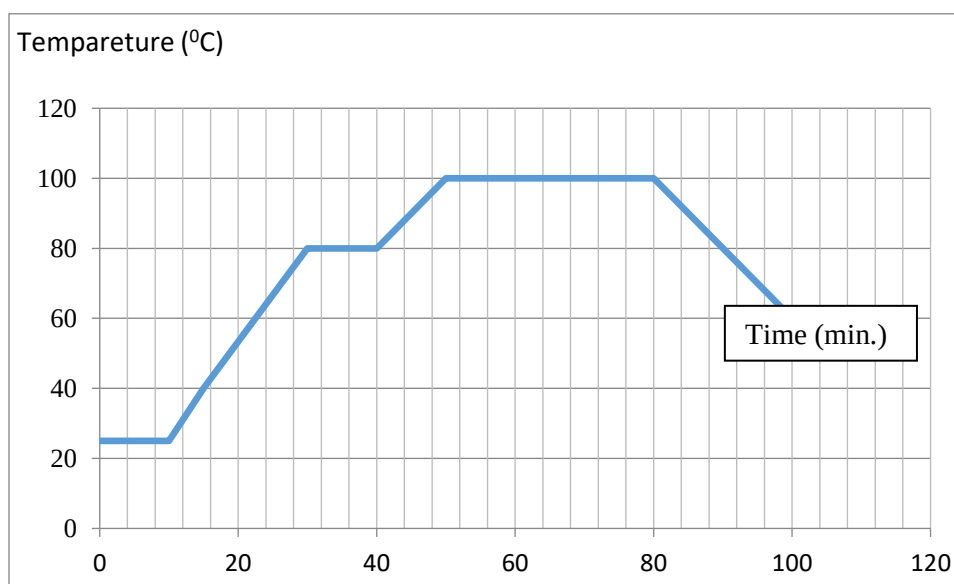


Figure 1. Dyeing process.

#### 2.1.3. Characterization

CIEL\*a\*b\*, HPLC-DAD, FTIR, and SEM-EDX analyses were performed to evaluate color properties, chemical interactions, and surface morphology.

#### 2.1.4. Color Measurements

The color properties of the dyed fabrics were evaluated using the CIEL\*a\*b\* color space system. In this system, **L\*** represents lightness (0 = black, 100 = white), **a\*** indicates the red (+) to green (–) axis, and **b\*** represents the yellow (+) to blue (–) axis.

In addition, **C\*** (chroma) expresses color intensity, and **h°** (hue angle) defines the color tone. The **K/S** values, calculated according to the Kubelka–Munk equation, were used to evaluate color strength.

These parameters enable a comprehensive quantitative assessment of color characteristics and uniformity in the dyed textiles. The color measurements are given in Figure 2.

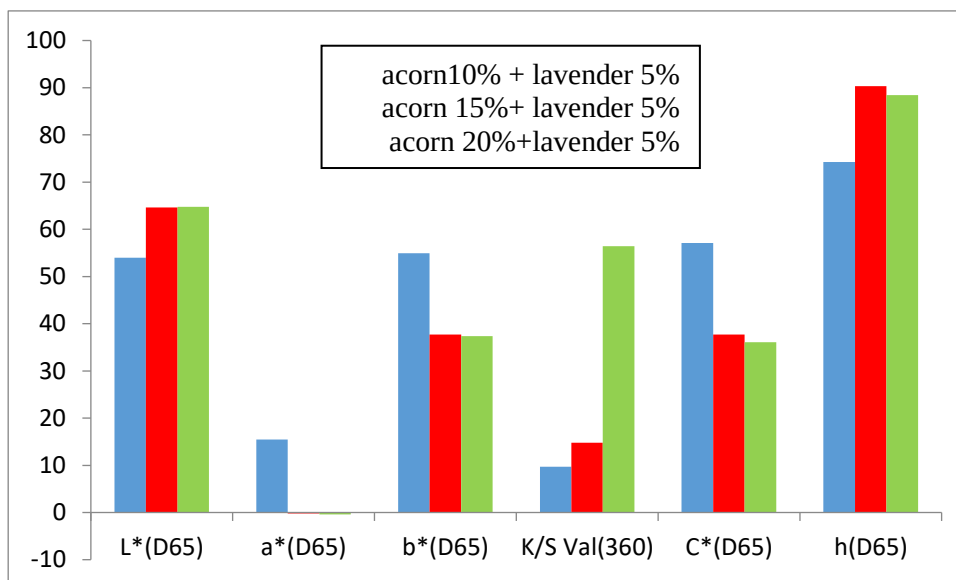


**Figure 2.** The color measurements on the dyed fabric.

#### 2.1.5. Fastness Tests

The color fastness of fabrics dyed with lavender and acorn extracts was evaluated according to ISO 105-C06 (washing), ISO 105-X12 (rubbing), and ISO 105-E04 (perspiration). Results were assessed using the gray scale and are presented in Table 1.

**Table 1.** Color fastness properties of fabrics dyed with lavender and acorn-based natural dyes.

| Light Fastness | Wash Fastness | Dry Rub Fastness | Wet Rub Fastness | Perspiration (Acid) | Perspiration (Alkali) |
|----------------|---------------|------------------|------------------|---------------------|-----------------------|
| 4              | 4-5           | 4-5              | 4                | 4                   | 4                     |

#### 2.1.6. SEM-EDX Analysis

SEM analysis showed that untreated fabrics had smooth surfaces, while fabrics dyed with lavender and acorn extracts exhibited a thin coating layer, indicating effective dye–fiber interaction. EDX analysis provided the elemental composition of the fiber surface, as presented in Figure 3 (SEM–EDX analysis of dyed cotton fabrics: surface morphology and elemental composition).

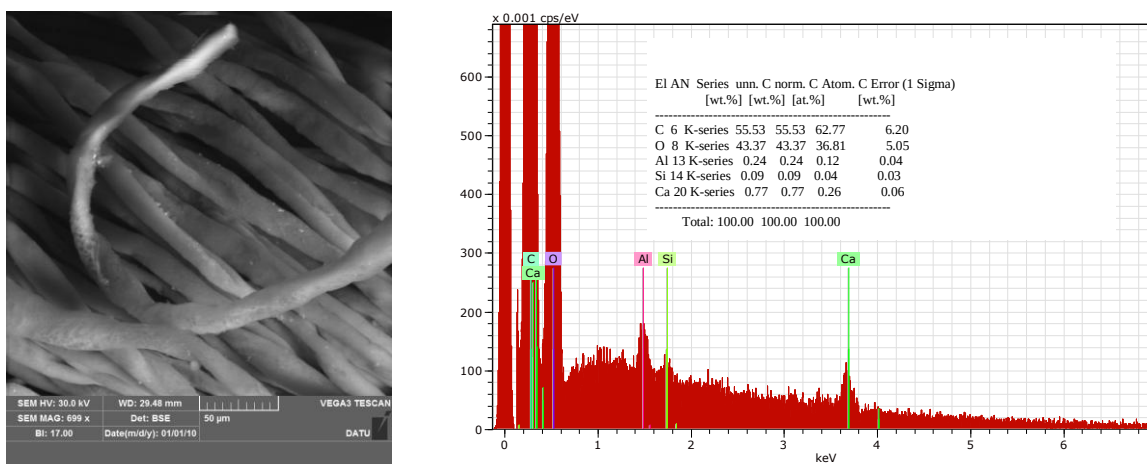


**Figure 3.** SEM–EDX analysis of dyed cotton fabrics: surface morphology and elemental composition.

### 2.1.7. HPLC-DAD Analysis

The dye components present in the dyed cotton fabrics were identified by HPLC-DAD using the analytical protocols previously described in [8]. The analysis revealed the main dye constituents and bioactive compounds derived from lavender and acorn extracts, particularly phenolics and tannins, which were found to contribute to both the coloration and the functional properties of the fabrics (Figure 4)

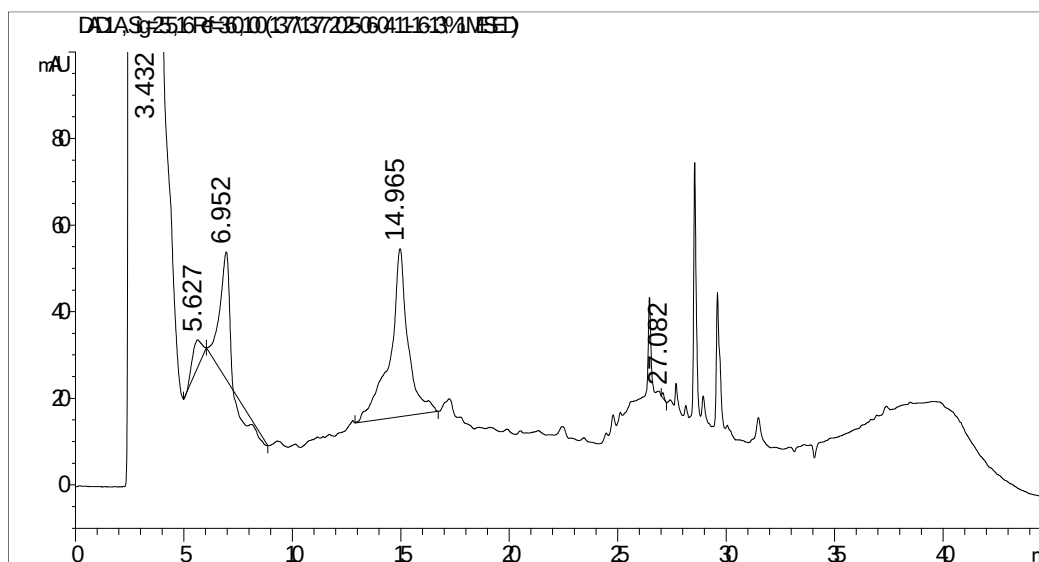


**Figure 4.** Chromatogram of the dyed sample (3.132 gallic acid, 5627 and 6.952 gallic acid derivatives, 14.965 ellagic acid, 27.082 ellagic derivative).

## 3. RESULTS

The results showed that lavender and acorn extracts successfully dyed cotton fabrics, producing natural shades with stable color properties. The dyeing process was found to be sustainable, highlighting the potential of these natural sources as eco-friendly alternatives to synthetic dyes. Moreover, the dyed fabrics exhibited good fastness properties. HPLC-DAD and SEM analyses confirmed the presence and uniform distribution of bioactive compounds on the fiber surface.

The incorporation of lavender-derived volatiles suggests potential slow-release behavior, contributing to aromatherapeutic effects. Acorn tannins enhanced dye fixation and fiber interaction.

#### **4. CONCLUSION**

Lavender and acorn extracts can be effectively used as natural dye sources for sleep-enhancing textile products. The developed fabrics exhibited both aesthetic and functional properties, including potential relaxation and sleep-supporting effects.

This approach offers a sustainable alternative [9,10] to synthetic dyes while introducing health-oriented functionalities into home textiles. Future studies should focus on durability and clinical validation of sleep-related effects.

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## ECO-FRIENDLY DYEING OF COTTON UNDERWEAR WITH WALNUT SHELLS FOR ENHANCED ANTIMICROBIAL PERFORMANCE

Elif Nihan Yıldız<sup>1</sup>, Murat Acar<sup>1</sup>, Recep Karadag<sup>2</sup>

<sup>1</sup>Flo Mağazacılık ve Pazarlama A.Ş

<sup>2</sup>Istanbul Aydın University

### ABSTRACT

The growing demand for sustainable and skin-friendly textiles highlights the importance of natural resources in functional product design. This study explores the application of walnut (*Juglans regia*) shells as a natural dye source for cotton-based underwear fabrics, with the dual objective of achieving eco-conscious coloration and providing enhanced antimicrobial protection. To reinforce resistance against microbial growth, gallnut extract (*Quercus infectoria*) was incorporated into the dyeing process. Walnut shells combined with gallnut extract (5%, 10%, and 20% weight ratios) were aqueous-extracted, and the resulting dye solution was applied to cotton underwear at varying concentrations, dyeing times, pH levels, and temperatures. The dyed fabrics were characterized through HPLC-DAD (High-Performance Liquid Chromatography with Diode Array Detection), SEM-EDX (Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy), FTIR (Fourier Transform Infrared Spectroscopy), and CIELab\* (International Commission on Illumination L\*a\*b\* Color Space) analyses. Their color performance as well as wash, rub, and perspiration fastness were evaluated according to international standards, including ISO 105-C06 / AATCC 61 (color fastness to washing), ISO 105-X12 / AATCC 8 (color fastness to rubbing), and ISO 105-E04 / AATCC 15 (color fastness to perspiration). Furthermore, antibacterial activity (*Staphylococcus aureus*, *Escherichia coli*) and antifungal activity (*Candida albicans*) were tested in accordance with AATCC 147, AATCC 100, ISO 20743 (Textiles — Determination of antibacterial activity of textile products), and ISO 13629-2 (Textiles — Determination of antifungal activity — Part 2: Mixed culture test). The findings demonstrate that walnut shells not only offer an environmentally friendly alternative for underwear coloration but also impart significant antimicrobial properties, particularly when combined with gallnut extract at 5%, 10%, and 20% concentrations. This study underlines the potential of natural dye-based waste valorization in creating high-value, sustainable, and health-conscious textile products.

**Keywords:** antimicrobial, cotton underwear fabric, eco-friendly dyeing, sustainable textiles, walnut shell



## EFFECT OF DIFFERENT ENVIRONMENTAL EXPOSURE CONDITIONS ON THE DEGRADATION OF CELLULOSE-BASED NONWOVEN FABRICS

Dragana Kopitar<sup>1,\*</sup>, Paula Stampalija<sup>1</sup>, Noa Ambs<sup>2</sup>

<sup>1</sup> University of Zagreb Faculty of Textile Technology, Department of Textile Design and Management, Zagreb, Croatia

<sup>2</sup> École Nationale Supérieure des Arts et Industries Textiles, Roubaix, France

\* dragana.kopitar@ttf.unizg.hr

### ABSTRACT

This study investigates the influence of different environmental exposure conditions on the degradation of nonwoven fabrics made on the same production line and with the same production parameters from jute, hemp, and viscose fibres, with a mass per unit area of 400 g/m<sup>2</sup>. Samples were exposed to field conditions and to outdoor conditions without soil contact, enabling the separation of the effects of UV radiation, precipitation, and temperature from soil-borne microbial activity. The exposure took place in Croatia's continental climate from May to November 2025. Samples were evaluated after 1 month and after 6 months of exposure. The analysis included mass and thickness changes, changes in mechanical properties (tensile strength and elongation), structural alterations assessed through air permeability (indicating changes in porosity and density), and microscopic imaging of fibre morphology. The mass per unit area of viscose nonwoven fabric increases under outdoor conditions without soil contact, but decreases in the open field. Jute nonwoven fabric shows little change in outdoor exposure, while its mass increases in the open field. Hemp nonwoven fabric mass increases outdoors but shows a slight decrease in the open field. Thickness changes follow a similar pattern, where viscose nonwoven fabric thickness decreases outdoors but increases in the open field. Contrary to viscose nonwoven fabric, the thickness of jute and hemp nonwoven fabrics increases under both environmental conditions. Consequently, changes in the nonwoven fabric's mass and thickness alter the breaking forces. The results reveal pronounced differences in degradation rates and mechanisms among the tested materials, highlighting the strong influence of environmental exposure and fibre type on the degradation behaviour of nonwoven fabrics. Testing materials under both exposure conditions provides a comprehensive understanding of different degradation mechanisms and supports the selection of the most suitable nonwoven material for specific applications, including agricultural mulches, soil-erosion control, horticultural agrotexiles, protective covering fabrics, horticultural materials not intended for biodegradation (such as nursery coverings without soil contact), and packaging or transport nonwoven textiles.

**Keywords:** *cellulose-based fibres; needle-punched nonwoven mulches; environmental exposure; mechanical and structural properties*

### 1. INTRODUCTION

Modern agriculture increasingly relies on the mulching technique to improve crop performance by maintaining soil moisture, balancing soil temperature and suppressing weeds. Nowadays, mulches have become a tool for improving yields under variable climatic conditions. Among them, conventional plastic films are used worldwide and can increase crop yields (by 24–40%) and improve water use efficiency (by 28–38%), particularly in arid and semi-arid regions. Their effectiveness is largely attributed to reduced soil evaporation, erosion control and weed suppression, therefore, creating a favourable soil environment [1,2]. However, despite agronomic benefits, their widespread use has raised serious environmental concerns. Plastic mulches and greenhouse films are major contributors to soil contamination by plastics, primarily because of progressive material degradation and difficulties in their disposal [1-3]. Plastic particles persist in agricultural soils, altering soil structure and microbiological activity, negatively affecting plant growth and soil quality. Their potential to enter food chains raises concerns related to food security and human health [1-4]. Consequently, the sustainability of conventional mulches is questioned, prompting the search

for environmentally friendly alternatives. Nonwoven agrotextiles have gained attention as a promising alternative. Their relatively low production cost and ability to be produced from natural and synthetic fibres make them highly favourable for agricultural applications such as mulches, crop covers, and weed-control fabrics [5]. Their structural design can be tailored to control functional properties, including porosity, permeability, and degradation rate, enabling soil moisture retention, temperature regulation, and weed suppression without contributing to microplastic pollution. Natural fibres are highly susceptible to environmental factors such as moisture, ultraviolet (UV) radiation, and microbial activity, leading to inconsistent degradation behaviour, as their performance strongly depends on local environmental conditions. To overcome these limitations, fibre blending (e.g., with polylactic acid, PLA) or specific treatments can be used, though they can increase costs and pose production challenges [5-8]. The degradation behaviour depends on environmental conditions and the complex interplay of abiotic and biotic factors, including UV radiation, temperature fluctuations, moisture dynamics, and soil microbial communities. Field studies indicate that mulch degradation influences soil microbial activity, which can, consequently, accelerate mulch deterioration and affect soil quality [5,9,10]. However, it remains challenging to separate the effects of these interacting factors. Under field conditions, multiple stressors (such as wet/dry and freeze/thaw cycles, soil type, pH, etc.) act simultaneously, making it difficult to isolate the contribution of individual factors [5,9-11]. Additionally, nonwoven materials undergo physical and structural changes during exposure, including mulch shrinkage and expansion and the accumulation of soil and plant residues. Therefore, indicators such as mass loss, thickness, or air permeability may not adequately describe degradation [5,9,10]. In contrast, laboratory studies simplify real field conditions by controlling or excluding important variables. For example, combining UV exposure and moisture (QUV testing device) in the absence of soil, or testing in soil under constant temperature and darkness (environmental chamber), does not imitate real agricultural environments [12,13]. Accordingly, the literature highlights a lack of field studies, largely due to complexity, high cost, time-consuming nature and challenges in standardising both biodegradable materials and soil conditions across diverse climates [8,11]. In response to these gaps, this study aims to investigate the influence of different environmental exposure conditions on the degradation of nonwoven mulches composed of jute, hemp, and viscose fibres. Particular emphasis is placed on distinguishing the effects of abiotic factors, such as UV radiation, temperature, and precipitation, from biotic soil components, primarily microorganisms. By comparing degradation rates and mechanisms under those exposures, the research clarifies the role of environmental conditions and fibre composition in determining material performance. The findings are intended to support the selection and design of more reliable and sustainable nonwoven mulches tailored to specific agricultural applications.

## 2. EXPERIMENTAL STUDY

The nonwoven mulches were produced from viscose (1.78 dtex, 40 mm), jute (31.02 dtex), and hemp (58.54 dtex) fibres supplied by Derotex NV, Wielsbeke, Belgium. They were produced on cards by a mechanical process, followed by needle punching, with the same technological parameters.

Mass per unit area of nonwoven fabrics was determined in accordance with ISO 9073-1:2023. The thickness was determined according to ISO 9073-2, with an applied pressure of 0,5 kPa. Air permeability was measured using an Air Tronic device (Mesdan S.p.A.) in accordance with ISO 9073-15:2007. Airflow was set to 10 L/min and regulated to maintain a pressure drop of 50 Pa across a circular test area of 10 cm<sup>2</sup>. The pressure drop was lower than that suggested by the standard due to difficulties with measuring significantly degraded samples. The breaking force and elongation were determined according to the ISO 9073-3:2023 for nonwoven fabric. The five samples per mulch type in the machine (MD) and five in the cross-machine direction (CD) were tested on the Tenso Lab 5000 Mesdan S.p.A tensile tester at a constant speed of 100 mm/min with a pretension of 5 N.

The nonwoven mulches were randomly placed on the soil in Zagreb County, Croatia, characterised by a humid continental climate. The samples were also mounted on a metal frame, oriented southward at a 45° angle, without contact with the soil. The experiment started on 20 May 2025. The first set of samples was collected and tested after one month, while the second set was collected after 6 months and tested afterwards.

### 3. RESULTS AND DISCUSSION

After 30 days of exposure, a decrease in mass per unit area was observed for jute and hemp nonwoven fabrics placed in the open field (0.47% for jute and 3.71% for hemp). In contrast, the mass per unit area of jute fabrics exposed on the metal frame (without soil contact) decreased by 8.41%, whereas for hemp fabrics an increase of 11.93% was recorded. This increase is likely related to moisture uptake and the accumulation of environmental particles or impurities on the fabric surface, rather than actual material growth.

Regarding density changes, field-exposed samples showed relatively similar variations for jute and hemp (15.17% and 15.74%, respectively), indicating a relatively uniform effect of biodegradation under soil-contact conditions. On the contrary, exposure without soil contact resulted in a more pronounced difference between the two samples. The jute exhibited a greater reduction in density (23.58%) compared to hemp (8.98%), suggesting a greater structural deterioration of the jute nonwoven fabrics.

**Table 1.** Properties of exposed nonwovens in the field and without soil contact.

| Exposure             | Time, days | Sample  | Mass per unit area, g m <sup>-2</sup> | Thickness, mm | Density, g cm <sup>-3</sup> |
|----------------------|------------|---------|---------------------------------------|---------------|-----------------------------|
| Unexposed            | 0          | Jute    | 420,28                                | 4,33          | 0,0971                      |
|                      |            | Hemp    | 273,66                                | 3,22          | 0,0850                      |
|                      |            | Viscose | 365,64                                | 4,46          | 0,0820                      |
| Field                | 30         | Jute    | 418,29                                | 5,08          | 0,0823                      |
|                      |            | Hemp    | 263,52                                | 3,68          | 0,0716                      |
|                      |            | Viscose | 355,92                                | 4,18          | 0,0851                      |
|                      | 180        | Jute    | 291,66                                | 4,58          | 0,0637                      |
|                      |            | Hemp    | 213,47                                | 3,34          | 0,0639                      |
|                      |            | Viscose | 305,43                                | 3,49          | 0,0875                      |
| Without soil contact | 30         | Jute    | 384,95                                | 5,19          | 0,0742                      |
|                      |            | Hemp    | 306,32                                | 3,96          | 0,0774                      |
|                      |            | Viscose | 384,95                                | 5,45          | 0,0706                      |
|                      | 180        | Jute    | 344,91                                | 4,54          | 0,0760                      |
|                      |            | Hemp    | 252,50                                | 6,16          | 0,0410                      |
|                      |            | Viscose | 304,01                                | 3,68          | 0,0826                      |

The observed differences in mass per unit area, thickness, and density can be attributed to different degradation mechanisms depending on exposure conditions. Samples placed in the field were in direct contact with soil, moisture, and microorganisms, which promoted biological degradation of the materials. According to previous studies, the field degradation of jute and hemp nonwoven fabrics typically begins with structural changes in the mulch, followed by microbial degradation of the fibres after a certain exposure period, indicating that a time is required for microbiological degradation of the bast fibres [7,9]. As a result, a moderate decrease in mass per unit area was recorded, more pronounced for hemp than for jute, indicating a potentially higher susceptibility of hemp fibres to early-stage microbial activity, likely associated with differences in fibre composition, particularly lignin content. In contrast, samples exposed without soil contact were more affected by UV radiation, temperature fluctuations, and atmospheric conditions. Samples mounted at a 45° angle on the metal frame are more intensively exposed to UV irradiation, precipitation, and wind impact, enhancing physical and photochemical degradation processes. Under these conditions, a higher variation in mass per unit area was observed for both jute and hemp compared to field-exposed samples. Changes in sample densities further confirm the presence of structural alterations in the materials. Similar density changes in field-exposed samples indicate a relatively uniform biodegradation process. A greater reduction in jute fabric density exposed without soil contact suggests a higher susceptibility to fibre disorientation and structural fabric change regarding the hemp sample. Differences in fibre fineness, rigidity, and overall morphology between jute and hemp fibres likely contributed to the pronounced deterioration of the jute fabric.

After 180 days of exposure, jute and hemp showed a significantly higher mass loss under field conditions (30.6%; 21.99%) compared to the exposure without soil contact (17.90%; 7.73%), which suggests microbial degradation in the field took place, while degradation due to UV irradiation and precipitation had less impact on the samples. Although photodegradation and weathering (UV radiation, precipitation, and temperature fluctuations) contribute to material deterioration, long-term mass loss is primarily governed by microbial degradation under soil-contact conditions.

The density decrease was also more pronounced in the field (34.39%; 24,80%) than exposure without soil contact (21.73%, 12,87%). Thickness reduction followed a similar trend, with a greater decrease in the field (5.77%, 3.73%) than exposed without soil contact (4.85%, 5.9%). The density and thickness changes indicate progressive fibre decomposition and structural weakening of samples under soil-influenced conditions, primarily by microbial degradation processes in the soil environment, then degradation due to UV irradiation and precipitation.

Although nonwoven bast fibre fabrics (jute and hemp) exhibited a similar trend of changes during exposure, the viscose nonwoven fabric showed a different behaviour pattern. After 30 days of field exposure, viscose exhibited a moderate mass loss (2.66%), accompanied by a reduction in thickness (6.28%) and an increase in density (3.86%). Unlike the nonwoven textiles made from jute and hemp fibres, the viscose nonwoven fabric exhibited thickness reduction. This behaviour suggests compaction of the fibrous structure, likely due to the highly hydrophilic nature of viscose fibres, which promotes repeated swelling and drying cycles. These cycles lead to fibre collapse and closer fibre packing, resulting in a thinner, more rigid, paper-like structure. This mechanism differs from the more heterogeneous degradation observed in jute and hemp nonwovens.

After 180 days, viscose showed a reduction in mass (16.47%) and an even more substantial decrease in thickness (21.75%) under field conditions, indicating progressive fibre degradation and structural disintegration. The stronger reduction in thickness compared to jute and hemp suggests a more severe collapse of the viscose fabric structure under prolonged soil exposure. Interestingly, density increased in field conditions (6.75%), in contrast to jute and hemp nonwovens, which can be explained by the fabric structure failure and fibre degradation, leading to compaction of the remaining fibre. which can be explained by the collapse of the porous structure and compaction of the remaining fibre mass rather than an improvement in material integrity. Exposure without soil contact followed the field trend but is less pronounced.

After 30 days of field exposure, the breaking force of jute nonwoven fabrics in the machine direction (MD) increases, followed by a decrease after 180 days. In the cross-machine direction (CD), jute fabric showed a steady decrease in breaking force throughout the open-field exposure period. The breaking force follows changes in fabric mass and thickness, i.e., structural changes indicating structural fibre rearrangement and consolidation after 30 days, followed by fibre degradation and loss of structural integrity under prolonged microbial and environmental conditions. Jute exhibited a similar trend as in field exposure, but with more pronounced changes, indicating that degradation due to UV radiation was significantly more intense. On the contrary, the hemp nonwoven fabric exhibited a continuous decrease in breaking force in the MD direction and an increase in the CD direction over the entire 180-day exposure period. The more pronounced reduction in breaking force observed for hemp fabric, and the trend in breaking force in MD and CD directions, can be attributed to fibre orientation in the fabrics produced on cards. The dominant fibre orientation in the CD direction suggests that the observed decrease in breaking force in the MD direction indicates fibre damage and breakage under field exposure. In contrast, the increase in breaking force in the CD direction can be attributed to fibre reorientation, structural densification, and increased inter-fibre friction, representing competing mechanisms where structural compaction may temporarily enhance breaking force despite ongoing fibre degradation.

**Table 2.** Tensile properties of exposed nonwovens in the field and without soil contact.

| Exposure             | Time, days | Sample  | Breaking force, N | Elongation at break, % | Breaking force, N | Elongation at break, % |
|----------------------|------------|---------|-------------------|------------------------|-------------------|------------------------|
| Fabric direction     |            |         | MD                |                        | CD                |                        |
| Unexposed            | 0          | Jute    | 36,86             | 23,29                  | 28,92             | 43,95                  |
|                      |            | Hemp    | 27,42             | 37,49                  | 17,84             | 51,13                  |
|                      |            | Viscose | 22,68             | 25,16                  | 13,62             | 25,91                  |
| Field                | 30         | Jute    | 38,60             | 25,18                  | 26,40             | 32,44                  |
|                      |            | Hemp    | 23,60             | 41,02                  | 26,80             | 25,99                  |
|                      |            | Viscose | 52,20             | 39,45                  | 53,40             | 28,25                  |
|                      | 180        | Jute    | 21,34             | 11,00                  | 20,28             | 19,55                  |
|                      |            | Hemp    | 13,00             | 25,95                  | 36,16             | 25,05                  |
|                      |            | Viscose | 28,38             | 10,33                  | 28,02             | 12,45                  |
| Without soil contact | 30         | Jute    | 30,80             | 16,88                  | 24,00             | 27,90                  |
|                      |            | Hemp    | 41,00             | 29,22                  | 27,20             | 44,55                  |

|  |     |         |       |       |       |       |
|--|-----|---------|-------|-------|-------|-------|
|  |     | Viscose | 55,00 | 25,74 | 35,00 | 39,17 |
|  | 180 | Jute    | 21,67 | 13,29 | 17,20 | 24,36 |
|  |     | Hemp    | 29,37 | 26,67 | 18,60 | 36,25 |
|  |     | Viscose | 7,77  | 6,54  | 6,97  | 9,92  |

The breaking force of hemp samples exposed without soil contact generally increases in both fabric directions. This trend can be explained by the absence of microbial degradation and the dominant influence of photodegradation and weathering processes (UV radiation, precipitation, and temperature fluctuations). These conditions promote structural densification, fibre rearrangement, and closer fibre packing, leading to increased inter-fibre friction and, consequently, increasing breaking force.

For viscose nonwoven fabrics, the breaking force in both MD and CD directions initially increased after 30 days of exposure, followed by a decrease after 180 days, regardless of exposure conditions. The initial increase in breaking force can be attributed to structural compaction of the fibres in the fabrics, caused by the hydrophilic nature of viscose fibres. Repeated wet–dry cycles promote fibre swelling and subsequent collapse, leading to closer fibre packing, increased inter-fibre contact, and higher frictional interactions, which temporarily enhance breaking force. However, with prolonged exposure (180 days), the breaking force decreases due to fibre degradation and structural disintegration. The significant reduction in mass and especially thickness, along with the increase in density, indicates collapse of the structure and compaction of the remaining fibre mass. Despite this densification, the integrity of individual fibres is compromised over time due to microbial activity (in field conditions) and combined photochemical and weathering effects (without soil contact), resulting in an overall loss of fabric breaking force.

#### 4. CONCLUSION

Nonwoven fabrics from jute and hemp fibres exhibited exposure-dependent degradation behaviour, with microbial degradation dominating under field conditions and leading to greater long-term mass loss, density reduction, and structural weakening. In contrast, exposure without soil contact was governed by photodegradation and weathering, resulting in more pronounced structural rearrangement, densification, and variability in mass changes, but overall lower long-term degradation compared to field conditions. Differences between jute and hemp were attributed to fibre composition, morphology, and orientation, influencing their susceptibility to degradation and mechanical performance.

Viscose nonwoven fabrics showed a distinct degradation mechanism, characterised by initial structural compaction due to their hydrophilic nature and wet–dry cycling, followed by structural disintegration. Although densification temporarily increased density and, in some cases, breaking force, prolonged exposure led to a loss of fibre integrity and reduced breaking force. Overall, the results highlight that degradation mechanisms and mechanical performance are strongly dependent on fibre type, structure, and environmental exposure conditions.

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## EFFECT OF QUILTING DIAMETER ON AIR PERMEABILITY AND THERMAL PERFORMANCE OF OUTERWEAR

Banu Bornovalı Bilby<sup>1</sup>, Demet Ateş<sup>1</sup>, Elif Salkım Türkoğlu<sup>1</sup>, Emine Dilara Koçak<sup>2</sup>, Özgür Atalay<sup>3</sup>

<sup>1</sup>Boyner Büyük Mağazacılık A.Ş.

<sup>2</sup>Marmara Üniversitesi

<sup>3</sup>İstanbul Teknik Üniversitesi

### ABSTRACT

Garments Air permeability is a critical parameter influencing thermal comfort and functional performance in outerwear garments. This study investigates the effect of quilting on air permeability by comparing a standard non-quilted outerwear garment with two quilted outerwear samples having different quilting diameters. All measurements were conducted using the ASTM D3574 air flow method. The results showed that the non-quilted outerwear sample exhibited a significantly higher air permeability value of 28.26 m<sup>3</sup>/m<sup>2</sup>/h. In contrast, both quilted samples demonstrated substantially lower air permeability, indicating that the quilting process significantly enhances resistance to airflow. Among the quilted samples, the structure with a 3 cm quilting diameter showed the lowest air permeability (2.56 m<sup>3</sup>/m<sup>2</sup>/h), whereas the sample with a 2 cm quilting diameter exhibited a higher value (3.66 m<sup>3</sup>/m<sup>2</sup>/h). These differences can be explained by variations in stitch density and structural configuration. Reducing the quilting diameter increases the number of stitched units per unit area, thereby increasing stitch density. Higher stitch density introduces more localized compression zones and creates additional airflow pathways along stitch lines, allowing air to pass more easily through the structure. Conversely, larger quilting diameters result in lower stitch density, limiting airflow channels and improving the material's ability to restrict air movement. Overall, the findings demonstrate that quilting significantly reduces air permeability compared to a standard non-quilted outerwear garment. Furthermore, larger quilting diameters appear to provide better thermal insulation performance by minimizing air permeability, making them more suitable for cold weather conditions.

**Keywords:** air permeability, quilting

# ELECTROTHERMAL PERFORMANCE OF BORIC ACID– FUNCTIONALIZED GRAPHENE OXIDE–COATED POLYESTER NEEDLE-PUNCHED NONWOVEN FABRICS

Özgen Özturan<sup>1,\*</sup>, Nergis Demirel Gültekin<sup>2</sup>, İsmail Usta<sup>2</sup>

<sup>1</sup> Department of Textile Engineering, Institute of Pure and Applied Sciences, Marmara University, İstanbul, Türkiye

<sup>2</sup> Department of Textile Engineering, Faculty of Technology, Marmara University, İstanbul, Türkiye

\* [ozgenozturan@marun.edu.tr](mailto:ozgenozturan@marun.edu.tr)

## ABSTRACT

In this study, boric acid-functionalized graphene oxide (BAGO) was synthesized via a simple solution-based method and applied to polyester needlepunched nonwoven fabrics using a combination of dip-coating and blade-coating techniques. Characterization analyses (SEM-EDS and FTIR) confirmed the successful incorporation of boron into the GO structure. Electro-thermal test revealed rapid and uniform heating under applied (10 V and 15V) voltages. The results suggest that BAGO coatings, applied via combined dip and blade-coating methods, offer a promising approach for the development of high-performance, flexible heating elements in wearable electronic textile applications.

**Keywords:** *Boric acid, Electro-thermal heating, Functionalization, Graphene oxide, Polyester nonwoven fabric.*

## 1. INTRODUCTION

Graphene oxide (GO) is a two-dimensional graphene derivative enriched with oxygen-containing functional groups, such as epoxide, hydroxyl, and carboxyl groups, which enhance its hydrophilicity and enable versatile chemical functionalization [1, 2]. The outstanding physical properties of graphene oxide make it an attractive material for the fabrication of various nanocomposites, polymer materials, high-performance microelectronic devices, energy storage materials, and for biomedical applications. Moreover, due to the hydrophilic character of GO, it could be easily dispersed in water. The oxygen functionalities in GO caused a severe decline in electrical properties, thermo-mechanical stability, and carrier mobility of carbon-based materials [3]. The heteroatom doping of graphene oxide is one of the most effective strategies for tailoring the electrochemical properties [4, 5]. The incorporation of heteroatoms into graphene simultaneously opens a bandgap and generates catalytically active sites [6]. The chemical doping of heteroatoms with different electronegativity and size, such as boron (B), nitrogen (N), phosphorus (P), fluorine (F), sulfur (S), and chlorine (Cl) into graphene will cause structural and electronic alterations [7, 8]. The addition of boron creates a band gap and makes it a p-type material [5]. Latif et al. [9] reported enhanced charge storage and high specific capacitance in N- and B-doped GO (NGO, BGO) prepared using urea and boric acid. Selvakumar et al. [10] produced B-doped rGO papers through GO self-assembly and thermal deoxygenation (400 °C, Ar), with successful doping verified by SEM, XRD, XPS, and Raman. Mu et al. [11] synthesized nitrogen-doped reduced graphene oxide (NRGO) by reducing graphene oxide with hydrazine hydrate and ammonium hydroxide. Boron- (BRGO) and phosphorus-doped (PRGO) RGO were prepared by annealing sodium borohydride-reduced RGO with boric and phosphoric acid, respectively.

In this study, boric acid-functionalized graphene oxide (BAGO) was synthesized via a simple solution-based method and applied to polyester needlepunched nonwoven fabrics using a combination of dip-coating and blade-coating techniques. Characterization analyses (SEM-EDS and FTIR) confirmed the successful incorporation of boron into the GO structure. Electro-thermal test revealed rapid and uniform heating under applied (10 V and 15V) voltages.

## 2. EXPERIMENTAL STUDY

### 2.1 Materials

Graphite flakes were purchased from Sigma-Aldrich. Hydrogen peroxide ( $\text{H}_2\text{O}_2$ , 35%), sulfuric acid ( $\text{H}_2\text{SO}_4$ , 95%–98%), phosphoric acid ( $\text{H}_3\text{PO}_4$ ), potassium permanganate ( $\text{KMnO}_4$ ), boric acid ( $\text{H}_3\text{BO}_3$ ), and hydrochloric acid ( $\text{HCl}$ , 37%) were purchased from Merck. L-ascorbic acid was procured from Carlo Erba. All chemicals were of analytical reagent grade and used without further purification. Distilled water was used throughout the experiments. Polyester needle-punched nonwoven fabric with a mass per unit area of  $150 \text{ g/m}^2$  was kindly provided by Hassan Textile, Türkiye.

### 2.2 Synthesis of Graphene Oxide

Graphene oxide was synthesized using the improved Hummers' method using flake graphite. Briefly, 360:40 mL of a mixture of  $\text{H}_2\text{SO}_4$  and  $\text{H}_3\text{PO}_4$  was placed into a flask, to which 3g of graphite flakes were added. The flask was gradually filled with 18g of  $\text{KMnO}_4$ . Following the full dissolution of the  $\text{KMnO}_4$ , the reaction was placed in an oil bath, heated to  $50^\circ\text{C}$ , and stirred for 12 hours. The reaction was then poured onto 400 mL of ice after being cooled to room temperature. 6 mL of 35%  $\text{H}_2\text{O}_2$  was added to terminate the reaction. The suspension was purified using ethanol (2 $\times$ ) and 1 M  $\text{HCl}$  by centrifugation. After washing, the centrifugation process was maintained until a pH of 4–5 was reached. The resulting sample was dried at  $60^\circ\text{C}$  to obtain solid GO nanosheets.

### 2.3 Boric Acid Functionalization of Graphene Oxide and Preparation of Coating Dispersions and Paste

The as-prepared GO was used for the preparation of boric acid (BA) functionalization, coating dispersions, and pastes. For the dip-coating process, 2 g/L aqueous dispersion of GO was prepared using the bath sonication method. The boric acid functionalized GO (BAGO) dispersion for dip-coating was obtained by adding 5g of BA powder to the 2 g/L GO dispersion and bath-sonicated for 60 min at ambient conditions, followed by magnetic stirring for about 60 min to obtain a homogeneous dispersion.

The blade coating pastes were prepared using GO nanosheets and distilled water, with a concentration of 20 g/L without adding any auxiliary chemicals. The boric acid functionalized GO coating paste was prepared with the same concentration by increasing the boric acid amount at the same rate as used for the GO dip coating dispersion. The mixtures were first bath sonicated and then magnetically stirred for about 60 min. After the viscosity increase was observed due to the swelling of GO nanosheets, mechanical stirring was applied to obtain a homogenous and well-dispersed coating paste.

### 2.4 GO Coatings of Polyester Nonwoven Fabric

The polyester needlepunched nonwoven fabric (NW) was coated with GO and BAGO with a subsequent coating and reduction process. The dip-coating process was first applied to the polyester nonwoven fabric at ambient conditions for 10 min, and then the fabric was dried in an oven at  $70^\circ\text{C}$ . The dip-coating process was repeated five times to increase the coating amount. After the dip-coating process, the GO and BAGO-coated nonwoven fabrics were coded as D-GO-NW and D-BAGO-NW, respectively. The reduction of GO was performed with L-ascorbic acid as a reducing agent. The D-GO-NW and D-BAGO-NW samples were treated with the 0.1 M aqueous L-ascorbic acid solution at  $95^\circ\text{C}$  for 60 min. Then, the reduced samples were rinsed with distilled water to remove the remaining materials, followed by drying at  $90^\circ\text{C}$  in an oven for 90 min. After the reduction process, the D-GO-NW and D-BAGO-NW samples were coded as D-RGO-NW and D-BARGO-NW, respectively. GO and BAGO coating pastes were applied to the dip-coated nonwoven fabric using a laboratory-type coating machine (Ataç-GK40 RKL). The GO paste was applied to the D-RGO-NW sample, whereas the BAGO paste was applied to the D-BARGO-NW sample. The coating parameters were determined as: blade-fabric distance was 0.30, coating speed was 2 m/min, and the samples were fixed at  $190^\circ\text{C}$  for 220 sec. Each side of the nonwoven fabric was coated twice. After the blade coating process, the reduction process was applied with the same procedure as was done after the dip-coating process. The resulting samples were coded as B-RGO-NW and B-BARGO-NW.

### 2.5 Characterization

Scanning electron microscopy (SEM-EDX, JEOL JSM-7100-F) was employed to observe the morphology of uncoated and coated samples. The surfaces of the samples were coated with Au/Pd before analysis. The

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elemental analysis was examined using an energy-dispersive X-ray spectroscopy (EDX). Using an attenuated total reflection Fourier transform infrared spectrometer (ATR-FTIR, Perkin Elmer Spectrum 100), the chemical composition of nonwoven fabric samples was determined. The electrical resistance of the nonwoven fabric samples was determined using a four-point probe technique. The configuration comprises a sourcemeter (Keithley 2450) and a four-point probe station (Everbeing International Corp.). The heating performance of samples was investigated with applying a DC voltage (Textronix PWS4305 30V, 5A power supply) varied from 0-20 V (in intervals of 5 V) for 60 s through the samples prepared as a 2.5×2 cm. An infrared camera (Testo 868) was used to visualize and to record the surface temperature of samples.

### 3. RESULTS

#### 3.1 SEM-EDS Analysis

Figure 1 and Table 1 present the surface morphology and elemental analysis results of polyester nonwoven fabric samples, respectively. Polyester fibers exhibit smooth, uniform, and defect-free surfaces (Figure 1a). The dip-coating process effectively facilitated the deposition of GO nanosheets onto the nonwoven fabric surface. The wrinkled and wavy structure of GO nanosheets can be observed between the polyester fibers, wrapping around the fibers (Figure 1b). The boric acid-functionalized GO dip-coated nonwoven fabric exhibits a fragmented BAGO nanosheet structure (Figure 1c). The boric acid functionalization of GO was confirmed by the presence of B at a percentage of 15.4%. The surface of the GO-blade-coated nonwoven fabric sample after the reduction process was entirely covered by RGO nanosheets, indicating a large-area and uniform film coating of RGO (Figure 1d). In the case of the BARGO sample after the reduction process, the coated layer exhibited a fragmented nanosheet structure with partial areal disappearance (Figure 1e). The elemental analysis of the sample indicates C, O, and B percentages of 74.1%, 17.3%, and 8.6%, respectively.

**Table 1.** Elemental analysis results of samples.

|                   | <b>C</b><br>(%) | <b>O</b><br>(%) | <b>B</b><br>(%) |
|-------------------|-----------------|-----------------|-----------------|
| <b>NW</b>         | 80.4            | 19.6            | -               |
| <b>D-GO-NW</b>    | 68.5            | 31.5            | -               |
| <b>D-BAGO-NW</b>  | 62.0            | 22.6            | 15.4            |
| <b>B-RGO-NW</b>   | 79.3            | 20.7            | -               |
| <b>B-BARGO-NW</b> | 74.1            | 17.3            | 8.6             |

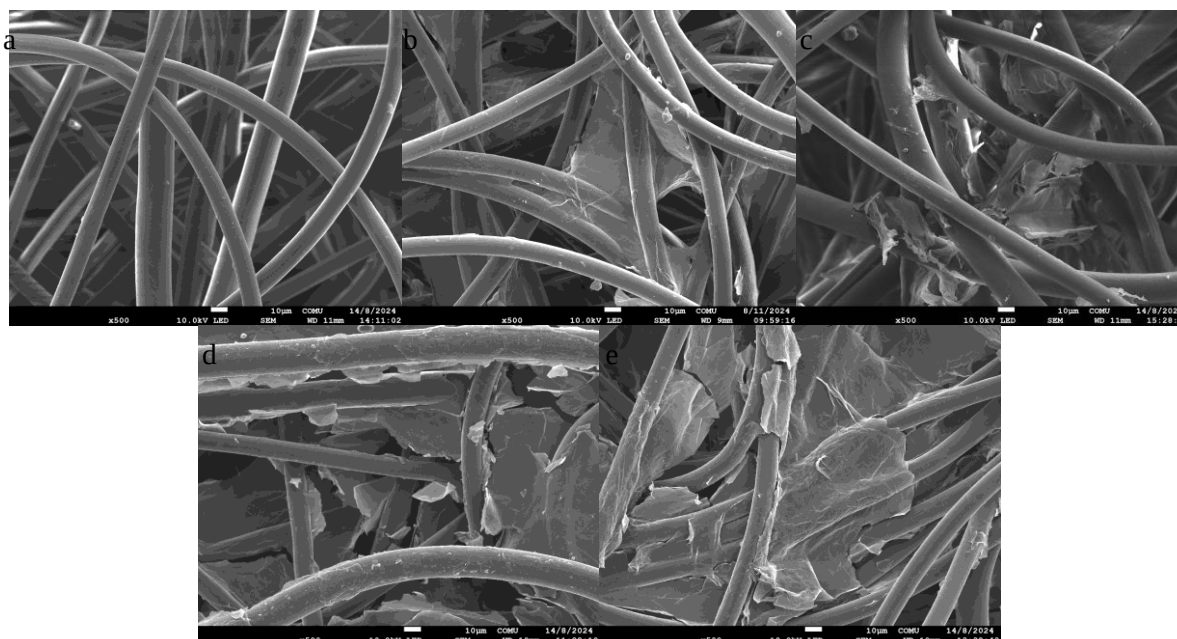


**Figure 1.** SEM images of NW(a), D-GO-NW(b), D-BAGO-NW(c), B-RGO-NW(d), and B-BARGO-NW(e).

### 3.2 FTIR Spectroscopy

The chemical characterization of polyester nonwoven fabric and coated samples was investigated by FTIR. Figure 2 represents the FTIR spectra of NW, D-GO-NW, D-BAGO-NW, B-RGO-NW, and B-BARGO-NW samples. The characteristic bands of polyester nonwoven fabric were shown at around 969, 1016, 1094, 1235, and 1712  $\text{cm}^{-1}$ , which correspond to the C-O stretching of glycol, benzene in-plane vibrations, ester C=O stretching vibration, and the C=O group of aromatic ester, respectively [12]. The peaks at 1408, 1339, 722 and 871  $\text{cm}^{-1}$  were assigned to bending and wagging vibrational modes of the ethylene glycol segment [13], and C-H bending and hydrogen atoms of the benzene ring, respectively [14]. The FTIR spectrum of the GO dip-coated sample showed a slight change with the appearance of a new peak at 1805  $\text{cm}^{-1}$ , corresponding to the stretching vibration of C=O. The notable changes were observed with the BAGO dip-coated sample. The presence of a broad peak at 3188  $\text{cm}^{-1}$  shows the stretching vibrations of the O-H bond, indicating the formation of strong intermolecular hydrogen bonds between the hydroxyl groups of boric acid and GO. The new peak at 1190  $\text{cm}^{-1}$  can be attributed to the B-C stretching vibrations, which confirms the functionalization of the carbon network with boron [15]. The reduction of GO blade-coated samples was caused to the disappearance of oxygen-containing functional groups. Also, the decrease in the intensity of all bands can prove the blade-coating of RGO.

### 3.3 Electrical Resistance

The square resistance of polyester nonwoven fabric and coated samples was measured. The square resistance results of the samples were given in Table 2. Polyester nonwoven fabric is an electrical insulator in nature, so it does not conduct electricity. The polyester nonwoven fabric has a high level of electrical resistance with  $1.31 \times 10^{11} \Omega/\text{sq}$ . Besides, it is also known that GO cannot conduct electricity due to the oxygen-containing functional groups attached to the surface and edges of the sheets [16]. Therefore, the electrical resistance values of D-GO-NW and D-BAGO-NW were obtained as  $1.38 \times 10^8$  and  $5.44 \times 10^7 \Omega/\text{sq}$ , respectively. The electrical resistance decreased further with blade coating and the subsequent reduction of GO as a result of an increased amount of GO and boric acid-functionalized GO on the nonwoven fabric. The lowest electrical resistance was obtained with the B-BARGO-NW sample as  $78.78 \Omega/\text{sq}$ .

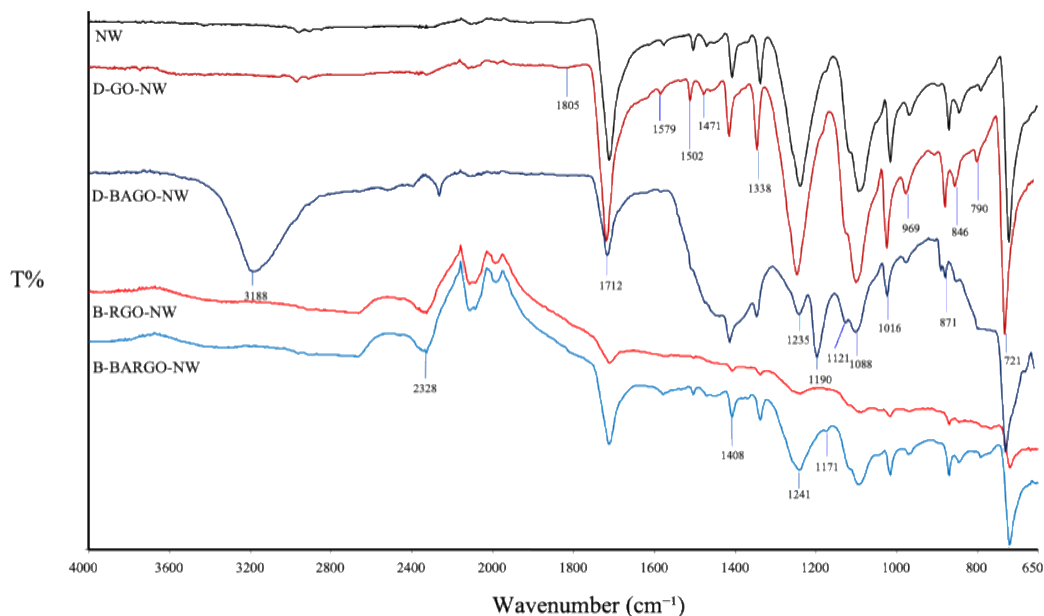


**Figure 2.** FTIR analysis of NW, D-GO-NW, D-BAGO-NW, B-RGO-NW, and B-BARGO-NW samples.



**Table 2.** Electrical resistance of samples.

|            | Electrical resistance<br>( $\Omega/\text{sq}$ ) | Standard<br>Deviation |
|------------|-------------------------------------------------|-----------------------|
| NW         | 1.31E+11                                        | 5.38E+10              |
| D-GO-NW    | 1.38E+8                                         | 2.07E+7               |
| D-BAGO-NW  | 5.44E+7                                         | 1.45E+7               |
| B-RGO-NW   | 85.69                                           | 6.90                  |
| B-BARGO-NW | 78.78                                           | 7.34                  |

### 3.4 Electro-Thermal Heating Performance

The heating behavior of RGO and BARGO blade-coated polyester nonwoven fabrics was analyzed using a DC voltage as a power supply and an infrared thermal camera. The fabric samples were heated by applying 10V and 15V. The thermal camera images were taken after 1 minute of applying voltage. Figure 3 shows the infrared thermal camera images of samples before and after applying a voltage. The surface temperature of the nonwoven fabrics increased immediately with the voltage applied and reached a steady state within 1 minute. Table 3 indicates the maximum and average surface temperatures of blade-coated polyester nonwoven fabric samples at 10V and 15V. The RGO sample showed a surface temperature increase 4.7°C at 10V, while the BARGO sample displayed a much higher temperature increase with 8.7°C. The surface temperature of the samples increased dramatically when the applied voltage was set to 15V. The surface temperature difference was obtained with the B-BARGO-NW sample as 15.1°C, while for the B-RGO-NW sample as 17°C. These results demonstrate that both RGO and BARGO coated nonwoven fabrics exhibit effective electrothermal behavior under applied voltage, with BARGO showing superior heating performance at lower voltage levels.

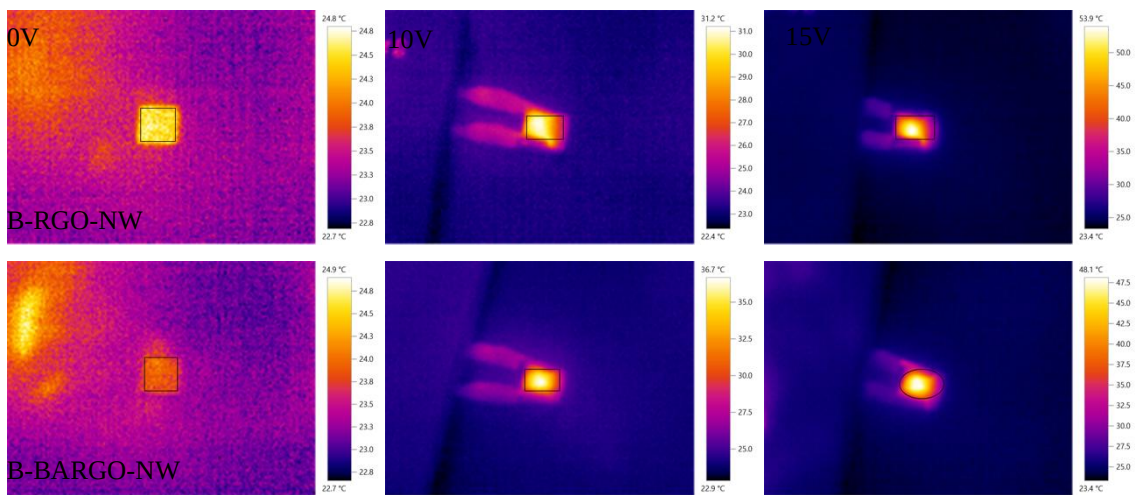


**Figure 3.** Infrared camera images of B-RGO-NW and B-BARGO-NW samples at different applied voltages.

**Table 3.** Heating performance of B-RGO-NW and B-BARGO-NW samples.

|            | 0 V                   |                           | 10 V                  |                           | 15 V                  |                           |
|------------|-----------------------|---------------------------|-----------------------|---------------------------|-----------------------|---------------------------|
|            | T <sub>max</sub> (°C) | T <sub>Average</sub> (°C) | T <sub>max</sub> (°C) | T <sub>Average</sub> (°C) | T <sub>max</sub> (°C) | T <sub>Average</sub> (°C) |
| B-RGO-NW   | 24.8                  | 24.5                      | 31.2                  | 29.2                      | 53.9                  | 41.5                      |
| B-BARGO-NW | 24.2                  | 23.9                      | 36.7                  | 32.6                      | 48.1                  | 39.0                      |

#### 4. CONCLUSION

In this study, the B-doped GO was synthesized by a simple solution process using boric acid. The effect of GO functionalization with boric acid on the properties of dip and blade-coated polyester needlepunched nonwoven fabric was examined. The SEM-EDS and FTIR analyses proved the presence of B on the GO structure, indicating the functionalization process was successfully achieved. The blade-coated and reduced samples showed a dramatic decrease in resistance, indicating an electrically conductive property. Moreover, the improvement in electrical conductivity was further enhanced with the boric acid functionalized GO blade-coated nonwoven fabric. The electro-thermal heating behavior of the blade-coated nonwoven samples showed fast and high heating when applying a 10V.

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## EMPIRICAL ANALYSIS OF THE ACCEPTANCE OF ZERO-WASTE DESIGN AND ITS APPLICATION IN TAILORING OPTIMIZATION

Franka Karin<sup>1,\*</sup>, Blaženka Brlobašić Šajatović<sup>2</sup>, Irena Šabarić Škugor<sup>3</sup>

<sup>1</sup> University of Zagreb Faculty of Textile Technology, Department of Textile and Clothing Design, Zagreb, Croatia

<sup>2</sup> University of Zagreb Faculty of Textile Technology, Department of Clothing Technology, Zagreb, Croatia

<sup>3</sup> University of Zagreb Faculty of Textile Technology, Department of Textile and Clothing Design, Zagreb, Croatia

\* [franka.karin@ttf.unizg.hr](mailto:franka.karin@ttf.unizg.hr)

### ABSTRACT

The paper presents a survey conducted to examine respondents' views on the importance of the zero-waste concept in clothing design and production. The survey included questions on awareness of the textile industry's environmental impact, perceptions of textile waste, and willingness to accept innovative design solutions that reduce intercutting material loss. The results indicate a high level of awareness among respondents regarding environmental issues and strong support for sustainable approaches in fashion design. The data relate to the analysis of the feasibility of implementing the zero-waste concept in clothing construction and design. Special emphasis was placed on integrating parts that would typically represent intercutting loss in traditional tailoring into the garment's design. This approach involves adjusting the cut pattern, creatively designing additional elements (such as details, inserts, applications, or functional accessories), and rationally planning the layout of cut parts. In conclusion, the research confirms that the zero-waste design concept has significant potential to reduce textile waste, with construction and creative design serving as key tools for achieving sustainable and environmentally responsible clothing production.

**Keywords:** *zero-waste, design, textile waste*

### 1. INTRODUCTION

The approach to clothing design that integrates the principles of sustainable development and the zero-waste concept represents a key strategy in the transformation of modern production processes with the aim of preserving the environment and rational management of natural resources. Sustainable fashion is based on environmentally friendly design and optimization of resource consumption, with special attention paid to efficient use of fabric. Striking a balance between economic, social and environmental aspects is essential for the long-term sustainability of the textile and clothing industry. The problem of excessive production and consumption of clothing results in considerable amounts of textile waste that is often inadequately disposed of, which further burdens the environment and emphasizes the need to develop innovative approaches in clothing design. Conventional methods of garment construction and tailoring generate between 15 and 25% waste fabric, while the zero-waste concept involves integrating technical and aesthetic design elements in accordance with dimensions, thus eliminating inter-cutting waste. Such an approach requires thorough consideration of the tailoring process and optimization of the layout of tailoring parts while preserving the aesthetic and functional properties of the garment. Previous research indicates significant progress in increasing the degree of fabric utilization by applying a zero-waste approach to clothing design, but at the same time confirms the existence of technical and production limitations, especially in the context of mass production, where additional competencies and adaptations of production systems are required. Therefore, further research and the development of new methodological solutions remain necessary for the wider implementation of sustainable design based on the zero-waste concept in clothing production [1- 4].

## **2. SUSTAINABLE FASHION AND THE IMPORTANCE OF THE NO-WASTE CONCEPT METHOD IN THE CONSTRUCTION AND MANUFACTURE OF CLOTHING**

Sustainable fashion represents an interdisciplinary approach in clothing production and fashion design that integrates ecological, economic, social and political criteria of sustainable development. It includes the use of environmentally friendly materials, rational use of natural resources, recycling and reuse of textiles to reduce textile waste. Emphasis is placed on product durability through timeless design, which extends the lifespan of clothing and reduces the need for re-production. Given the significant environmental impact of the fashion industry, which includes resource depletion, high water consumption, greenhouse gas emissions and the generation of textile waste, the adoption of circular business models and sustainable production practices is necessary. Although sustainable fashion has become an important segment of contemporary environmental discourse, its implementation faces numerous challenges, especially in the context of fast fashion and consumer habits driven by marketing strategies. Research points to insufficient information among consumers and a limited ability to distinguish sustainable from unsustainable products, whereby an increase in awareness does not necessarily result in a change in consumers. The total fabric utilization in conventional clothing construction methods is expressed as the ratio of the area of the cut parts to the total area of the cut pattern and in industrial practice averages 80–90%, while full utilization is possible only in rare cases with cut parts that have regular geometric shapes. Since inter-cutting loss depends on the optimal combination of construction and segments, various strategies for optimizing the layout of cutting parts are applied. New methods of construction and production of clothing according to the concept of zero waste, resulting from awareness of sustainable development, often achieve fabric utilization of up to 100% due to the pre-thought-out design of the garment consisting of cutting parts of geometric shapes, which achieves maximum fabric utilization or the rest of the fabric that remains after cutting is used for functional or aesthetic components on the same garment [5- 9].

## **3. EXPERIMENTAL STUDY**

The empirical analysis in this paper aims to demonstrate the awareness of designers, constructors and consumers about the importance of accepting and applying methods according to the zero-waste concept according to sustainable development criteria. A survey was conducted to examine the level of information about the concepts of sustainable development in fashion, awareness of the importance of applying sustainable principles in clothing production, and the perception of aesthetic and functional characteristics according to the basic construction of clothing and methods of the zero-waste concept. It was also analyzed whether the methods of the zero-waste concept meet aesthetic criteria, suitability and production, and to what extent it is accepted among the respondents. The questionnaire was conducted via the Google Forms platform on a sample of 131 respondents in the Republic of Croatia aged 18 to 55, including 46 designers, 19 constructors and 66 consumers. Participation was voluntary and anonymous, and the instrument contained 22 multiple-choice questions. The collected data were analyzed using descriptive statistics in the IBM SPSS Statistics program. In this paper, the results for selected questions from the survey questionnaire have been extracted for the purpose of an empirical analysis of the acceptance of methods of the zero-waste concept and their application with the maximum possible utilization of fabric. The questions relate to: the age of the respondents, the group of respondents, the term sustainable fashion, knowledge of methods for making clothes according to the zero-waste concept, an assessment of whether the zero-waste concept is a good method for reducing textile waste that occurs after tailoring clothes, an assessment of consumers whether they would buy clothes made using the zero-waste concept method, an assessment of consumer awareness of clothes made according to sustainable development criteria, and an assessment of whether clothes made according to the zero-waste concept can have an equal or better aesthetic component compared to clothes made according to the basic construction [10].

## 4. RESULTS

### 4.1. Age and group of respondents

Table 1 shows an overview of the three groups of respondents and their age, from which it is evident that the most common age of the respondents is in the range of 35 to 40 years, of which 53.3% are designers, 10.0% are constructors, and 36.7% are consumers [10].

**Table 1.** Age of respondents by respondent groups [10].

| Age          | Designers<br>% | Constructors<br>% | Consumers<br>% | Total<br>% |
|--------------|----------------|-------------------|----------------|------------|
| 18-25        | 55,0           | 5,0               | 40,0           | 100,0      |
| 25-30        | 40,7           | 3,7               | 55,6           | 100,0      |
| 30-35        | 22,2           | 22,2              | 55,6           | 100,0      |
| 35-40        | 55,3           | 10,0              | 36,7           | 100,0      |
| 40-45        | 11,8           | 17,6              | 70,6           | 100,0      |
| 45-50        | 7,7            | 46,2              | 46,2           | 100,0      |
| 50-55        | 16,7           | 16,7              | 66,7           | 100,0      |
| <b>Total</b> | 35,1           | 14,5              | 50,4           | 100,0      |

### 4.2. The term sustainable fashion

Regarding the knowledge of the term sustainable fashion, 83.2% of the total number of respondents responded positively, and 16.8% responded negatively. Table 2 shows the awareness of the term sustainable fashion by groups, which shows that of the total number of respondents, designers were the most familiar with the term, 42.2% [10].

**Table 2.** Understanding the term sustainable fashion [10].

| The term<br>sustainable<br>fashion | Answer<br>"Yes"<br>% | Answer<br>"No"<br>% | Total<br>% |
|------------------------------------|----------------------|---------------------|------------|
| Designers                          | 42,2                 | 0,0                 | 35,1       |
| Constructors                       | 16,5                 | 4,5                 | 14,15      |
| Consumers                          | 41,3                 | 95,5                | 50,4       |
| <b>Total</b>                       | 100,0                | 100,0               | 100,0      |

### 4.3. Awareness of the design and production of clothing according to the zero-waste concept

About the knowledge of the process of designing and making clothes according to the zero-waste concept, 79.4% of the total number of respondents answered with a positive answer, and 20.6% with a negative answer. Table 3 shows the knowledge of the method of designing and making clothes according to the no-waste concept, from which it is evident that out of the total number of respondents, most designers are familiar with this method, 41.3% [10].

**Table 3.** Knowledge of the method of making clothes according to the zero-waste concept [10].

| Zero waste<br>concept | Answer<br>"Yes"<br>% | Answer<br>"No"<br>% | Total<br>% |
|-----------------------|----------------------|---------------------|------------|
| Designers             | 41,3                 | 11,1                | 35,1       |
| Constructors          | 16,3                 | 7,4                 | 14,15      |
| Consumers             | 42,3                 | 81,5                | 50,4       |
| <b>Total</b>          | 100,0                | 100,0               | 100,0      |



#### 4.4. The no-waste concept as a good method for reducing textile waste

Respondents were given the option of an affirmative or negative answer, whether they consider the no-waste concept a good method for reducing textile waste generated after tailoring clothes. Out of the total number of respondents, 97.7% responded with an affirmative answer, and 2.3% with a negative answer. Table 4 shows the opinion of respondents according to groups, from which it is evident that consumers gave the most positive answers, 50.0% [10].

**Table 4.** Evaluating the zero-waste concept as a good method for reducing textile waste generated after clothing tailoring [10].

| Zero waste method assessment | Answer “Yes” % | Answer “No” % | Total % |
|------------------------------|----------------|---------------|---------|
| Designers                    | 35,9           | 0,0           | 35,1    |
| Constructors                 | 14,1           | 33,3          | 14,15   |
| Consumers                    | 50,0           | 66,7          | 50,4    |
| Total                        | 100,00         | 100,00        | 100,00  |

#### 4.5. Buying clothes made according to the zero-waste concept

Respondents were given the opportunity to answer affirmatively or negatively whether they would buy clothes made using the zero-waste concept method. Of the total number of respondents, 92.4% answered affirmatively, and 6.9% answered negatively. Table 5 shows the opinions of the respondents by group, from which it is evident that consumers responded most positively, 49.6% [10].

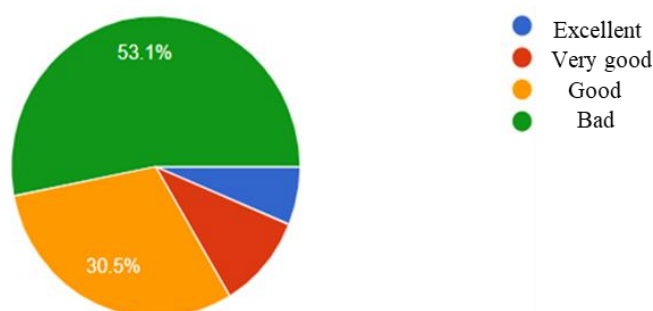
**Table 5.** Respondents' willingness to purchase clothing made according to the zero-waste concept [10].

| Buying zero waste clothes | Answer “Yes” % | Answer “No” % | Total  |
|---------------------------|----------------|---------------|--------|
| Designers                 | 35,5           | 33,3          | 35,1   |
| Constructors              | 14,9           | 0,0           | 14,15  |
| Consumers                 | 49,6           | 66,7          | 50,4   |
| Total                     | 100,00         | 100,00        | 100,00 |

#### 4.6. Consumer awareness of sustainable clothing production

A graphic representation of the most common response from the total number of respondents is shown in Chart 1, which shows that 53.1% of respondents rate consumer awareness of clothing made according to sustainable development criteria as poor, with the following answers offered: excellent, very good, good or poor [10].

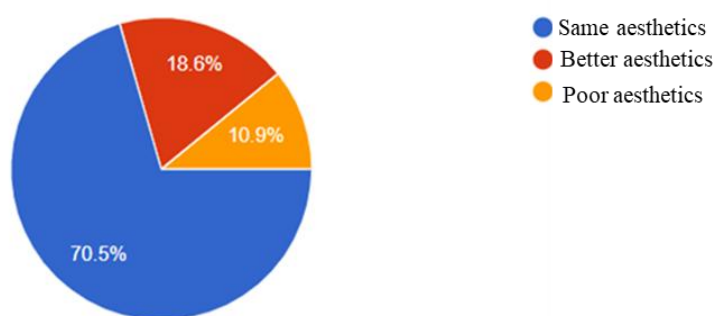
**Chart 1.** Assessment of consumer awareness of clothing made according to sustainable development criteria [10].



#### **4.7. Evaluation of the aesthetic component of women's clothing modeled according to the basic construction of the garment and the zero-waste concept**

Respondents were given the opportunity to answer whether they believe that clothing made according to the zero-waste concept can have an equal or better aesthetic component compared to clothing modeled according to the basic construction. A graphical representation of the most common answer from the total number of respondents is shown in Chart 2, which shows that 70.5% of respondents believe that clothing made according to the zero-waste concept can have an equal aesthetic component compared to clothing modeled according to the basic construction, from the offered answers: equal aesthetic component, better aesthetic component, worse aesthetic component [10].

**Chart 2.** The aesthetic component of clothing made according to the zero-waste concept compared to clothing modeled according to the basic construction [10].



## **5. CONCLUSION**

A subjective evaluation was carried out for three groups of respondents: designers, constructors and consumers in order to establish whether zero waste methods are an acceptable solution for the design, construction, modeling and production of clothing according to the basic principles of sustainable development. Of the total number of respondents, 97.7% consider the zero-waste concept to be a good solution for reducing textile waste, and 53.4% believe that the fashion industry would be willing to accept the zero-waste concept as a new direction for clothing production. Of the total number of respondents, 92.4% are willing to buy clothes according to the zero-waste concept, and 76.7% believe that clothes made according to the zero-waste concept can have an equally good fit as clothes made according to the basic construction. The majority of respondents consider the fit of clothing according to zero waste methods to be excellent, 83.2% believe that zero waste methods could be well accepted by the fashion industry, and 90.1% of respondents believe that they could be accepted by consumers, of which consumers are 50.4%. The conducted research showed good results of the acceptance of zero waste methods in the context of sustainable development in the field of clothing design and construction as a good foundation for further research. The results of the questionnaire also show good results on the knowledge of sustainable development criteria and methods of making clothes according to the zero waste concept, as well as good awareness among all three groups of respondents about the benefits of sustainable development for the environment and the reduction of textile waste that occurs after tailoring clothes using basic clothing construction. The results of the research confirm that both the fit and aesthetic criteria are equally good for clothes made using basic construction and zero waste methods, which were subjectively evaluated by the respondents, and the possibility of accepting zero waste methods by the fashion industry and consumers is confirmed, which satisfies the aesthetic criteria, fit and production possibilities.

## **ACKNOWLEDGMENT**

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## EVALUATION OF THE RELATIONSHIP BETWEEN HUMAN PERCEPTION OF WOVEN FABRIC ROUGHNESS AND OBJECTIVE MEASUREMENTS USING THE FABRIC TOUCH TESTER

Rebeka Solomun<sup>1</sup>, Snježana Brnada\*<sup>1</sup>, Ana Palčić<sup>2</sup>, Ana Kalazić<sup>1</sup>, Sandra Flinčec Grgac<sup>2</sup>

<sup>1</sup> University of Zagreb Faculty of Textile Technology, Department of Textile Design and Management, Zagreb, Croatia

<sup>2</sup> University of Zagreb Faculty of Textile Technology, Department of Textile Chemistry and Ecology, Zagreb, Croatia

\* [sbrnada@ttf.unizg.hr](mailto:sbrnada@ttf.unizg.hr)

### ABSTRACT

Surface roughness of fabrics represents a key factor influencing product quality, tactile comfort, and durability. The aim of this study was to quantify fabric roughness through objective measurements and to evaluate subjective tactile perception among users. Seven fabric samples were woven from identical cotton yarns, differing in weave type and density. Objective measurements of surface roughness were conducted using the Fabric Touch Tester (FTT), analyzing the profile in both warp and weft directions. Subjective assessments were performed on a group of 30 participants, whose tactile sensitivity was categorized using the Two-Point Discrimination (2PD) test. The results revealed noticeable differences between objectively measured and perceived roughness values, indicating that tactile perception is influenced by some additional surface characteristics. The findings contribute to a more comprehensive understanding of the relationship between fabric structure and tactile perception, providing a basis for the design of fabrics with improved comfort and functional quality.

**Keywords:** *weave, surface roughness, Fabric Touch Tester (FTT), tactile perception*

### 1. INTRODUCTION

The surface roughness of woven fabrics is crucial for textile quality and use, as it affects tactile perception, friction, wear, and durability. In the clothing industry, roughness influences both the subjective comfort and the functional properties of fabrics. Objective assessment enables control of the manufacturing process and ensures the quality of finished products. Surface roughness depends on the weave type, fabric density, yarn properties etc. [1-3]. However, a general challenge lies in matching objective evaluations with the subjective perception of fabric roughness, and the aim of this research is to explore this relationship further.

The aim of this research was to examine the relationship between fabric structural parameters and their roughness by comparing objective measurements and participants' subjective tactile perception. Objective analysis was performed using the Fabric touch tester (FTT), while subjective perception of roughness was evaluated through roughness assessment by having the participants touch the fabric front side along the warp direction. Performance of 2PD test, allowed categorization of participants' sensitivity.

### 2. EXPERIMENTAL STUDY

#### 2.1 Materials and Methods

For the purpose of this research, seven fabric samples were woven on a weaving loom using 100% cotton single yarn with a fineness of 36 tex and a twist level of 505 tpm. After weaving, the fabrics were subjected to washing and drying processes to stabilize their structure. The fabrics were woven in different weave structures and varying densities. The GSM ranged from 150 to 185 g/m<sup>2</sup>.

**Table 1.** Testing samples

| Weave Type | DESIGNATION | EPC/PPC |
|------------|-------------|---------|
| PLAIN      | P1/1        | 24/24   |
| BASKET     | Pa2/2       | 22/22   |
| RIB        | R1/1(2+2)   | 22/20   |
| TWILL      | K1/3S       | 18/18   |
| TWILL      | K2/2S       | 20/20   |
| SATIN      | A1/4(2)_20  | 20/22   |
| SATIN      | A1/4(2)_24  | 22/24   |

### 2.1.1. Measurement using the FTT Device

The Fabric Touch Tester was used to quantitatively assess the surface properties of the woven samples, with special attention to the roughness. The measurements were performed under controlled conditions (RH  $65 \pm 2\%$ , T  $20 \pm 2^\circ\text{C}$ ).

The FTT testing produced a set of raw data that was subsequently processed in the statistical software to generate roughness profiles and calculate corresponding statistical variables. Since the FTT does not record roughness data at the beginning and end of the measurement, data in the range of 0–30 mm and above 49 mm were excluded. The remaining data were sorted according to the segment length with a step of 0.05 mm and subjected to statistical analysis. For each sample, the arithmetic mean of measurements was calculated, forming the basis for defining the primary roughness profile in the warp and weft directions, as well as at angles of  $45^\circ$  and  $135^\circ$ .

### 2.1.2. Measurement using the FTT Device

In addition to objective measurements performed with the Fabric Touch Tester, a subjective evaluation of fabric roughness was conducted with a group of 30 participants aged 20 to 59, of both genders. Prior to the subjective evaluation, participants underwent the Two-Point Discrimination (2PD) test to determine individual levels of tactile sensitivity. This method, most commonly used in the medical field, was applied in this study to categorize participants according to the sensibility of their tactile perception.

A custom-made tool with tip distances ranging from 1 to 7 mm (Figure 1) was used, and the measurement was performed using the dynamic method on the fingertips of the dominant hand, where the concentration of nerve endings is the highest. Based on the 2PD test results, participants were classified into corresponding categories of tactile sensitivity according to the defined scale.

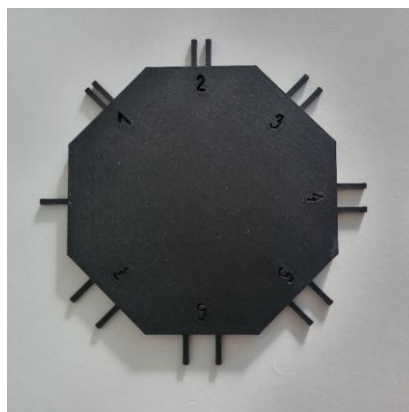


**Figure 1.** Two-point discrimination tool



For each participant, a table was created containing specific questions related to the perception of roughness among different fabric samples. The participants were presented with pairs of samples and asked to determine which one felt rougher; however, they were also allowed to express indecision if they could not perceive a difference. The assessment was conducted solely through tactile exploration using the participants' index finger, following the Two-point method. The finger moved randomly across the fabric surface, ensuring that movements were made in multiple directions to allow roughness evaluation in all directions. For analysis purposes, the mean values of roughness obtained from all directions were combined into a single representative roughness value. This approach enabled a comparative analysis of objective and subjective data, providing a basis for establishing a statistically relevant correlation between participants' tactile perceptions and the objectively measured fabric roughness.

### 3. RESULTS

The standard profile roughness parameters analyzed were arithmetic mean deviation (Ra), root mean square deviation (Rq), skewness (Rsk), and kurtosis (Rku).

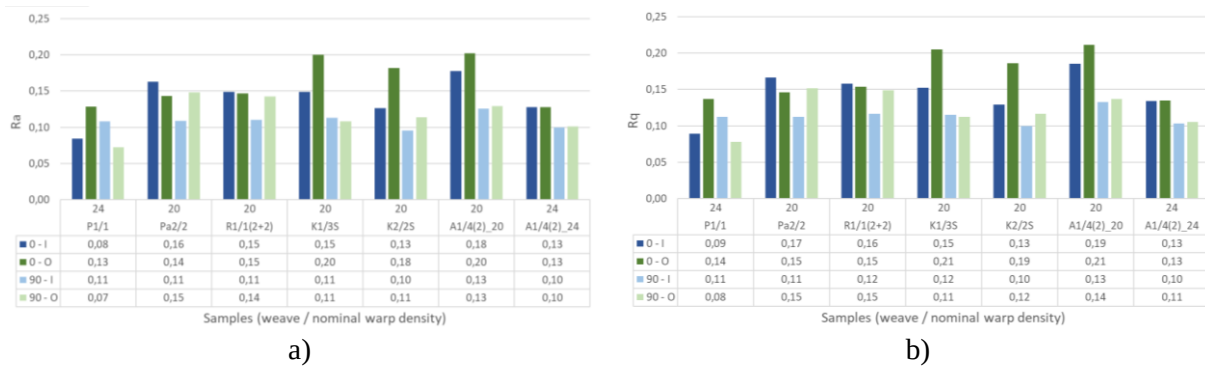


**Figure 2.** Surface roughness parameters

The results in Fig. 2a and 2b show that the fabric in plain weave (P1/1) has the lowest value of arithmetic mean deviation (Ra), which is a consequence of higher fabric density, reduced floating, and greater surface compactness. Conversely, the samples in satin and basket weaves exhibited the highest roughness values due to greater surface waviness and larger spacing between yarns. In most samples, roughness was more pronounced in the warp direction, while the fabric front side generally showed higher Ra and Rq values than the back side, which can be explained by the mechanical stresses on the yarns during the weaving process.

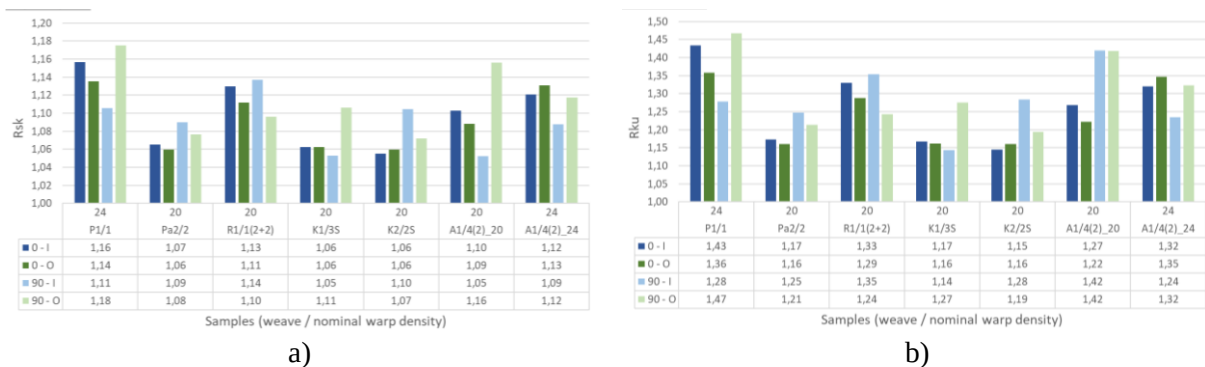


**Figure 3.** Surface morphology parameters

The profile skewness (Rsk) values (Fig. 3a) were positive for all samples, indicating the predominance of peaks. The plain weave showed the highest Rsk value due to more pronounced protrusions and a greater number of interlacings. The kurtosis (Rku) values (Fig 3b) are below 3 for all samples, suggesting that the surfaces did not have sharp peaks or deep valleys. Among the fabrics, the plain weave sample has the highest Rku value, while the twill and basket weave samples exhibited more uniform surfaces. In general, both profile morphology parameters (Rsk and Rku) showed a strong correlation with fabric density, while

differences between the front and back sides of the samples, as well as between warp and weft directions, were not consistent.

Table 2 presents the ranking of fabric samples according to the subjective evaluations of participants who compared each sample with all others, where rank 1 is the roughest sample and rank 7 is the smoothest.

**Table 2.** Ranking of participants subjective evaluations of woven samples surface roughness

| Samples    | Average Rank | Rank 2PD=0 | Rank 2PD=1 | Rank 2PD=2 | Rank 2PD=3 | Rank R <sub>q</sub> | Rank R <sub>ku</sub> | Rank R <sub>sk</sub> |
|------------|--------------|------------|------------|------------|------------|---------------------|----------------------|----------------------|
| P1/1       | 2            | 3          | 3          | 2          | 4          | 7                   | 1                    | 1                    |
| R1/1(2+2)  | 1            | 1          | 1          | 1          | 1          | 4                   | 2                    | 2                    |
| Pa2/2      | 3            | 2          | 2          | 3          | 5          | 1                   | 7                    | 7                    |
| A1/4(2)_20 | 5            | 4          | 4          | 5          | 2          | 2                   | 5                    | 5                    |
| A1/4(2)_24 | 6            | 3          | 5          | 6          | 6          | 6                   | 3                    | 3                    |
| K1/3S      | 4            | 3          | 4          | 4          | 3          | 3                   | 6                    | 6                    |
| K2/2S      | 7            | 4          | 6          | 7          | 7          | 5                   | 4                    | 4                    |

Based on these comparisons, each participant created a ranking list in which the roughest sample was assigned rank 1, and smoother samples received progressively higher ranks. Cumulative ranks enabled the calculation of the average subjective roughness for each sample (second column).

Participants were divided into four categories of tactile sensitivity measured by 2PD test (0–3), and mean values were calculated for each group to analyze correlations with objective roughness parameters. Due to a single participant in the 2PD = 0 category, their perception was excluded from further analysis. The subjective comparison was performed by randomly moving the hand over the surface, while the objective surface profile parameters (R<sub>q</sub>, R<sub>ku</sub>, R<sub>sk</sub>) were calculated based on measurements in both directions. The last three columns of the table show the ranks of the objective parameters, allowing for detailed comparison with subjective assessments and preparation of data for statistical analysis of their agreement.

The average ranks of perceived fabric roughness were compared with the objectively measured roughness values using Spearman’s rank correlation coefficient ( $\rho$ ). The Spearman correlation coefficient, or rank correlation, is calculated when one of the data sets follows an ordinal scale or when the data distribution significantly deviates from normality, including the presence of notable outliers. The strength of the relationship, represented by the Spearman coefficient, is shown in the table 3.

**Table 3.** Strength of the Relationship Between Variables Based on Spearman’s Correlation Coefficient

| Absolute Value of the Correlation Coefficient | Strength of the Relationship Between Variables |
|-----------------------------------------------|------------------------------------------------|
| $ r  = 1$                                     | Perfect correlation                            |
| $0,8 \leq  r  < 1$                            | Strong correlation                             |
| $0,5 \leq  r  < 0,8$                          | Moderate correlation                           |
| $0,2 \leq  r  < 0,5$                          | Relatively weak correlation                    |
| $0 <  r  < 0,2$                               | Negligible correlation                         |
| $ r  = 0$                                     | No correlation                                 |

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**Table 4** Spearman’s Rank Correlation Coefficient Between Subjective and Objective Ratings by 2PD Category (Absolute Values)

| Roughness Parameters | RQ   | RSK  | RKU  |
|----------------------|------|------|------|
| All Participants     | 0,08 | 0,29 | 0,29 |
| 2PD = 1              | 0,42 | 0,23 | 0,23 |
| 2PD = 2              | 0,08 | 0,29 | 0,29 |
| 2PD = 3              | 0,33 | 0,11 | 0,11 |

Table 4 presents the results of the statistical analysis illustrating the degree of correlation between subjective and objective roughness ratings, classified according to participants’ tactile sensitivity categories (2PD). The analysis shows that none of the objective roughness parameters reaches a moderate or higher level of correlation in any participant category. In the 2PD = 1 category, a relatively weak correlation is observed, while in less tactile-sensitive participants, the same parameters show correlations within the negligible range.

These results indicate a relatively weak relationship between subjective and objective measurements of fabric roughness. Achieving higher agreement would require including additional fabric characteristics that may influence roughness perception, such as the coefficient of friction, hardness etc. The lack of alignment between objective measurements and subjective perception can partly be attributed to the fact that the differences in texture among the tested samples were too subtle for reliable detection by human tactile perception.

#### 4. CONCLUSION

The comparison between objective measurements and subjective evaluations of fabric roughness revealed a low level of agreement between the two approaches. Although the Fabric Touch Tester (FTT) successfully quantified variations in roughness caused by different weave types and densities, participants were not consistently able to perceive these differences through touch. This suggests that human tactile perception of roughness is not determined solely by surface topography but is also influenced by other physical parameters such as surface friction, compressibility, and yarn stiffness. Statistical analysis using Spearman’s rank correlation confirmed a relatively weak relationship between subjective and objective assessments, particularly among participants with lower tactile sensitivity (higher 2PD values). Morphological roughness parameters (Rsk and Rku) showed slightly stronger correlations with perceived roughness than the arithmetic and quadratic mean deviations (Ra and Rq), indicating that profile asymmetry and curvature may contribute more strongly to tactile perception.

The originality of this study lies in its integrative approach, combining objective surface characterization with psychophysical testing of human tactile sensitivity. The results highlight the limitations of current tactile assessment methods and emphasize the need for standardized testing protocols that control factors such as hand movement speed, applied pressure, and contact duration. Future research should expand the analysis to include additional surface and mechanical parameters such as friction coefficient and fabric stiffness, to establish a more accurate predictive model of fabric tactile comfort.

These findings contribute to the understanding of how physical fabric parameters influence human tactile perception and provide valuable insights for the development of high-comfort textile materials.

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## EXPLORING THE POTENTIAL OF AUXETIC KNITTED FABRICS FOR VARIOUS APPLICATIONS

Ioana-Otilia Rusu\*, Mihaela Perdevară, Cristina Grosu, Andreea Plăcintă, Mirela Blaga

"Gheorghe Asachi" Technical University from Iasi, Faculty of Industrial Design and Business Management, 67 Prof. D. Mangeron Blvd. 700050, Iasi, Romania

\* [ioana-otilia.rusu@student.tuiasi.ro](mailto:ioana-otilia.rusu@student.tuiasi.ro)

### ABSTRACT

Auxetic materials exhibit a distinctive behaviour: they expand laterally when stretched and contract laterally when compressed, characterised by a negative Poisson's ratio (NPR). Flat weft knitting technology offers a simple yet highly effective method for producing auxetic fabrics from conventional yarns. These fabrics are typically produced in a single stage on the knitting machine, without subsequent operations, thus minimising production time and energy consumption, and providing a resource-efficient manufacturing model. The three-dimensional geometry of links-links knitted structures allows deformation through the opening of the folded structure. More tightly folded fabrics can produce a smaller opening angle and, consequently, higher NPR values. Interest in these materials arises from the fact that auxetic fabrics can be used in areas such as functional clothing, sportswear, medical care, packaging, and sound and shock absorption. They adapt to the body, making them suitable for pregnant women or people with weight concerns, as there is no need to discard clothing after childbirth or completing a weight loss process.

An experimental study was conducted to produce foldable links-links knitted structures on a Stoll CMS 502HP E 2.5.2 knitting machine, using acrylic and cashmere yarns, with three stitch densities and varying repeating ratios. The fabrics were constructed by combining front and reverse loops arranged in a zigzag pattern with repeating unit ratios of  $4 \times 4$ ,  $6 \times 6$ , and  $8 \times 8$ . Auxetic behaviour was evaluated by measuring dimensional changes during stretching and calculating Poisson's ratio. The results indicate that both yarn properties and the size of the repeating unit cell significantly affect the folding ability of knitted structures. Stitch length is particularly important: generally, reducing stitch length produces tighter fabrics that better retain their shape, resulting in more negative Poisson's ratio values. At the same stitch lengths and knitted patterns, fabrics made from acrylic yarns show more negative Poisson's ratios than those made from cashmere, owing to their higher elasticity and greater capacity to accommodate auxetic deformation. Among the repeating ratios studied, fabrics with a  $6 \times 6$  unit cell exhibited the greatest lateral expansion, providing sufficient space for loop rotation while maintaining adequate structural integrity to achieve significant auxetic behaviour.

**Keywords:** *auxetic, negative Poisson's ratio, weft knitted fabrics.*

### 1. INTRODUCTION

Auxetic materials exhibit a negative Poisson's ratio (NPR), meaning they expand laterally when stretched and contract laterally when compressed [1]. This behaviour improves the material's mechanical properties, such as increased fracture toughness, shear modulus, indentation resistance, and energy absorption [2]. Due to this enhanced range of characteristics, auxetic materials can be used in various fields, including medicine, civil engineering, the textile industry, composites, and the automotive industry [3].

These materials can be classified into two groups: natural and man-made. The first category includes biological substances (salamander skin, sponge bone of human tibia) and mineral-origin substances (iron pyrites, silicates, zeolites), while the second category includes auxetic polymers, composites, textiles (fibres, yarns, fabrics), and foams [3,4]. To produce man-made auxetic materials, one of the following fabrication methods must be used: additive manufacturing (3D printing), thermomechanical processing, or fabrication technologies specific to the textile industry. In recent years, there has been great interest in producing auxetic materials using technologies specific to the textile industry, including auxetic fibres and



polymers, yarns, and fabrics [5]. Auxetic fabrics can be produced using various textile technologies such as weaving, warp knitting, weft knitting, and nonwoven methods, either by using auxetic yarns as raw materials or by employing conventional yarns and patterns with different auxetic geometries [6,7].

Among these technologies, flat knitting stands out as one of the most adaptable methods, offering exceptional versatility and enabling the production of a wide range of designs and structures [3, 5]. Furthermore, this technology is more sustainable, as fabrics are produced in a single stage on the knitting machine, eliminating the need for additional operations, reducing production time and energy consumption, and providing a resource-efficient manufacturing model.

Weft knitted fabrics with a negative Poisson's ratio are classified into three structures: foldable structures, re-entrant hexagonal, and rotating rectangles [8]. Various studies have examined auxetic weft knitted fabrics and the effect of different parameters on their auxetic behaviour [9,10]. Steffens et al. [10] produced weft-knitted auxetic fabrics based on foldable structures, and their results showed that increasing the loop length improves auxetic behaviour. In addition, Xu et al. [11] designed three types of auxetic weft-knitted fabrics based on rotational, foldable and double-headed arrow auxetic geometries, with different loop lengths. The experiment showed that all three knitted fabrics exhibited an auxetic effect. Blaga et al. produced weft-knitted samples with auxetic potential based on zigzag structures, using two different yarns for all designs, with the aim of evaluating the compressibility of these structures for various applications [12]. Aghazadeh et al. developed weft-knitted auxetic materials with a horizontal zigzag structure, using polyester yarns of different counts. The results indicated that a smaller initial opening angle improved auxetic behaviour in the course direction, while a larger initial opening angle enhanced auxetic behaviour in the wale direction [4]. Regarding yarn type and pattern, Boakey et al. created arrow-headed auxetic tubular fabrics with varying numbers of face and reverse loops, using three types of yarns (nylon, PES and cotton) as raw materials [13]. Owing to their unique properties and low production costs, auxetic knitted materials have a wide range of applications, including smart bandages, synthetic orthopedic tape, tissue engineering scaffolds, agricultural products and defense industry uses [4,5,14].

## **2. EXPERIMENTAL STUDY**

### **2.1. Materials**

Weft knitted fabrics were designed using M1Plus® software and produced on a Stoll CMS 502 HP E 2.5.2 automatic flat knitting machine. The materials were constructed by combining front and reverse loops arranged in a zigzag pattern with repeating unit ratios of  $4 \times 4$ ,  $6 \times 6$ , and  $8 \times 8$ . For each fabric made with acrylic and cashmere yarns, the cam setting for the front and reverse loop length was adjusted on the knitting machine to 10, 11, and 12. For fabrics made with cashmere yarns, the cam setting used was the same for all samples (NP 11), while the pattern structure varied. After knitting, the fabrics tend to curl and form a three-dimensional shape due to the interaction between the face and reverse loops. All samples were produced under constant machine conditions, knitting speed, and main take-down load.

### **2.2. Poisson's ratio calculation**

Before deformation measurements and to eliminate residual stresses induced during knitting, all specimens were conditioned for 48 hours in a relaxed state on a flat, non-restrictive surface. Conditioning was carried out under standard atmospheric conditions of  $20 \pm 1$  °C and 60–65% relative humidity, in accordance with conventional textile testing protocols to ensure equilibrium moisture content and dimensional stabilisation. The negative Poisson's ratio (NPR) behaviour was evaluated using a FRYMA Dual Extensometer, following the procedure described in BS 4294:1968. Rectangular specimens were cut to dimensions of  $75 \times 85$  mm and marked to ensure consistent gauge length definition. Each sample was mounted in the extensometer by clamping both ends, with careful alignment along the wale direction to avoid misalignment-induced shear effects. The specimens were then subjected to uniaxial tensile deformation, applied manually in a controlled manner. Transverse deformation was recorded for the evaluation of NPR characteristics, as shown in Fig. 1.



**Figure 1.** Deformations measurement

The next step was to calculate the strains using the following equations:

$$\varepsilon_x = \frac{x_n - x_0}{x_0} \quad \text{Eq.1}$$

$$\varepsilon_y = \frac{y_n - y_0}{y_0} \quad \text{Eq.2}$$

Where  $x_0$  and  $y_0$  are the initial distances and  $x_n$  and  $y_n$  are the distances after deformation.

The NPR was calculated as the negative ratio between transverse and longitudinal strain, ensuring direct comparability across all structural configurations. The Poisson’s ratio was determined from the ratio of transverse strain to longitudinal strain under uniaxial loading, by using Eq.3.

$$\nu_{x,y} = -\frac{\varepsilon_y}{\varepsilon_x} \quad \text{Eq.3}$$

where:

- $\nu$ = Poisson’s ratio
- $\varepsilon_y$ = transverse strain (course direction, on measurement orientation)
- $\varepsilon_x$ = longitudinal strain (direction of applied load, i.e., wale direction in this study)

The NPR values of PAN and cashmere fabrics, obtained by varying the zigzag pattern unit size and stitch cam position, are summarized in Table 1.

**Table 1.** Poisson’s ratio of knitted samples.

| Fabric code | Pattern    | Stitch cam position (NP) | Yarns type | Poisson’s ratio |
|-------------|------------|--------------------------|------------|-----------------|
| FP4x4.10    | Zigzag 4x4 | 10                       | Acrylic    | 0,026           |
| FP4x4.11    | Zigzag 4x4 | 11                       | Acrylic    | -0,127          |
| FP4x4.12    | Zigzag 4x4 | 12                       | Acrylic    | -0,082          |
| FP6x6.10    | Zigzag 6x6 | 10                       | Acrylic    | -0,095          |
| FP6x6.11    | Zigzag 6x6 | 11                       | Acrylic    | -0,158          |
| FP6x6.12    | Zigzag 6x6 | 12                       | Acrylic    | -0,180          |
| FP8x8.10    | Zigzag 8x8 | 10                       | Acrylic    | -0,065          |
| FP8x8.11    | Zigzag 8x8 | 11                       | Acrylic    | -0,081          |
| FP8x8.12    | Zigzag 8x8 | 12                       | Acrylic    | -0,132          |
| FC4x4.11    | Zigzag 4x4 | 11                       | Cashmere   | -0,121          |
| FC6x6.11    | Zigzag 6x6 | 11                       | Cashmere   | -0,160          |
| FC8x8.11    | Zigzag 8x8 | 11                       | Cashmere   | -0,073          |

### 3. RESULTS and DISCUSSIONS

#### 3.1. Poisson’s ratio

The maximum NPR value was obtained for the FP6×6.12 sample, fabricated from acrylic yarn and produced with a stitch length setting of NP12. This configuration corresponds to the most pronounced auxetic response among all tested specimens, indicating an optimal combination of material compliance and structural geometry for the development of negative Poisson’s ratio behaviour. In contrast, the FP4×4.10 sample did not exhibit auxetic behaviour, as evidenced by non-negative NPR values determined using the

same methodology described in Section 2.2. This absence of auxetic response suggests that the structural configuration and loop parameters of this sample are insufficient to activate the deformation mechanisms required for transverse expansion, thereby preventing the formation of a negative Poisson's ratio response.

### 3.2. Influence of yarn type

The type of yarn used in the fabrication of the knitted structures has a significant influence on the NPR response, as illustrated in Fig. 2. It can be observed that fabrics produced using cashmere yarns exhibit a reduced auxetic effect compared to those manufactured using acrylic yarns, under identical loop length and structural configurations. This difference is directly reflected in the measured NPR values, with acrylic-based fabrics showing more negative Poisson's ratio values and, therefore, a stronger auxetic response. This behaviour is attributed to differences in the intrinsic mechanical properties of the constituent yarns. In particular, acrylic yarns exhibit higher elastic recovery and greater structural resilience under tensile loading, which enhances loop reconfiguration and promotes transverse expansion, as captured by the NPR formulation introduced in Section 2.2. Consequently, acrylic-based structures demonstrate a greater ability to accommodate auxetic deformation mechanisms. In contrast, cashmere yarns, characterized by lower elastic efficiency and increased internal friction, restrict loop mobility and limit the development of negative Poisson's ratio behaviour.

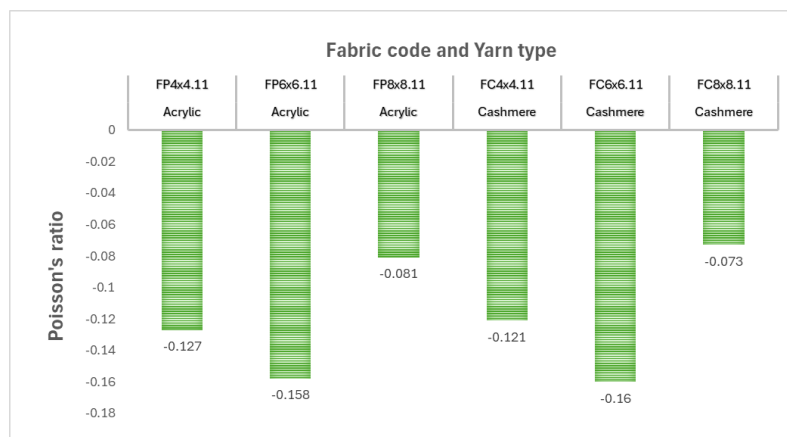


Figure 2. Influence of raw material on the auxetic behaviour of knitted samples

### 3.3. Influence of loop length

Figure 3 presents the influence of loop length on the auxetic response of the knitted samples, quantified through the NPR defined in Section 2.2. For structures with unit ratios of  $6 \times 6$  and  $8 \times 8$ , an increase in loop length leads to a progressive enhancement of the auxetic response, reflected by increasingly negative NPR values. This trend is primarily attributed to the reduction in stitch density associated with longer loop lengths, since loop length is inversely proportional to fabric compactness. The resulting reduction in structural constraint increases loop mobility and enhances the ability of the fabric network to undergo transverse expansion under longitudinal deformation, thereby amplifying the negative Poisson's ratio response. A different mechanical response is observed for the structure with a  $4 \times 4$ -unit ratio, where the maximum auxetic effect is achieved at a loop length of 11, corresponding to the most negative NPR value. In contrast, at a loop length of 10, the structure does not exhibit auxetic behaviour, as indicated by a transition to non-negative Poisson's ratio values. This suggests the existence of a critical structural threshold governing the onset of auxeticity, where minor variations in loop geometry significantly alter deformation kinematics. In this case, the balance between loop mobility and geometric constraint appears to govern whether the deformation mode satisfies the condition for negative Poisson's ratio, as defined by the strain ratio formulation introduced earlier.

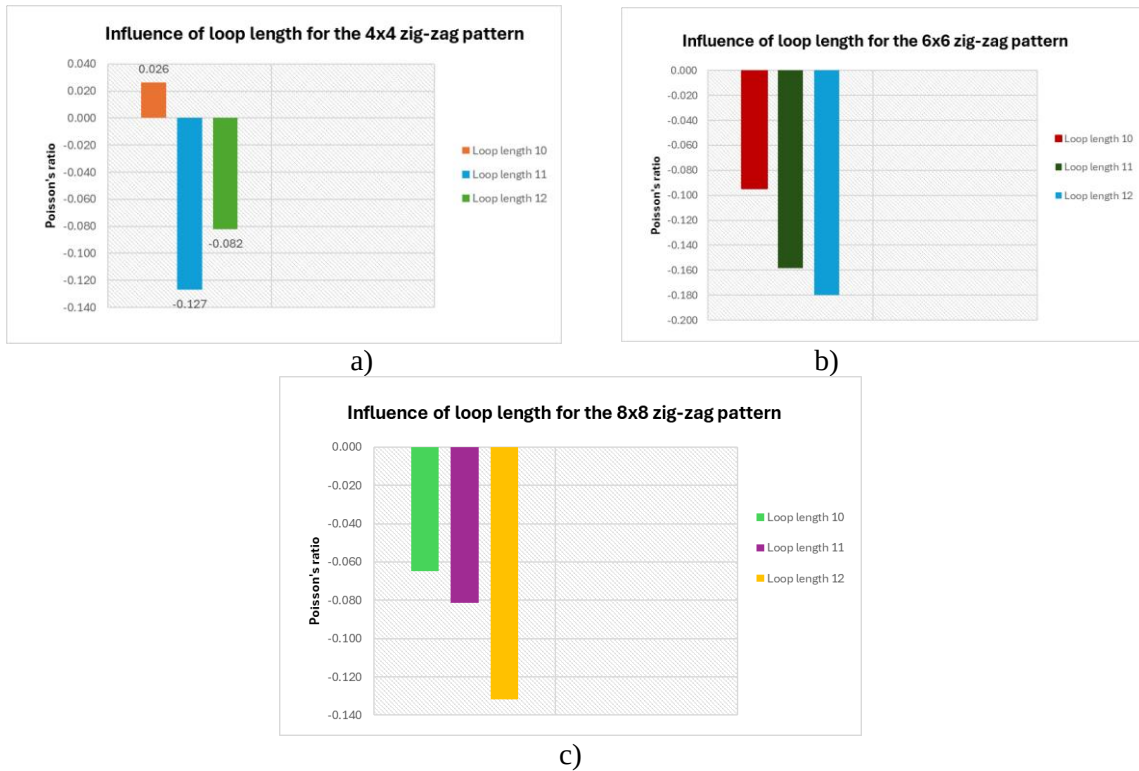


**Figure 3.** Influence of loop length for the  
a) 4x4 zig-zag pattern b) 6x6 zig-zag pattern c) 8x8 zig-zag pattern

#### 4. CONCLUSIONS

This study investigated the auxetic behaviour of knitted fabrics produced on a flatbed knitting machine (gauge 2.5.2) using acrylic and cashmere yarns, three zigzag unit-cell geometries, and varying loop lengths. The results demonstrated that the negative Poisson's ratio (NPR) response is governed by a combined effect of yarn type, loop length, and unit-cell configuration.

Among the investigated parameters, yarn type significantly influenced auxetic performance, with acrylic-based fabrics exhibiting higher NPR values compared to cashmere-based structures. This improvement is attributed to the higher elastic recovery and greater structural adaptability of acrylic yarn, which facilitates enhanced loop deformation and reconfiguration under tensile loading.

Loop length was also identified as a critical parameter affecting auxetic behaviour. Increasing loop length generally enhanced NPR values by reducing stitch density and increasing structural compliance. Conversely, lower loop lengths restricted loop mobility, resulting in reduced or absent auxetic response, as observed for the FP4×4.10 configuration.

In addition, unit-cell geometry played a decisive role in governing deformation mechanisms. Structures with a  $6 \times 6$  unit-cell configuration exhibited the most pronounced lateral expansion, indicating an optimal balance between rotational freedom and structural stability required for auxetic behaviour.

Overall, the findings confirm that auxetic performance in knitted fabrics can be effectively tailored through controlled variation of yarn type and structural parameters. The proposed approach demonstrates the potential of conventional knitting technologies for the fabrication of textile-based metamaterials. This offers a scalable and energy-efficient route toward functional textiles with potential applications in adaptive and size-responsive garments.

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## FERMENTED BIOLEATHER AS A SUSTAINABLE MATERIAL FOR TEXTILE AND FASHION

Ivana Schwarz<sup>1,\*</sup>, Helena Schultheis Edgeler<sup>2</sup>, Tia Mihinjač<sup>3</sup>

<sup>1</sup> University of Zagreb Faculty of Textile Technology, Department of Textile Design and Management, Zagreb, Croatia

<sup>2</sup> University of Zagreb Faculty of Textile Technology, Department of Textile and Clothing Design, Zagreb, Croatia

<sup>3</sup> University of Zagreb Faculty of Textile Technology, student, Zagreb, Croatia

\* [ivana.schwarz@ttf.unizg.hr](mailto:ivana.schwarz@ttf.unizg.hr)

### ABSTRACT

The environmental impact of conventional leather production has driven research into bio-based, biodegradable alternatives that meet functional requirements for textile and fashion applications. This study investigates fermented bioleather from kombucha as a sustainable and environmentally responsible alternative to conventional leather. Using controlled biofabrication and standardised physical-mechanical testing, the study establishes a link between cultivation parameters and the material's functional properties. Fermented bioleather was produced by static aerobic fermentation of sweetened tea with a symbiotic culture of bacteria and yeast (SCOBY), resulting in in situ biosynthesis of bacterial cellulose at the air-liquid interface. Extended cultivation led to layered deposition and densification of the cellulose matrix. After harvesting and drying without chemical purification or plasticisation, the material was conditioned and tested in accordance with relevant ISO standards. Results show that fermented bioleather has a compact, cohesive structure typical of bacterial cellulose-based materials, with mechanical properties within the functional range of conventional bovine leather. The material demonstrated stable tensile behaviour, substantial elongation, and strong resistance to repeated mechanical loading, indicating a favourable balance of flexibility and structural stability. Its moderate rigidity suggests it is suitable for structured textile applications. This study provides quantitative data confirming that kombucha-derived bacterial cellulose can form a mechanically robust material. While biological variability remains a consideration for industrial standardisation, the findings highlight the potential of fermented bioleather as a low-impact, chromium-free, and biodegradable material for sustainable and regenerative systems.

**Keywords:** *Fermented bioleather, Sustainable material, Physical-mechanical properties*

### 1. INTRODUCTION

The textile and fashion industries are among the most resource-intensive and environmentally impactful sectors globally. Large-scale livestock farming for bovine leather production contributes significantly to greenhouse gas emissions (up to approximately 110 kg of CO<sub>2</sub>-equivalent per square meter), land degradation, and water consumption, while synthetic alternatives based on polyurethane (PU) or polyvinyl chloride (PVC) introduce persistent microplastics and rely on fossil-derived feedstocks. The environmental burden associated with conventional material systems has intensified research into bio-based, biodegradable, and low-impact alternatives that meet functional and aesthetic requirements in textile applications [1-4]. Recent material innovation has therefore shifted towards bio-fabricated solutions, including plant-based materials such as cactus leather and fungal or mycelium-based composites [5-7]. These emerging biomaterials aim to replicate the durability, flexibility and tactile qualities of animal leather while significantly reducing ecological impact and eliminating animal-derived components. Within this expanding field, fermented bioleather derived from kombucha has attracted growing interest due to its



simplicity of cultivation, renewable origin and compatibility with decentralised production systems. Kombucha fermentation relies on a symbiotic culture of bacteria and yeast (SCOBY) that metabolises sweetened tea and produces a cellulose-rich biofilm at the air-liquid interface. This biofilm consists primarily of bacterial cellulose, a highly pure biopolymer synthesised by acetic acid bacteria. Unlike plant-derived cellulose, bacterial cellulose is produced free from lignin and hemicellulose and organises into a three-dimensional nanofibrillar network with notable mechanical integrity. These intrinsic characteristics have led to increasing interest in its application across advanced material systems [8-10]. In contrast to industrially purified bacterial cellulose, kombucha-derived films retain minor residual fermentation components, which may influence density, flexibility and surface morphology. When harvested and dried, the resulting material exhibits leather-like properties, including a compact fibrous structure and the ability to be cut, sewn and shaped. From a sustainability perspective, fermented bioleather requires minimal raw materials, primarily water, tea and sugar, while avoiding the energy-intensive processes and toxic tanning chemicals associated with conventional leather production. Furthermore, when used untreated or dyed with natural pigments, the material remains fully biodegradable, aligning with circular economy principles and regenerative strategies. Despite increasing experimental exploration in design contexts, systematic mechanical characterisation of fermented bioleather remains limited. For meaningful integration into textile and fashion systems, it is essential to quantitatively evaluate thickness uniformity, apparent density, tensile behaviour, cyclic bending resistance and stiffness, as these parameters directly determine sewability, structural stability, drape behaviour and long-term durability. Accordingly, this study focuses on the controlled cultivation of fermented bioleather and its comprehensive mechanical assessment in accordance with relevant ISO standards to determine its suitability for structured textile and apparel applications. By combining biofabrication with quantitative material analysis, the research contributes to scientific understanding of kombucha-derived cellulose as a viable component in sustainable textile innovation.

## **2. EXPERIMENTAL STUDY**

### **2.1 Cultivation of Fermented Bioleather**

Fermented bioleather was produced through static aerobic fermentation of sweetened black tea using a symbiotic culture of bacteria and yeast (SCOBY), enabling in situ biosynthesis of bacterial cellulose at the air-liquid interface. Unlike kombucha prepared for consumption, the cultivation protocol was adjusted to prioritise structural thickness and material integrity over beverage quality. The nutrient medium consisted of distilled water, black tea infusion and sucrose as the primary carbon source. Black tea was selected for its stable nutrient composition and compatibility with acetic acid bacteria involved in cellulose synthesis. A continuous carbon supply was maintained to promote prolonged metabolic activity and continuous cellulose deposition. Fermentation was initiated using a liquid starter culture, without introducing a pre-formed pellicle, as preliminary trials indicated that inserting an existing SCOBY resulted in localised structural irregularities in the newly formed cellulose layer. Cultivation was conducted under static conditions at ambient laboratory temperatures (21–25 °C) for 40 days. Static fermentation ensured uninterrupted cellulose formation at the oxygen-rich air-liquid boundary. The extended cultivation period enabled progressive, layered deposition and densification of the cellulose network, resulting in thicker, more compact pellicles. Following harvesting, the pellicles were rinsed with distilled water to remove residual fermentation by-products. No chemical purification, alkaline treatment or addition of plasticisers was applied, as the aim was to evaluate the intrinsic behaviour of untreated bioleather. Drying was performed under ambient conditions on a flat wooden substrate to promote gradual moisture evaporation and dimensional stability. Given the biological origin of the material, a degree of variability in thickness and internal organisation is inherent; however, controlled nutrient composition, temperature range and cultivation time were maintained constant to enhance reproducibility.

### **2.2 Structural Basis of Fermented Bioleather**

The material obtained through static fermentation is fundamentally composed of bacterial cellulose synthesised extracellularly by acetic acid bacteria during kombucha fermentation. In contrast to plant-derived cellulose, which coexists with lignin and hemicellulose within complex cell wall architectures, bacterial cellulose is secreted in highly pure form and self-assembles into an ultrafine three-dimensional nanofibrillar network. During cultivation, individual bacterial cells continuously extrude cellulose nanofibrils that aggregate into ribbon-like microfibrils at the air-liquid interface. These fibrils, typically with diameters of a few nanometres, entangle to form a densely interconnected matrix stabilised primarily

through hydrogen bonding. As successive layers accumulate under static conditions, fibrillar packing increases and macro-porosity decreases, resulting in structural consolidation [8,10]. The extended cultivation period applied in this study directly influenced matrix compactness and structural cohesion. The resulting architecture is relatively homogeneous compared with conventional leather structures, exhibiting reduced macro-scale voids and a tightly packed fibrillar arrangement. This nanoscale organisation differs fundamentally from the hierarchical collagen bundle architecture of conventional bovine leather. While conventional bovine leather derives its mechanical behaviour from multi-scale collagen fibre bundles chemically stabilised through tanning processes, fermented bioleather is based on a carbohydrate polymer network formed through biological self-assembly. Collagen fibres exhibit inherent interfibrillar spacing and structural anisotropy, whereas bacterial cellulose forms a more isotropic and densely packed nanofibrillar system [11,12]. This distinction in fibre organisation underpins the mechanical behaviour discussed in the following section.

### 2.3 Physical and Mechanical Characterisation

The physical-mechanical evaluation strategy was designed to determine whether the structural characteristics of the investigated bioleather translate into functional properties suitable for textile and apparel applications. The selected tests describe properties that influence stability, flexibility, durability, and garment construction. Thickness, apparent density and mass per unit area were determined according to ISO 2589:2016 and ISO 2420:2017. These parameters provide quantitative insight into matrix compactness and fibre network cohesion within the bioleather. In the context of bacterial cellulose-based materials, apparent density is particularly relevant, as it reflects the degree of nanofibrillar packing achieved during static cultivation and therefore serves as an indirect indicator of structural consolidation. Resistance to cyclic bending was evaluated according to ISO 5402-1:2017 in order to assess durability under repeated mechanical deformation. Since garments are continuously subjected to flexing during body movement, resistance to crack formation, delamination or fatigue-related degradation represents a critical performance criterion for leather alternatives. Tensile strength and elongation at break were measured in accordance with ISO 3376:2012, with minor dimensional adjustments to accommodate the biofabricated material's structural characteristics. Tensile properties determine resistance to tearing and the ability to redistribute mechanical stress. Elongation behaviour is particularly important for evaluating the capacity of the nanofibrillar matrix to withstand dynamic loading without abrupt failure. Bending stiffness was determined using a cantilever-based method. Although this approach is not standardised within ISO frameworks, it is widely accepted in textile research for evaluating drape behaviour and bending rigidity. Rectangular specimens ( $15.0 \times 2.5$  cm) were placed on a horizontal platform and gradually displaced beyond their edges until the free segment bent under its own weight. The overhanging length corresponding to a deflection angle of  $41.5^\circ$  was recorded as the bending length. Based on this length and the measured mass per unit area, bending resistance ( $U$ , g/cm) was calculated as an indicator of structural rigidity. In textile applications, bending stiffness governs silhouette formation, shape retention and wearer mobility. Materials with higher bending resistance exhibit stronger structural definition, whereas lower values indicate greater adaptability and softer drape behaviour. For bio-based leather alternatives, achieving a balance between sufficient structural stability and adequate flexibility remains a key material challenge. By integrating controlled biofabrication, interpretation of structural characteristics and targeted testing, the experimental framework establishes a direct relationship between cultivation parameters, the resulting material and functional performance within sustainable textile systems.

## 3. RESULTS

The physical-mechanical characterisation of fermented bioleather yielded the parameters summarised in Tables 1–3.

**Table 1.** Physical properties of fermented bioleather

| Parameter                                    | Value   |
|----------------------------------------------|---------|
| Thickness, $t$ (mm)                          | 1.590   |
| Diameter, $d$ (mm)                           | 113     |
| Mass, $m$ (g)                                | 20.6407 |
| Apparent density, $D_a$ (kg/m <sup>3</sup> ) | 1295.9  |

| Parameter                                     | Value  |
|-----------------------------------------------|--------|
| Mass per unit area, $m_a$ (g/m <sup>2</sup> ) | 2059.2 |

A thickness of 1.590 mm falls within the typical range for garment-grade conventional bovine leather (0.8-2.0 mm). The apparent density of 1295.9 kg/m<sup>3</sup>, however, exceeds standard values for conventional bovine leather, which usually range from 860 to 1100 kg/m<sup>3</sup> depending on processing [13]. The mass per unit area of 2059.2 g/m<sup>2</sup> further confirms the material’s compact structure. This elevated density reflects the compact cellulose architecture discussed in Section 2.2, indicating substantial structural consolidation.

**Table 2.** Tensile properties of fermented bioleather

| Parameter                              | Mean   | Max    | Min    | CV (%) | $\sigma$ |
|----------------------------------------|--------|--------|--------|--------|----------|
| Maximum force, F (N)                   | 223    | 240    | 202    | 6.288  | 14       |
| Elongation at break, $\varepsilon$ (%) | 72.26  | 82.58  | 61.29  | 13.745 | 9.93     |
| Tensile strength, T (N/mm)             | 9      | 10     | 8      | 6.288  | 1        |
| Work to rupture, W (cN·mm)             | 529386 | 629911 | 444838 | —      | 81019    |

A tensile strength of 9 N/mm places the material in the lower-to-moderate performance range of conventional bovine leather, which typically ranges from 8 to 25 N/mm depending on thickness and processing [13]. Notably, this performance was achieved without tanning agents, chromium crosslinking, or fatliquoring treatments. The low coefficient of variation for tensile strength (6.288%) indicates acceptable structural consistency despite the material’s biological origin. A standard deviation of 1 N/mm further confirms controlled mechanical behaviour across specimens. Elongation at break averaged 72.26%, with values from 61.29% to 82.58%. Conventional bovine leather typically exhibits elongation of 40%-70%, influenced by collagen fibre orientation and lubrication [13]. The higher elongation here suggests a strong capacity for stress redistribution within the bacterial cellulose network. The nanofibrillar structure allows gradual realignment and sliding of fibrils before fracture, enabling the material to withstand significant deformation without sudden failure [14]. The slightly higher variability in elongation (CV 13.745%) likely results from minor differences in layer thickness and internal fibril organisation due to biological self-assembly. The work to rupture (529386 cN·mm) further demonstrates the material’s ability to absorb mechanical energy before fracture. This parameter is especially relevant for textile applications requiring resistance to dynamic loading.



**Figure 1.** Sample of fermented bioleather after 10,000 cycles.

Cyclic bending resistance tests showed notable durability. After 10,000 flexing cycles according to ISO 5402-1:2017, no cracking, delamination, or structural rupture occurred in the flex zone. Minor temporary elongation and slight surface lightening were observed, but did not affect structural integrity. In conventional bovine leather, repeated flexing can cause microcracking or fatigue-related degradation depending on finishing and lubrication [11,13]. The absence of fatigue damage in fermented bioleather suggests strong interfibrillar cohesion in the hydrogen-bonded cellulose matrix. The nanoscale fibrillar

network accommodates repeated mechanical deformation without structural breakdown, which is especially important for garment applications where continuous bending is common.

**Table 3.** Bending stiffness of fermented bioleather

| Mass per unit area (g/m <sup>2</sup> ) | Bending length, C (cm) | Bending resistance, U (g/cm) |
|----------------------------------------|------------------------|------------------------------|
| 2059.2                                 | 8.6                    | 16.38                        |

A bending resistance of 16.38 g/cm indicates moderate to high structural rigidity. Unlike softened conventional bovine garment leather, which is treated to improve suppleness, untreated fermented bioleather shows stronger inherent shape retention. This stiffness correlates with high apparent density and the absence of plasticisers. While increased rigidity may reduce drape fluidity, it enhances dimensional stability and structural definition, which can benefit structured garments or design applications requiring architectural form.

#### 4. CONCLUSION

This study demonstrates that mechanically functional, leather-like sheet materials can be produced through controlled static fermentation of bacterial cellulose without reliance on conventional tanning chemistry or synthetic modification. By systematically linking cultivation parameters with measurable performance outcomes, the research confirms that fermentation duration and process stability directly influence matrix densification and mechanical response. The results show that structural coherence in fermented bioleather arises from a self-assembled, hydrogen-bonded nanofibrillar network that forms during growth. Mechanical stability, flex durability and bending resistance are therefore governed by intrinsic network organisation rather than chemical crosslinking or hierarchical fibre bundling. This establishes biofabrication not only as a production method, but as a structural design mechanism. Through ISO-aligned quantitative evaluation, the study provides technical validation that kombucha-derived bacterial cellulose sheets meet functional requirements for structured textile and apparel applications. In doing so, it moves fermented bioleather beyond conceptual sustainability discourse toward a technically characterised material system. Although biological variability remains a factor for large-scale industrial implementation, the demonstrated consistency in mechanical performance suggests that controlled cultivation strategies can enhance reproducibility. By achieving functional material behaviour without chromium tanning and intensive processing, fermented bioleather represents a structurally credible and environmentally aligned material pathway within sustainable textile and fashion development.

#### ACKNOWLEDGMENT

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## FLEXIBILITY OF FULL GRAIN LEATHER FOR FOOTWEAR: INFLUENCE OF LEATHER PROCESSING LEVEL

Antoneta Tomljenović<sup>1</sup>, Juro Živičnjak<sup>1,\*</sup>

<sup>1</sup> University of Zagreb Faculty of Textile Technology, Department of Materials, Fibres and Textile Testing, Zagreb, Croatia

\* juro.zivicnjak@ttf.unizg.hr

### ABSTRACT

Full grain leather is the most durable part of cattle hide, consisting of the grain layer and part of the underlying corium, and displays the most natural characteristics of leather. It is primarily composed of long, fine collagen fibres and fibre bundles interwoven in a three-dimensional, densely packed structure, which gives full grain leather its unique physical and mechanical properties. These properties include flexibility, relatively high tensile strength, resistance to tearing, and the ability to be stretched and compressed without distorting the surface. Leather properties are also affected by the tanning and finishing processes used during production. Full grain leather, rather than undergoing extensive finishing, sometimes only undergoes an ironing process, which reduces production costs. To analyse the influence of processing level and tanning type, this paper evaluates the flexibility of differently tanned (synthetic and chromium), finished, and unfinished cattle full grain leather sampled from side leather cuts. Their suitability for footwear uppers was evaluated by measuring leather thickness, apparent density, tensile strength and percentage elongation at break, repeated flex and linear compression resistance, flexural rigidity, and softness, all according to standard test methods. The research results show that full grain leathers possess different flexibility depending on the manufacturing process, which defines their suitability for specific types of footwear uppers and confirms the applicability of full grain leathers that, instead of finishing (after preparation, tanning, and crusting), underwent only an ironing process.

**Keywords:** *Full grain leather, Leather processing level, Flexibility, Leather Testing, Footwear*

### 1. INTRODUCTION

Full grain leather is the most durable part of cattle hide, consisting of the grain layer and part of the underlying corium, and displays the most natural characteristics of leather. It is primarily composed of long, fine collagen fibres and fibre bundles interwoven in a three-dimensional, densely packed structure. The corium fibre bundles are relatively large (0.1 mm in diameter) and interweave at a high angle relative to the surface. The hide of mature cattle is generally 4 to 6 mm thick, with the grain layer occupying about one-sixth of the total thickness. This thickness is too great for shoe uppers and is therefore split into two layers. The outer layer, consisting of the grain layer and part of the underlying corium, should be split to a thickness of 1.3 to approximately 2 mm for shoe uppers [1]. The properties of full grain leather depend not only on its total thickness but also on the proportion of corium tissue and the frequency with which the corium fibres interweave and cross. In full grain leather made from mature cattle hide, the grain layer can be as deep as 0.6 mm. The large size of the corium fibres affects how often they can interweave in the remaining corium tissue layer. This gives full grain leather its unique physical and mechanical properties, including flexibility, relatively high tensile strength, resistance to tearing, and the ability to be stretched and compressed without distorting the surface [1-4]. Leather properties are also influenced by the tanning and finishing processes used during production. The process of making full grain leather involves three main stages: preparation, tanning, and crusting. During crusting, the leather is thinned, tanned again, and lubricated. Colouring is often introduced at this stage, but the primary purpose of crusting is to dry and soften the leather. A fourth step may be added, in which the leather receives a surface coating or finish. Full grain leather, instead of undergoing extensive finishing, sometimes only undergoes an ironing process that



uses varying degrees of pressure and heat until the desired sheen is achieved [1, 5], which also reduces production costs. To analyse the influence of processing level and tanning type, this paper evaluates the flexibility of differently tanned (synthetic and chromium), finished, and unfinished cattle full grain leather sampled from side leather cuts. Their suitability for footwear uppers was assessed by measuring leather thickness, apparent density, tensile strength, percentage elongation at break, repeated flex and linear compression resistance, flexural rigidity, and softness.

## **2. EXPERIMENTAL STUDY**

### **2.1 Materials**

The study was conducted on four cattle full grain leather samples intended for footwear uppers: CL1 – non-finished leather cut (synthetic tanned and re-tanned, drum dyed in cyan, waterproofed, antimicrobial treated, slightly lubricated, vacuum dried, stretched, and softened shoe upper leather); CL2 – finished leather cut (synthetic tanned and re-tanned, antimicrobial treated, slightly lubricated, vacuum dried, stretched, and softened lining leather, surface treated with slightly beige pigmented casein and polyurethane polymerization binders); CL3 – non-finished leather cut (chromium tanned and re-tanned, drum dyed in black, waterproofed, antimicrobial treated, slightly lubricated, vacuum dried, stretched, and softened shoe upper leather); CL4 – non-finished leather cut (chromium tanned and re-tanned, waterproofed, slightly lubricated, vacuum dried, stretched, and softened wet blue lining leather).

### **2.2 Methods**

Leather specimens were selected from the leather sides for physical and mechanical tests in accordance with EN ISO 2418:2023 from the bend (butt) area and conditioned according to EN ISO 2419:2024 at a temperature of  $23^{\circ} \pm 2^{\circ}\text{C}$  and a relative humidity of  $50\% \pm 5\%$ . The following leather properties were measured, with test pieces prepared in two directions – parallel and perpendicular to the backbone, where applicable: thickness according to EN ISO 2589:2016 using a thickness tester 2000-U (Richard Hess MBV GmbH, Germany) with a circular pressure foot diameter of 10 mm under a pressure of 49.1 kPa; apparent density according to EN ISO 2420:2017; tensile strength and percentage elongation at break according to EN ISO 3376:2020 using a strength tester Tensolab 3000 (Mesdan S.p.A., Italy) with a gauge length of 50 mm and an elongation rate of 100 mm/min; dry and wet flex resistance using a flexometer according to EN ISO 5402-1:2022 (visual examination with a magnifier after 150,000 dry and 50,000 wet flex cycles); dynamic water resistance by repeated linear compression equivalent to 10% compression of the test piece using a penetrometer according to EN ISO 5403-1:2025 (measuring the time for water to penetrate the test piece and determining the percentage mass of water absorbed); flexural rigidity using the bending length of a leather strip determined with a Shirley stiffness tester according to ASTM D1388-18; and leather softness according to EN ISO 17235:2015 using a softness tester Calati 300AST, Danese Srl, Italy, with a test force of 6 N and an aperture of 25 mm. The results include average values calculated with the corresponding coefficient of variation.

## **3. RESULTS**

The results of the investigations are presented in Tables 1 to 4. Table 1 presents the average thickness values measured in leather specimens (CL1–CL4) taken from the butt area (five measurements, rounded to the nearest 0.01 mm); the average apparent density values calculated for leather specimens (CL1–CL4) from the butt area (by dividing the mass by the volume of three leather disk test pieces); and the average values of tensile strength and elongation at break, calculated for leather specimens (CL1–CL4) from the butt area, with test pieces oriented both parallel and perpendicular to the backbone (three in each direction).

**Table 1.** Average values of thickness, apparent density, tensile strength, and percentage elongation at break for tested full grain leather specimens (CL1–CL4), with corresponding coefficients of variation expressed as percentages.

| Leather sample | Thickness, mm | Apparent density, kg/m <sup>3</sup> | Tensile strength, MPa |            | Breaking elongation, % |             |
|----------------|---------------|-------------------------------------|-----------------------|------------|------------------------|-------------|
|                |               |                                     | ↑                     | →          | ↑                      | →           |
| CL1            | 2.14/0.39     | 727.17/0.39                         | 19.40/2.72            | 14.09/2.05 | 80.07/20.02            | 107.53/2.14 |
| CL2            | 1.30/1.00     | 736.25/1.00                         | 17.73/4.62            | 12.03/0.80 | 80.13/7.38             | 82.47/1.88  |
| CL3            | 1.57/0.45     | 765.52/0.81                         | 21.05/5.40            | 10.82/5.96 | 56.66/3.16             | 60.33/13.52 |
| CL4            | 1.34/0.32     | 730.08/0.15                         | 17.09/8.01            | 12.52/5.75 | 66.58/7.44             | 72.00/7.92  |

↑ parallel to the backbone; → perpendicular to the backbone

The butt area, the central part of the leather back, is characterised by uniform thickness, tightness, and evenly and densely intertwined leather tissue, with the densest tangle of collagen fibres arranged almost vertically [1]. As the apparent (bulk) density indicates the overall fullness, density, and compactness of the structure of the tested leather specimens, this is confirmed by all leather samples showing low coefficients of variation for thickness and apparent density values (Table 1). Leathers CL1 and CL3, intended for the outer parts of footwear uppers, are thicker and heavier, while lining leathers CL2 and CL4, intended for the inner parts of footwear uppers, are thinner and lighter. A comparison of the apparent density of the thicker chromium tanned full grain leather CL3 and the chrome-free, synthetic tanned leather CL1 showed higher values in CL3, indicating greater compactness and better cross-linking of the fibrillar structure. This results from the different chemistry of the tanning materials used and the distinct mechanisms of the chrome and synthetic tanning agents [6]. When comparing the apparent density values of synthetic tanned leathers CL1 and CL2, a somewhat higher value was found in the thinner CL2 leather, which is attributed to the structure of the finished leather surface containing casein and polyurethane polymerisation binders.

On average, tensile strength values are higher in the direction parallel to the backbone for all leather samples. Thicker leathers have higher tensile strength values; however, in thinner chromium tanned leather, CL3 exhibited higher tensile strength than the thicker synthetic tanned leather, CL1, in the direction parallel to the backbone. For thinner leathers tanned differently, this was not observed, indicating that the proportion of corium tissue in the full thickness and the type of tanning agent used affect the results. Percentage elongation at break, determined for all tested leather samples, is higher in the direction perpendicular to the backbone. Higher values were found in synthetic tanned leathers compared with chromium tanned leathers, influenced primarily by thickness, apparent density, and the orientation and cross-linking of collagen fibres (Table 1).

After 150,000 dry and 50,000 wet flex cycles using a flexometer, no visible damage or cracks were observed on the grain surface of any leather specimens (CL1–CL4) tested in either direction. The grain surface appearance of leather specimens (CL1–CL4) taken from the butt area, following visual inspection under 20× magnification, is shown in Table 2.

Table 3 presents the water resistance results for tested full grain leather specimens (CL1–CL4) after repeated linear compression using a penetrometer. It shows the average values of water penetration time and water absorption measured in leather specimens (CL1–CL4) taken from the butt area, with test pieces oriented both parallel and perpendicular to the backbone. Non-finished, full grain, waterproofed, thicker leathers CL1 and CL3 showed water penetration times greater than 4 hours. In contrast, the finished, non-waterproofed, thinner lining leather CL2 showed the highest water absorption value. No significant difference in water resistance results was found between the different leather directions tested.

**Table 2.** Surface appearance of tested full grain leather specimens (CL1–CL4) taken from the butt area after 150,000 dry and 50,000 wet flex cycles using a flexometer (magnification 20×).

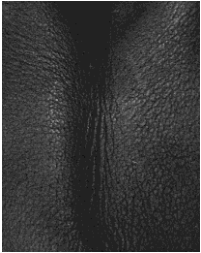
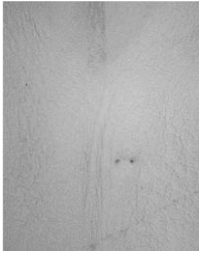
| Leather sample | Dry flex resistance                                                                 |                                                                                     | Wet flex resistance                                                                  |                                                                                       |
|----------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
|                | Parallel to the backbone                                                            | Perpendicular to the backbone                                                       | Parallel to the backbone                                                             | Perpendicular to the backbone                                                         |
| CL1            |    |    |    |    |
|                |    |    |    |    |
| CL3            |  |  |  |  |
|                |  |  |  |  |

**Table 3.** Water resistance of tested full grain leather specimens (CL1–CL4) after repeated linear compression using a penetrometer [7].

| Leather sample | Water penetration time, h:min |       | Water absorption, % |       |
|----------------|-------------------------------|-------|---------------------|-------|
|                | ↑                             | →     | ↑                   | →     |
| CL1            | 5:14*                         | 5:14* | 9.96                | 10.36 |
| CL2            | 0:01*                         | 0:01* | 81.03               | 82.60 |
| CL3            | 4:14*                         | 4:56* | 9.62                | 11.21 |
| CL4            | 3:16**                        | 3:16* | 9.49                | 9.86  |

↑ parallel to the backbone; → perpendicular to the backbone; \* damp patch formed on the surface;  
 \*\* droplet of water formed on the surface

Table 4 presents the average softness values measured in leather specimens (CL1–CL4) taken from the butt area (three measurements, rounded to the nearest 0.01 mm), where a cylindrical rod was lowered onto a securely clamped area of leather and the resulting distension was recorded; the average bending length

values measured for leather specimens (CL1–CL4) from the butt area (using a Shirley stiffness tester, which bends test pieces under their own weight on a platform with smooth, low-friction, flat surfaces inclined at 41.5°); and the average flexural rigidity values calculated for leather specimens (CL1–CL4), with test pieces oriented both parallel and perpendicular to the backbone (three in each direction).

**Table 4.** Average values of softness and flexural properties for tested full grain leather specimens (CL1–CL4), with corresponding coefficients of variation expressed as percentages.

| Leather sample | Softness, mm | Bending length, cm |          | Flexural rigidity, mg cm |               |
|----------------|--------------|--------------------|----------|--------------------------|---------------|
|                |              | ↑                  | →        | ↑                        | →             |
| CL1            | -2.04/-1.71  | 8.2/1.9            | 8.4/6.0  | 11,706.9/15.5            | 19,287.7/13.1 |
| CL2            | -5.41/-2.56  | 4.5/3.3            | 4.1/2.3  | 801.1/9.0                | 558.5/19.8    |
| CL3            | -1.47/-1.25  | 11.7/3.5           | 11.5/5.2 | 24,072.1/12.3            | 21,510.5/40.8 |
| CL4            | -3.56/-2.54  | 6.1/13.5           | 5.8/13.8 | 2513.0/34.8              | 3618.3/45.0   |

↑ parallel to the backbone; → perpendicular to the backbone

Table 4 shows that the thinner lining leathers (CL2 and CL4) are softer than the thicker leathers (CL1 and CL3) used for footwear uppers. Synthetic tanned leathers (CL1 and CL2), which have a relatively inefficient crosslinking structure, are softer than chrome tanned leathers (CL3 and CL4), which have a denser, more cross-linked structure.

Flexural rigidity measures the stiffness of leather and relates to the bending length of the strip test piece under gravitational force. It is usually attributed to the rigidity of collagen fibres in the leather [4]. Table 4 indicates that chrome tanned full grain leathers (CL3 and CL4) are stiffer than chrome-free synthetic tanned leathers (CL1 and CL2), which is also related to the bending length of the leather test pieces. Additionally, thicker full grain leathers (CL1 and CL3) intended for the outer parts of footwear uppers show greater flexural rigidity than thinner, finer lining leathers (CL2 and CL4).

#### 4. CONCLUSION

The research results show that full grain leathers have varying flexibility depending on the manufacturing process, which determines their suitability for specific types of footwear uppers. The findings also confirm the applicability of full grain leathers that, instead of being finished after preparation, tanning, and crusting, underwent only an ironing process, which significantly reduces production costs.

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## HALOGEN-FREE FLAME-RETARDANT BACK COATINGS FOR UPHOLSTERY FABRICS: A READY-TO-USE SOLUTION

Hülya Aydemir<sup>1\*</sup>, Zeynep İnce<sup>2</sup>, Pelin Sevinç<sup>3</sup>

<sup>1,2,3</sup> RUDOLF DURANER Company, R&D Center, Nilüfer/BURSA

\* email address of corresponding author zeynepi@rudolf-duraner.com.tr

### ABSTRACT

This study aims to develop a halogen-free environmentally traceable and high-performance flame-retardant compound product for back coating of polyester (PES) upholstery textiles. While halogen-containing flame-retardant products have been used in the current market until today, they were included in the banned product list in the November revision of the SVHC. Therefore, the use of RUCO-COAT 717-HF, a halogen-free flame-retardant compound product, is gaining importance as a replacement for halogen-containing products in the textile market. The innovative aspects of the project include the absence of halogens, successful performance of PES upholstery fabrics in British Standard BS 5852-0:1979: source 0 Ignitability of Upholstery Fabrics Cigarette test and BS 5852-1:1979: source 1 Ignitability of Upholstery Fabrics Match test, ensuring BS 5651:1978 soaking durability, applicability in paste/foam form. Key objectives also include maintaining a soft fabric handle, no migration of the product on the front side (Blooming). As a result of laboratory and pilot-scale trials, a formulation that met all target criteria was achieved. This study provides sustainable, halogen free, application friendly and high-performance flame-retardant compound product for PES upholstery fabrics was developed and commercialized under the trade name RUCO-COAT 717-HF.

**Keywords:** *Halogen-free, Flame-retardant, Upholstery fabrics, Back coating*

### 1. INTRODUCTION

Flame retardancy is a critical requirement for upholstery textiles due to strict fire safety regulations and increasing environmental concerns. Polyester (PES) fabrics, although widely used for their durability and cost efficiency, are highly flammable because of their thermoplastic structure and melt-dripping behavior during combustion. Traditionally, halogen-containing flame retardants have been used to comply with standards such as BS 5852-0:1979: source 0 Ignitability of Upholstery Fabrics Cigarette test and BS 5852-1:1979: source 1 Ignitability of Upholstery Fabrics Match test however, their toxicity, persistence, and potential formation of hazardous by-products have led to regulatory restrictions, particularly under REACH legislation [1,2].

Halogen-free systems, especially phosphorus- and nitrogen-based formulations, have emerged as sustainable alternatives due to their char-forming mechanisms and lower toxic emissions [3]. Nevertheless, achieving high flame-retardant performance together with soaking durability, soft handle, no blooming, and industrial applicability remains technically challenging.

This study presents the development of a halogen-free, environmentally traceable flame-retardant compound for back coating of PES upholstery fabrics, meeting BS 5852-0:1979: source 0 Ignitability of Upholstery Fabrics Cigarette test and BS 5852-1:1979: source 1 Ignitability of Upholstery Fabrics Match test cigarette and match test requirements while maintaining fabric performance and commercial applicability.

## 2. EXPERIMENTAL STUDY

In this study, halogen-free flame-retardant compound was formulated for the back coating of PES upholstery fabrics. The formulation was designed to be applicable in paste and foam forms and optimized to ensure uniform coating without front-side migration (blooming) while maintaining soft fabric handle. The compound was applied to the reverse side of the fabric using a controlled coating process, followed by drying and curing under defined conditions. Flame-retardant performance was evaluated according to PES upholstery fabrics in British Standard BS 5852-0:1979: source 0 Ignitability of Upholstery Fabrics Cigarette test and BS 5852-1:1979: source 1 Ignitability of Upholstery Fabrics Match test, ensuring BS 5651:1978 soaking durability, applicability in paste/foam form. Laboratory and pilot-scale trials were conducted to verify compliance with fire safety, durability, and performance requirements.

### 2.1 Formulation design

Basic formula in the formulation design stage, a systematic approach was followed to develop a flame-retardant coating system that meets performance, application, and handle requirements simultaneously. During the development process, flame retardancy performance, foam applicability, soft handle, and dust-free behaviour were considered as the primary criteria.

#### 2.1.1. Binder Selection (Add 1)

The binder was carefully selected to ensure minimum negative impact on flame retardancy performance, foam stability, and fabric handle. Different binder types were screened in preliminary laboratory trials with particular attention to their compatibility with the flame-retardant system. The selected binder provided sufficient film formation and adhesion while maintaining the soft handle of PES upholstery fabrics. In addition, its influence on foam structure and expansion ratio was evaluated to ensure stable and homogeneous foam application.

#### 2.1.2. Ratio Optimization (Add 2)

After determining the appropriate binder type, the ratios of binder, flame retardant, and dispersant were optimized. A series of experimental formulations were prepared by varying component concentrations. The objective was to: Achieve the required flame-retardant performance according to BS 5852-1:1979: source 1 Ignitability of Upholstery Fabrics Match test ensure suitable rheological properties for foam application, maintain a soft and textile-like handle after curing, prevent surface dusting and powdering during and after application. The dispersant concentration was adjusted to ensure homogeneous distribution of flame-retardant particles within the paste system, thereby improving stability and application consistency. Rheological measurements and foam density evaluations were performed to confirm that the final paste exhibited appropriate viscosity and foamability characteristics for industrial application.

#### 2.1.3. Performance Criteria of the Final Product

The optimized formulation was evaluated in laboratory and pilot-scale trials. The final product was required to: Pass flame-retardancy tests according to BS 5852-1:1979: source 1 Ignitability of Upholstery Fabrics Match test be suitable for foam application processes, provide a soft handle without stiffening the fabric structure, prevent dust formation during processing and end use. All formulation parameters were refined iteratively until these criteria were simultaneously satisfied.

**Table 1.** Samples definitions.

| <b>SAMPLE</b>           | <b>FABRIC 1</b>                  | <b>FABRIC 2</b>                  |             |
|-------------------------|----------------------------------|----------------------------------|-------------|
| <b>RUCO-COAT 717-HF</b> | <b>1000</b>                      | <b>1000</b>                      | <b>Part</b> |
| Foam density            | 500                              | 500                              | g/l         |
| Drying                  | 170/2                            | 170/2                            | °C/min      |
| Fabric sample           | %100 PES woven upholstery fabric | %100 PES woven upholstery fabric |             |

|                                    |     |     |                  |
|------------------------------------|-----|-----|------------------|
| Untreated fabric weight            | 307 | 380 | g/m <sup>2</sup> |
| Dry add-on                         | 149 | 100 | g/m <sup>2</sup> |
| (Based on fabric weight)<br>Add-on | 46  | 26  | %                |



**Figure 1.a** Sample FABRIC 1.



**Figure 1.b** Sample FABRIC 2.

**Table 2.** Some of test results

| SAMPLE                                                                           | RUCO-COAT 717-HF |                 |                    |                                                                                 |
|----------------------------------------------------------------------------------|------------------|-----------------|--------------------|---------------------------------------------------------------------------------|
| <b>Ignitability of Upholstery Fabrics Match test</b><br>BS 5852-1:1979: source 1 | <b>FABRIC 1</b>  | <b>FABRIC 2</b> | <b>REQUIREMENT</b> | Atmosphere for testing:<br>15-30 °C temperature,<br>%20-70 relative humidity.   |
| Flame application time                                                           | 20 s             | 20 s            | 20 s               |                                                                                 |
| Sample behavior after flame                                                      | Melting          | Melting         | -                  | Atmosphere for conditioning:<br>20±2°C temperature,<br>%65±4 relative humidity. |
| Does the flame reach the top edge in 2 min                                       | No               | No              | No                 |                                                                                 |
| <b>CONCLUSION</b>                                                                | <b>PASS</b>      | <b>PASS</b>     | <b>PASS</b>        |                                                                                 |

### 3. RESULTS

In this section, the fire performance, soaking durability, handle properties, and blooming behaviour of the developed halogen-free back-coating formulation are evaluated and discussed in relation to the targeted British Standards and application requirements.

### 4. CONCLUSION

This study successfully developed a halogen-free, environmentally traceable flame-retardant compound for the back coating of PES upholstery fabrics. The formulated product met the requirements of BS 5852-0:1979: source 0 Ignitability of Upholstery Fabrics Cigarette test and BS 5852-1:1979: source 1 Ignitability of Upholstery Fabrics Match test and demonstrated compliance with BS 5651:1978 soaking durability. In

addition to achieving high fire performance, the formulation maintained a soft fabric handle, showed no front-side migration (blooming), and proved suitable for paste and foam application processes. As a result of laboratory and pilot-scale trials, a formulation that met all target criteria was achieved. The sustainable, halogen-free, application-friendly, and high-performance flame-retardant compound developed in this study was successfully commercialized under the trade name RUCO-COAT 717-HF.

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## IMPACT OF PRETREATMENT OPERATIONS ON THE SUCCESS OF COTTON/POLYESTER FABRIC FUNCTIONALIZATION WITH CHITOSAN

Sandra Flinčec Grgac<sup>\*1</sup>, Martina Ivančić<sup>1</sup>, Ana Palčić<sup>1</sup>, Snježana Brnada<sup>2</sup>

<sup>1</sup> University of Zagreb Faculty of Textile Technology, Department of Textile Chemistry and Ecology, Zagreb, Croatia

<sup>2</sup> University of Zagreb Faculty of Textile Technology, Department of Textile Design and Management, Zagreb, Croatia

\* [sflincec@ttf.unizg.hr](mailto:sflincec@ttf.unizg.hr)

### ABSTRACT

The development of sustainable textile finishing processes has become increasingly important in reducing the use of harmful chemicals in the textile industry. Chitosan, a biodegradable, non-toxic natural polymer with antimicrobial properties, has attracted significant attention for multifunctional textile treatments. Its effective application depends on fiber type, pretreatment, concentration, processing conditions, and the selection of appropriate crosslinking agents to improve durability. This study investigates the bonding efficiency of chitosan crosslinked with citric acid on cotton/polyester fabric samples pretreated with an 8% NaOH solution, with and without a subsequent rinsing step. The aim was to evaluate how individual pretreatment operations affect chitosan binding and the resulting antimicrobial performance according to AATCC TM 147-2016, as well as moisture management properties measured using a Moisture Management Tester (MMT, SDL Atlas, Switzerland), before and after washing cycles. The results showed that the rinsing step following alkaline pretreatment did not significantly influence the antimicrobial effectiveness of chitosan-treated samples, either before or after washing. Both treated samples exhibited improved moisture transfer compared to the untreated control, as indicated by the lower wetting speed of the untreated fabric before washing (2.63 mm/s). After washing, wetting speed increased for all samples, while cumulative one-way transport capacity decreased, suggesting structural changes in the fabric. These findings contribute to the optimization of pretreatment conditions for chitosan-based functionalization of cotton/polyester fabrics and support the potential for sustainable industrial-scale applications.

**Keywords:** Cotton/polyester fabric, Alkaline pretreatment operations, Chitosan, Antimicrobial efficiency, liquid moisture transport properties

### 1. INTRODUCTION

In recent decades, the textile industry has increasingly emphasized the development of sustainable and environmentally friendly textile finishing processes. This approach aims to reduce the use of harmful chemicals in finishing operations. In this context, chitosan, as a natural polymer, has proven to be a suitable choice due to its biodegradable, non-toxic, and antimicrobial properties [1–4]. The successful application of chitosan depends on several factors, including the type of fiber, material pretreatment, concentration, processing conditions, and the type of crosslinking agent used to improve treatment durability. Previous studies have shown that chitosan, especially when used in combination with crosslinking agents such as polycarboxylic acids, can effectively bind to cellulose fibers and their blends and provide efficient antimicrobial protection [4-6]. It has also been established that certain fabric pretreatments, as well as chitosan concentrations, significantly influence the effectiveness and stability of the treatment [3]. Despite the known achievements, the question remains regarding the appropriate combination of processing



conditions and individual operational steps that allow the functionality to be preserved even after washing cycles.

This study focuses on investigating the possibility of chitosan bonding using citric acid as a crosslinking agent on cotton/polyester fabric samples previously treated in an 8% NaOH solution. The aim of the study was to evaluate how individual pretreatment operations influence the durability of chitosan binding to cotton/polyester material. The results of the study showed that the method of pretreatment affects the durability of the treatment, the achievement of desired antimicrobial properties, and the efficiency of moisture transport.

## 2. EXPERIMENTAL STUDY

### 2.1 Materials

A cotton/polyester fabric with a 50:50 blend ratio was used in this study, woven in a satin weave with a weft density of 26 threads per centimeter. Fabric samples were finished using a finishing formulation whose composition is shown in Table 1, applying different operations during the treatment process.

**Table 1.** Composition of the treatment bath

| Finishing agents                                         | mass concentration, g/l |
|----------------------------------------------------------|-------------------------|
| Citric acid (T.T.T. d.o.o., Croatia)                     | 20                      |
| Chitosan (Tricomed, Poland)                              | 10                      |
| Sodium hypophosphite monohydrate (SHP, Aldrich, Germany) | 30                      |
| Wetting agent (Felosan NOF, BEZEMA, Switzerland)         | 1                       |

### 2.2 Methods

The differences relate to the pretreatment procedure. For sample Ap1, after pretreatment in an 8% NaOH solution with the addition of 8 g/L of the agent SUBITOL MLF (BEZEMA, Switzerland), neutralization with 1% acetic acid was carried out followed by rinsing to pH 7, after which the treatment was performed in the finishing bath prepared with a bath ratio of 1:20. For samples Ap2, after pretreatment with the previously mentioned solution, the samples were immersed directly in the finishing bath without rinsing or neutralization. The finishing bath contained 20 g/L citric acid, 10 g/L chitosan, 1 g/L Felosan NOF, and 30 g/L SHP. Due to the lower pH value of the solution, 2.75 mL of 32% NaOH solution was added to adjust the pH. During bath preparation, citric acid was first dissolved in water, after which chitosan was gradually added with stirring on a magnetic stirrer at 400 rpm. Finally, SHP and the non-ionic surfactant were added. The pH of the bath at 23.7 °C was 3.57. To enable chitosan reactivity and prevent acid damage to the cellulose component of the material, the bath pH was adjusted to 5.83 using a 32% NaOH solution. After bath preparation, the samples were impregnated using a padding mangle, with a pick-up of 93%. The samples were then placed in a Mathis processing device (Turbomat P4502, Switzerland) at 40 °C for 1 hour, followed by aging in the bath for 20 hours.

Afterward, the samples were squeezed and dried at 100 °C for 2 minutes, followed by thermocondensation at 160 °C for 3 minutes, performed on a Benz tenter frame dryer with padding unit (Sweden). Half of the samples from each finishing treatment were subjected to washing according to a modified program based on the EN ISO 15797:2017 standard. Washing was performed using the standard detergent WFK 88060, which contains optical brighteners, does not contain phosphates, and includes the disinfecting agent phthalimidoperoxyhexanoic acid (PAP). The washing process was carried out on a Wascator FORM71 CLS laboratory device (Electrolux, Sweden) at 50 °C, after which the samples were dried in a laboratory dryer Electrolux T5130-LAB (Sweden). The legend describing the samples is presented in Table 2.

**Table 2.** Description of samples

| Samples            | Description of abbreviations                                                                                                                                                                                    |
|--------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| CO_PES_A_26        | Untreated sample; cotton (CO)/polyester (PES) blend fabric, satin (A) weave, weft yarn count 26.                                                                                                                |
| CO_PES_A_26_1W     | Untreated washed sample; cotton (CO)/polyester (PES) blend, satin (A) weave, weft yarn count 26, washed with one washing cycle (1W)                                                                             |
| CO_PES_A_26_AP1    | Cotton (CO)/polyester (PES) blend, satin (A) weave, weft yarn count 26; pretreated with rinsing, followed by treatment with a chitosan and citric acid solution (AP1).                                          |
| CO_PES_A_26_AP1_1W | Cotton (CO)/polyester (PES) blend, satin (A) weave, weft yarn count 26; pretreated with rinsing, followed by treatment with a chitosan and citric acid solution (AP1), washed with one washing cycle (1W)       |
| CO_PES_A_26_AP2    | Cotton (CO)/polyester (PES) blend, satin (A) weave, weft yarn count 26; pretreated and then subjected to chitosan and citric acid solution treatment without rinsing (AP2)                                      |
| CO_PES_A_26_AP2_1W | Cotton (CO)/polyester (PES) blend, satin (A) weave, weft yarn count 26; pretreated and then subjected to chitosan and citric acid solution treatment without rinsing (AP2), followed by one washing cycle (1W). |

Antimicrobial effectiveness was tested according to the modified AATCC TM 147-2016 method: “Antibacterial Activity Assessment of Textile Materials: Parallel Streak Method”, at the The Andrija Stampar School of Public Health. The effectiveness was evaluated against the Gram-positive bacterium *Staphylococcus aureus* ATCC 6538 (*S. aureus*, *Sa*), the Gram-negative bacterium *Escherichia coli* ATCC 8739 (*E. coli*, *Ec*), and the fungus *Candida albicans* ATCC 10231 (*C. albicans*, *Ca*). Samples were cut into 1 × 1 cm pieces and prepared under controlled conditions. They were then placed on the nutrient agar surface inoculated with a high concentration of bacteria and incubated under prescribed conditions. The method is based on observing the zone of inhibition around the sample, indicating the migration and effectiveness of the antimicrobial agent from the textile material [2, 5].

Comfort properties were tested using the Moisture Management Tester (MMT) by SDL Atlas (Switzerland), according to AATCC TM 195-2017: “Liquid Moisture Management Properties of Textile Fabrics.” Before testing, samples were conditioned under standard atmospheric conditions (20 ± 2 °C and 65 ± 2% relative humidity) to ensure measurement stability and reliability. For each sample, three specimens were prepared. The test results were expressed as mean values and coefficients of variation (CV) for the following parameters measured separately for the top surface (T) and bottom surface (B) of the fabric: Wetting Time (WT) – time required for the fabric surface to become wet; Absorption Rate (AR) – rate at which the fabric absorbs moisture; Maximum Wetted Radius (MWR) – distance to which moisture spreads within the fabric; Spreading Speed (SS) – speed of moisture spreading across the fabric surface; Accumulative One-way Transport Capability (R) – ability to transport moisture from one side of the fabric to the other; Overall (liquid) Moisture Management Capability (OMMC) [7].

### 3. RESULTS AND DISCUSSION

Table 3 presents the results of antimicrobial efficiency testing for all treated and untreated fabric samples before and after washing cycles. The results in Table 3 show that all treated samples, both before and after washing, exhibit antimicrobial effectiveness with a developed inhibition zone of 1 mm against the Gram-positive bacterium *S. aureus*.

**Table 3.** Results of antimicrobial activity

| Samples            | <i>Sa</i> | <i>Ec</i> | <i>Ca</i> |
|--------------------|-----------|-----------|-----------|
| CO_PES_A_26        | -         | -         | -         |
| CO_PES_A_26_1W     | -         | -         | -         |
| CO_PES_A_26_AP1    | + (1 mm)  | + (1 mm)  | + (1 mm)  |
| CO_PES_A_26_AP1_1W | + (1 mm)  | +/-       | +/-       |
| CO_PES_A_26_AP2    | + (1 mm)  | + (1 mm)  | + (1 mm)  |
| CO_PES_A_26_AP2_1W | + (1 mm)  | +/-       | +/-       |

Description of abbreviations: \**Staphylococcus aureus* (*Sa*), *Escherichia coli* (*Ec*), *Candida albicans* (*Ca*); (+) a distinct inhibition zone around the sample; microorganisms are not present on the fabric surface, underneath, or around the fabric. (+/-) microorganisms are not visible on the fabric surface or underneath it, but no inhibition zone is observed. (-) no inhibition zone; microorganisms are present on the fabric surface and underneath it.

The results also indicate that all samples demonstrate antimicrobial effectiveness against the Gram-negative bacterium *E. coli* and the fungus *C. albicans*, with an inhibition zone of 1 mm before the first washing cycle. However, after washing the inhibition zone is no longer visible, although no microbial strains were detected on or beneath the samples.

**Table 4.** Moisture management properties of cotton/polyester blended fabrics

| Samples   |   | CO_PES_A_26 |        | CO_PES_A_26_1W |       |
|-----------|---|-------------|--------|----------------|-------|
|           |   | Mean        | CV     | Mean           | CV    |
| WT (s)    | T | 4.331       | 0.06   | 2.635          | 0.032 |
|           | B | 4.594       | 0.09   | 2.559          | 0.040 |
| AR (%/s)  | T | 11.921      | 0.083  | 65.024         | 0.009 |
|           | B | 27.929      | 0.2271 | 62.242         | 0.011 |
| MWR (mm)  | T | 20          | 0      | 25             | 0     |
|           | B | 20          | 0      | 25             | 0     |
| SS (mm/s) | T | 2.629       | 0.035  | 5.848          | 0.016 |
|           | B | 2.629       | 0.041  | 6.122          | 0.022 |
| R (%)     |   | 328.118     | 0.128  | 49.984         | 0.154 |
| OMMC      |   | 0.605       | 0.108  | 0.506          | 0.017 |

Meaning of abbreviations: Coefficient of variation (CV); wetting time (WT); absorption rate (AR); maximum wetted radius (MWR); spreading speed (SS) for the top surface (T) and bottom surface (B); accumulative one-way transport capability (R); overall moisture management capacity (OMMC).

From Table 4 it can be observed that samples treated with citric acid and chitosan (CO\_PES\_A\_26\_AP1, CO\_PES\_A\_26\_AP1\_1W, CO\_PES\_A\_26\_AP2, CO\_PES\_A\_26\_AP2\_1W) show slightly shorter wetting times compared to untreated samples before and after washing (CO\_PES\_A\_26, CO\_PES\_A\_26\_1W). This indicates that chitosan partially covers the fibers and enables faster moisture absorption. After washing the untreated sample, the wetting time decreases even further, suggesting improved moisture absorption capacity. The absorption rate for sample CO\_PES\_A\_26\_AP1 is lower on the face side but increases on the reverse side compared to sample CO\_PES\_A\_26\_AP2, which was not rinsed after pretreatment. After washing both treated samples (CO\_PES\_A\_26\_AP1\_1W, CO\_PES\_A\_26\_AP2\_1W), the absorption rate values decreased. The maximum wetted radius increased for samples CO\_PES\_A\_26\_AP1 and CO\_PES\_A\_26\_AP2 compared to the untreated sample (CO\_PES\_A\_26), while after washing it decreased both for untreated (CO\_PES\_A\_26\_1W) and treated samples (CO\_PES\_A\_26\_AP1\_1W, CO\_PES\_A\_26\_AP2\_1W).

**Table 5.** Moisture management properties of treated cotton/polyester blended fabrics.

| Samples   |   | CO_PES_A_26_AP1 |       | CO_PES_A_26_AP1_1W |       | CO_PES_A_26_AP2 |       | CO_PES_A_26_AP2_1W |       |
|-----------|---|-----------------|-------|--------------------|-------|-----------------|-------|--------------------|-------|
|           |   | Mean            | CV    | Mean               | CV    | Mean            | CV    | Mean               | CV    |
| WT (s)    | T | 3.331           | 0.098 | 3                  | 0.049 | 3.169           | 0.172 | 3.194              | 0.030 |
|           | B | 3.237           | 0.101 | 3.037              | 0.017 | 3               | 0.129 | 3.081              | 0.055 |
| AR (%/s)  | T | 53.098          | 0.091 | 52.986             | 0.013 | 54.869          | 0.132 | 53.410             | 0.024 |
|           | B | 57.355          | 0.074 | 53.277             | 0.023 | 58.093          | 0.115 | 50.958             | 0.018 |
| MWR (mm)  | T | 23              | 0.119 | 21                 | 0.107 | 23              | 0.119 | 21                 | 0.107 |
|           | B | 24              | 0.093 | 22                 | 0.125 | 23              | 0.119 | 21                 | 0.107 |
| SS (mm/s) | T | 4.575           | 0.108 | 4.675              | 0.063 | 4.359           | 0.136 | 4.506              | 0.027 |
|           | B | 4.756           | 0.074 | 5.076              | 0.066 | 4.607           | 0.124 | 4.762              | 0.058 |
| R (%)     |   | 102.963         | 0.259 | 40.161             | 1.280 | 105.271         | 0.216 | -5.023             | 2.815 |
| OMMC      |   | 0.552           | 0.064 | 0.470              | 0.127 | 0.552           | 0.013 | 0.414              | 0.043 |

Meaning of abbreviations: Coefficient of variation (CV); wetting time (WT); absorption rate (AR); maximum wetted radius (MWR); spreading speed (SS) for the top surface (T) and bottom surface (B); accumulative one-way transport capability (R); overall moisture management capacity (OMMC).

This indicates that treated samples have faster moisture transport, whereas untreated samples show reduced moisture transfer speed, which is confirmed by the low spreading speed values before washing (2.63 mm/s) (Table 5). Spreading speed increases after washing, while the accumulative one-way transport capability decreases, indicating structural changes in the fabric.

The chitosan layer enables faster moisture transfer along the fibers, making the fabric more hygroscopic. After washing, the wetting time further decreases, meaning that the fabrics absorb moisture even faster. Such changes may indicate partial removal of unbound chitosan and the presence of bound chitosan within the fabric structure. Rinsing after pretreatment in sample CO\_PES\_A\_26\_AP1 enables more uniform binding of chitosan within the fabric structure, contributing to improved balance between moisture transport and moisture retention capacity.

#### 4. CONCLUSION

The aim of this study was to investigate the influence of finishing operations on the durability of cotton/polyester fabric treatment with chitosan using citric acid as a crosslinking agent. It is assumed that citric acid contributed to the binding of chitosan to the cotton/polyester material (CO\_PES\_A\_26\_AP1, CO\_PES\_A\_26\_AP1\_1W, CO\_PES\_A\_26\_AP2, CO\_PES\_A\_26\_AP2\_1W). Before washing, both treated samples show visible chitosan deposits, which are partially removed during washing, as reflected in the decrease in accumulative moisture transport capacity and reductions in maximum wetted radius and spreading speed, while antimicrobial efficiency remains present. In addition to chitosan, citric acid itself also contributes to antimicrobial activity. Samples that were rinsed after pretreatment and then treated with chitosan and citric acid (CO\_PES\_A\_26\_AP1, CO\_PES\_A\_26\_AP1\_1W) show improved moisture absorption, while non-rinsed samples (CO\_PES\_A\_26\_AP2, CO\_PES\_A\_26\_AP2\_1W) contain larger agglomerated chitosan deposits on the surface, which reduce cumulative moisture transport. Overall, it can be concluded that pretreatment followed by rinsing provides slightly better final properties, considering both hydrophilicity and antimicrobial efficiency. Based on the obtained results, further research will continue toward the development of potential environmentally friendly finishing processes for application in the textile industry, particularly in the development of medical textiles

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## IMPROVING TEXTILE PRACTICES ON SUSTAINABILITY: AN INTEGRATED DESIGN FRAMEWORK

Hacer Elif OZAYDIN<sup>1\*</sup>, Aze Elida YILDIZ<sup>2</sup>, Berfin AYYILDIZ<sup>3</sup>, Dilanur KARAGOZ<sup>4</sup>, Selin Hanife ERYÜRÜK<sup>1</sup>, Özgür ATALAY<sup>1</sup>, Marina TOETERS<sup>2</sup>

<sup>1</sup> Istanbul Technical University, Textile Engineering Department, Istanbul, Turkey

<sup>2</sup> Fashion Tech Farm, Eindhoven, Netherlands

\* [eryuruk@itu.edu.tr](mailto:eryuruk@itu.edu.tr), [atalayoz@itu.edu.tr](mailto:atalayoz@itu.edu.tr)

### ABSTRACT

The global textile industry is currently facing a paradigm shift necessitated by high resource consumption, hazardous chemical usage, and systemic supply chain opacity. This study proposes an integrated sustainability framework designed to transcend traditional "green marketing" by synthesizing technical engineering advancements with verifiable consumer value. The primary objective is to develop and evaluate sustainable improvement strategies that simultaneously consider production processes, material selection, and digital traceability. Methodologically, the framework integrates clean manufacturing technologies and circular design principles such as functional longevity and zero-waste patterns with advanced traceability tools like the Digital Product Passport (DPP). Data collection involves a structured survey applied to Turkish textile and clothing companies to gain information about their sustainable textile marketing practices. The prominent results indicate that a transparent supply chain, coupled with technically substantiated sustainability claims, effectively mitigates information asymmetry and enhances consumer Willingness to Pay (WTP). This research provides a strategic roadmap that aligns environmental efficiency with commercial success in the modern textile economy.

**Keywords:** *Life Cycle Assessment (LCA), Digital Product Passport (DPP), Analytic Hierarchy Process (AHP), Circular Design, Willingness to Pay (WTP).*

### INTRODUCTION

The global textile and apparel industry is currently navigating a period of unprecedented transformation, catalysed by the urgent need to transition from a linear "take-make-dispose" economy to a circular and regenerative framework [7]. As one of the most environmentally burdensome sectors, the textile industry is frequently cited as the second most polluting industry worldwide due to its extensive consumption of water, energy, and chemicals [1]. Recent data indicates that global fiber production has doubled since 2000, resulting in approximately 92 million tons of textile waste generated annually [1]. Furthermore, the industry faces increasing pressure from tightening environmental regulations, such as the EU Strategy for Sustainable and Circular Textiles, which mandates higher standards for durability, reparability, and traceability [2].

Despite these challenges, conventional textile production systems remain characterized by intensive resource usage and a significant lack of transparency across complex global supply chains [6]. The current situation is defined by a persistent "Intention-Behavior Gap," where consumers' pro- environmental attitudes fail to translate into actual purchasing actions [3]. This disconnect is primarily driven by profound Information Asymmetry, as the complexity of sustainable manufacturing makes it difficult for consumers to differentiate between authentic commitment and superficial greenwashing [4]. While isolated technical improvements have been made, there is a distinct lack of a holistic framework that simultaneously integrates production efficiency, circular design, and digital traceability [5].



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The primary purpose of this study is to develop and evaluate an integrated sustainability framework that improves textile practices across production, design, and supply chain dimensions [5]. By synthesizing technical engineering advancements—such as Life Cycle Assessment (LCA) and zero-waste pattern engineering—with digital tools like the Digital Product Passport (DPP), this research aims to bridge the gap between technical data and consumer value perception [7]. Ultimately, the study provides a strategic roadmap proving that sustainability can be systematically embedded into textile engineering to achieve both ecological preservation and competitive market success [6].

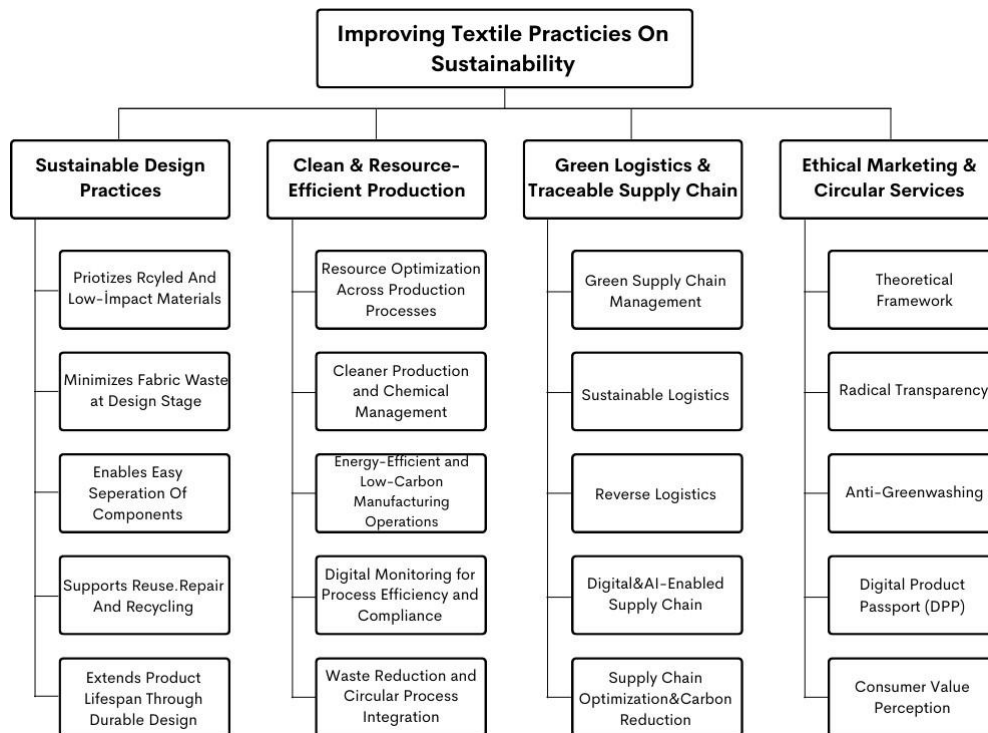
## EXPERIMENTAL STUDY

The methodology of this research is structured as a multi-stage analytical process, transitioning from technical data collection to empirical validation through a comparative survey method.

### Methodology and Survey Instrument

The empirical phase utilizes a structured survey methodology designed to gather qualitative and quantitative data from textile enterprises. The survey is applied Turkish textile and clothing companies to gain information about their sustainable textile marketing practices. The main objectives of the study is presented in Figure 1

Figure 1. Objectives of the study



## Sampling and Data Collection

**The survey targets integrated textile manufacturers to evaluate the implementation of "Clean Production." The questionnaire measures:**

- Operational Maturity: Adoption of low-liquor ratio dyeing and ZDHC-compliant management.
- Digital Readiness: Infrastructure for DPP and Industry 4.0 applications.
- Value Perception: Correlation between verified data and consumer WTP.

## Data Processing and Multi-Criteria Optimization

Data collected from the survey participants is processed to identify key performance indicators in sustainable textile manufacturing. This analysis allows for a realistic assessment of how companies balance material quality, cost efficiency, and environmental performance based on reported industry data.

## **RESULTS**

The evaluation demonstrates that sustainability performance is highly sensitive to system coherence. Technical transparency acts as a "hard signal" that effectively mitigates information asymmetry in the market [9].

### **Production Line & Technical Improvements**

Technical evaluations reveal that adopting low-liquor ratio dyeing systems and advanced wastewater treatment like membrane bioreactors (MBR) can achieve freshwater reductions of up to 87.5% [6]. AI-driven defect detection minimizes material waste by detecting anomalies in real-time, preventing defective materials from progressing to downstream processes [6].

### **Sustainable Design & Zero-Waste Patterns**

Zero-waste design eliminates substantial fabric waste at the production stage by prioritizing material utilization over standardized forms. Results suggest that functional longevity, which balances physical durability with emotional attachment, is a central concept for slowing down consumption [7].

### **Supply Chain & Logistics Optimization**

Sustainability is strongly shaped by Green Supply Chain Management (GSCM) and reverse logistics [6]. Compliance with Extended Producer Responsibility (EPR) and the EU Green Deal mandates product take-back systems, making circularity an operational necessity [2].

### **Sustainability Marketing & Transparency**

Radical Transparency, involving the disclosure of both production ethics and price breakdowns, creates a significant shift in purchase intentions [8]. The Digital Product Passport (DPP) interface enhances "Green Value Perception" by providing consumers with verified sustainability scores and localized recycling incentives [7].

## **CONCLUSION**

This study confirms that sustainability in the textile industry requires a holistic "system design" approach that transcends traditional functional boundaries [1]. By integrating technical engineering data with digital traceability (DPP) and survey-validated marketing strategies, the research provides a roadmap for industrial resilience [7]. Verified honesty, supported by clean manufacturing and transparent supply chains, is concluded to be the most valuable asset for competitive success in the circular economy.

## **ACKNOWLEDGMENT**

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## INVESTIGATION OF PHOTO-EXCITATION MECHANISMS IN PAN-BASED FIBERS

Selin GÜMRÜKÇÜ<sup>1</sup>, Semih DOĞAN<sup>1</sup>

<sup>1</sup>R&D and Sustainability Group Department, AKSA Akrilik Kimya Sanayii, 77602 Taşköprü Çiftlikköy-Yalova, Türkiye.

### ABSTRACT

Ultraviolet (UV) exposure is a critical environmental stressor for polyacrylonitrile (PAN)-based (acrylic) fibers used in outdoor textiles, awnings, and technical fabrics. In this study, the photo-excitation mechanisms of PAN-based fibers were systematically investigated to elucidate the underlying electronic transitions and subsequent photochemical processes. Spectroscopic analyses were performed to evaluate changes in optical absorption and emission characteristics upon UV exposure. Under long-lasting irradiation, PAN-based fibers can exhibit premature whitening, typically observed as a bleaching-like increase in lightness ( $\Delta L^*$ ) and a loss of color depth, which compromises aesthetic performance and may signal the onset of material aging. Hence, UV-induced whitening is associated with the concurrent development of photo-oxidative chemical modifications and surface/microstructural alterations. These processes disrupt the optical homogeneity of the fiber surface and enhance diffuse light scattering, resulting in a visible whitening effect. To clarify the key reaction pathways and physical triggers leading to whitening in PAN fibers under UV and oxygen exposure, the stabilization strategies and Accelerated photo-aging was conducted using controlled irradiation at selected UV (and near-UV) wavelengths, enabling wavelength-specific assessment of photoinduced degradation phenomena in accordance with established textile durability evaluation practices. Degradation indicators were monitored through an integrated analytical approach: CIELAB colorimetry ( $\Delta L^*$ ,  $\Delta b^*$ ,  $\Delta E^*$ ), UV-Vis reflectance/absorbance analysis, FT-IR spectroscopy, gel permeation chromatograph, and SEM. The dataset was evaluated through root-cause analysis using a standard commercial acrylic fiber and a UV-sensitive reference fiber to illustrate general PAN behavior. In parallel, formulation-related variables including comonomer composition, residual additives, and surface finish chemistry were assessed as potential photosensitizers and modifiers of oxygen diffusion. The results contribute to the development of more durable PAN-based fibers for outdoor service environments.

**Keywords:** Polyacrylonitrile; Photo-Excitation; Whitening; Outdoor textiles; UV durability.

## MULTI-PURPOSE/FUNCTIONAL MEN'S OUTERWEAR DESIGN FROM UNUSED PRODUCTS THROUGH REPURPOSING

Seda Kızıl<sup>1\*</sup>

<sup>1</sup> ÇGS-ÇETİNKAYA GİYİM SANAYİ, TASARIM MERKEZİ

\*skizil@cetinkaya.com.tr

### ABSTRACT

Repurposing is conceptualized within sustainable marketing as the practice of extending the life cycle of a product or its components by transforming them into a new product that serves a different function. From another viewpoint, repurposed products experience a shift in identity, evolving from their former state into a new and valuable form with a distinct character. In essence, repurposing involves modifying an existing product to provide it with a renewed or secondary life. Upcycling can be regarded as a specific subset of repurposing.

Today, with new consumer attitudes, technological advancements, and growing environmental awareness, a consciousness of environmentally responsible and sustainable design has emerged, particularly through the reuse of waste, leftover, or surplus materials in design processes. Within this framework, samples from different seasons, surplus collection items, and second-quality products stored in the company's design department—which would otherwise be discarded—were reviewed. Considering the high quantity of men's outerwear among these items, multi-purpose/functional men's outerwear designs were developed. A new coat created using components from a coat and a shirt, a new anorak produced from a vest and a cardigan, a new upper garment designed from elements of a flannel shirt and a coat, and a new convertible coat formed by combining a leather coat with a vest are among the designs developed through the repurposing approach in the conducted studies. In this way, repurposing unused stockroom products helped reduce waste, support the environment, and generate economic returns for the company through the sale of the new collection.

**Keywords:** *Design, Men's wear, Repurpose, Sustainability*

### 1. INTRODUCTION

Repurposing is conceptualized within sustainable marketing as the practice of extending the life cycle of a product or its components by transforming them into a new product that serves a different function. From another viewpoint, repurposed products experience a shift in identity, evolving from their former state into a new and valuable form with a distinct character. In essence, repurposing involves modifying an existing product to provide it with a renewed or secondary life, where upcycling can be regarded as a specific, value-adding subset of this practice (Ağlargöz, 2022; De Leede et al., 2021). The contemporary fashion industry faces significant scrutiny due to overproduction and post-industrial waste generation. Within the framework of circular economy principles, extending the life cycle of existing products through functional and aesthetic redesign serves as a critical intervention to prevent premature disposal and reduce waste (Kamleitner et al., 2019)

Within this respect, the aim of this project has been to develop a sustainable and design-oriented repurposing strategy for underutilized men's outerwear garments available in the company's design department, including seasonal samples, excess collection items, and second-quality products. By transforming obsolete or idle products into new multifunctional and value-added garments, the project seeks to demonstrate an innovative application of sustainable fashion with tangible commercial

potential. Beyond environmental and economic outcomes, this initiative aims to enhance industrial designers' awareness, knowledge, and practical competence in circular manufacturing workflows.

## 2. METHOD

The methodology of this project follows a structured, practice-based "Repurpose Driven Design" framework, executed through the following sequential phases:

1. **Inventory & Evaluation:** Underutilized men's outerwear garments within the Çetinkaya Design Center stockrooms were gathered and rigorously evaluated based on their material compositions, structural patterns, and aesthetic features.
2. **Deconstruction & Component Mapping:** Selected deadstock garments—comprising jackets, shirts, vests, cardigans, and coats—were partially or fully deconstructed to isolate functional components (bodies, sleeves, collars, pockets, and fastening systems).
3. **Recombination & Redesign:** Using creative draping and hybrid pattern-making techniques, these isolated components were rearranged and combined to form entirely new outerwear structures. Special emphasis was placed on modularity (e.g., zipper-assembled detachable components) to ensure multifunctionality.
4. **Prototyping:** The finalized configurations were sewn and finalized as commercial-grade prototypes adhering strictly to sustainable design and circular economy metrics.

## 3. RESULTS AND DISCUSSION

Through the active design phase, a total of six innovative garments were successfully engineered. The functional properties and structural composition of the developed designs are detailed in Table 1:

**Table 1.** Properties and structural composition of the developed designs

| Design ID            | Original Garment Components       | Key Technical & Functional Features                                          |
|----------------------|-----------------------------------|------------------------------------------------------------------------------|
| Design 1<br>(Fig. 1) | Jacket + Shirt                    | Thicker, integrated hybrid jacket optimized for practical layered clothing.  |
| Design 2<br>(Fig. 2) | Vest + Cardigan                   | Water-repellent body with detachable knit sleeves using armhole zippers.     |
| Design 3<br>(Fig. 3) | Lumberjack Shirt + Jacket         | High aesthetic value outerwear utilizing distinct flannel contrasts.         |
| Design 4<br>(Fig. 4) | Outerwear + Zipper Adjustments    | Adjustable, modular garment featuring structural silhouette transformations. |
| Design 5<br>(Fig. 5) | Worn Leather Jacket + Wool Coat   | Convertible bomber-style jacket / wool vest with zippered sleeves.           |
| Design 6<br>(Fig.6)  | Water-Repellent Jacket + Design 5 | Cold-weather layerable jacket using a double-sided attachment zipper.        |

**Design 1:** Produced by combining structural components from a standard jacket and an idle shirt. Due to simultaneously changing weather conditions, multi-layered clothing has recently become increasingly popular and practical for the modern male consumer. The final product integrates an outerwear piece with an inner front zipper, resulting in a thicker, highly functional hybrid jacket that provides a versatile and practical daily clothing alternative (Fig. 1).





**Figure 1.** Photograph of Design 1

**Design 2:** An anorak developed by integrating the body of a lightweight, water-repellent vest with the sleeves of an unused knitted cardigan. To maximize functionality, zippers were strategically placed at the armholes, allowing the sleeves to be completely detached from the main body. This design successfully creates the visual illusion of wearing a knit cardigan underneath a vest. When the vest is worn standalone in urban environments, the detached sleeves can be conveniently stored inside the large functional pockets or a small bag (Fig. 2).



**Figure 2.** Photograph of Design 2

**Design 3:** Created by blending the components of a classic flannel lumberjack shirt with an unused corporate jacket. This hybrid piece integrates the casual, textured pattern of the flannel shirt with the formal silhouette of the jacket to deliver a distinctive, stylish, and high-value outerwear product, fully reflecting the project's aesthetic repurposing goals (Fig. 3).



**Figure 3.** Photograph of Design 3

Design 4: Developed as a zippered, adjustable outerwear piece designed to tackle rapid environmental and temperature changes. By adding durable fastening systems along the hemline and core connection points, the garment's length and ventilation can be modified seamlessly by the user. This prototype showcases how technical hardware can give idle garments an adaptable, utility-driven secondary life (Fig. 4).



**Figure 4.** Photograph of Design 4

**Design 5:** Developed as a high-end convertible garment that seamlessly pairs with Design 6 to form a complex, heavy-duty outerwear system. In this configuration, the sleeves of an idle, worn leather jacket were repurposed and attached to the body of a second-quality wool coat by means of hidden zippers at the armholes. Consequently, the user is offered a highly versatile 2-in-1 garment: it can be worn either as a clean wool vest or transformed instantly into a leather-look, bomber-style jacket (Fig. 5).



**Figure 5.** Photograph of Design 5

Design 6: A specialized water-repellent protective jacket designed explicitly to support layered dressing configurations. By attaching the modular Design 5 product directly into the inner core of this jacket

using an integrated double-sided zipper system, the garment transforms into a heavy, insulated outerwear system perfectly suited for sub-zero, harsh cold weather conditions (Fig. 6).



**Figure 6.** Photograph of Design 6

## CONCLUSION

This project successfully establishes that creative repurposing within design departments serves as a viable, actionable model for sustainable product development. The systematic utilization of unused stockroom products and seasonal samples directly contributes to post-industrial waste reduction, lowering the environmental footprint of fashion manufacturing. Concurrently, the commercially viable aesthetic identities given to these repurposed garments present clear economic benefits through resource optimization and deadstock monetization. Finally, embedding these practices into design centers fosters institutional knowledge of circular economy principles, enhancing the practical competencies and ecological awareness of design teams for future collections.

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## ORGANIC-INORGANIC SOL-GEL COATINGS FOR REVERSIBLE COLORIMETRIC SWEAT PH SENSING IN SMART TEXTILES

Agnese D'Agostino<sup>1</sup>, Mariam Hadhri<sup>1</sup>, Raphael Rosa<sup>1</sup>, Giuseppe Rosace<sup>1,2,\*</sup>, Valentina Trovato<sup>1</sup>

<sup>1</sup> University of Bergamo, Department of Engineering and Applied Sciences, Dalmine (BG), Italy

<sup>2</sup> Local CSGI (Inter-University Center for Colloid and Surface Science) Research Unit, Dalmine (BG), Italy

\* [giuseppe.rosace@unibg.it](mailto:giuseppe.rosace@unibg.it)

### ABSTRACT

Recent progress in textile nanotechnology has accelerated the development of smart fabrics that enable chemical, physiological, and biochemical sensing. Integrating pH-responsive, dye-doped mesostructured phases into textiles is particularly attractive for diagnostic and monitoring applications. Sweat is a readily accessible biofluid for non-invasive, real-time physiological monitoring because it consists predominantly of water and contains electrolytes (e.g., Na<sup>+</sup>, K<sup>+</sup>, Cl<sup>-</sup>), metabolites (e.g., lactate, urea), and other low-molecular-weight biomarkers. Among these, pH is a key parameter, typically observed in the mildly acidic to near-neutral range (typically 4-7) under physiological conditions. Furthermore, because sweat pH correlates with several physiological conditions, continuous tracking can inform hydration and re-mineralisation strategies.

In this work, litmus was covalently linked to the silica precursor 3-glycidoxypyltrimethoxysilane (GPTMS) via a sol-gel route, yielding a porous, mechanically stable, and suitably polar sensing matrix. The covalent dye-silane linkage is designed to suppress indicator leaching during repeated wet exposures, while sol-gel silica provides an optically transparent matrix compatible with reflectance-based readout. Fourier transform infrared spectroscopy confirmed the formation of the hybrid dyestuff-silane network and its immobilisation on cotton and polyester substrates. Scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS) was employed to examine fibre-surface morphology and map the elemental distribution of the silica-derived coating, thereby confirming its successful, homogeneous deposition on the textile substrates. The resulting halochromic fabrics exhibited reversible, repeatable color changes over the pH range of 4.0-8.0. Diffuse reflectance measurements, complemented by color-space analysis, enabled quantitative pH estimation with an uncertainty of approximately  $\pm 0.5$  pH units, supporting the feasibility of this sol-gel strategy for wearable pH diagnostics. Overall, this platform is well-positioned for biomedical wearables that require non-invasive pH measurement, including monitoring applications in which local pH shifts may be clinically informative.

**Keywords:** *sol-gel coating, halochromic dye, wearable sensor, sweat pH, smart textiles*

### 1. INTRODUCTION

Smart textiles are increasingly explored as skin-conformal platforms that merge the comfort and drape of fabrics with sensing and actuation capabilities, enabling unobtrusive monitoring in healthcare and human-machine interfaces [1,2]. Within this landscape, textile-integrated chemical sensors are particularly attractive because they can interrogate biofluids at the body-environment interface without invasive sampling.

Sweat is a readily accessible matrix that carries electrolytes and metabolites, and its temporal evolution can reflect hydration status, thermoregulation, and other physiological processes [3]. Compared with intermittent sampling, continuous tracking on a garment can capture transient changes and reduce user

burden, provided the sensing layer remains stable under mechanical deformation and exposure to salts, humidity, and repeated washing. Among sweat-related parameters, pH is of interest because it is linked to perspiration composition and rate and can co-vary with electrolyte levels. Early textile-sol-gel approaches demonstrated that an organically modified silicate (ORMOSIL) network can host halochromic indicators and be interfaced with miniaturized optoelectronics; for instance, GPTMS-based hybrid xerogels chemically coupled to Methyl Red enabled wearable pH readout with adequate operational stability [4]. Building on this concept, covalently bonded litmus-GPTMS coatings were later coupled to low-power electronics and used for optical sweat pH monitoring, including preliminary on-body measurements [5].

Optical and colorimetric transduction offers practical advantages for textiles: it can be implemented with simple reflectance or absorbance measurements, is compatible with low-cost imaging or compact color sensors, and avoids direct electrical contact with the biofluid [6]. Solid-state colorimetric sensors based on halochromic molecules have also been developed using natural or synthetic dyes, highlighting the appeal of reagent-embedded substrates for green and wearable analytical devices [7]. However, for fabrics, the main technological bottlenecks remain dye leaching, drift under cyclic pH exposure, and performance losses after laundering.

Hybrid organic-inorganic sol-gel chemistry enables porous silica-based matrices that physically entrap and/or chemically anchor functional molecules. In GPTMS-derived systems, epoxy ring-opening reactions can be exploited to form covalent linkages with nucleophilic groups on pH indicators, improving retention within the inorganic network and strengthening affinity for cellulose surfaces [4,5,8]. Because the chemical structure of cotton contributes characteristic IR bands and can overlap with siloxane features, careful spectroscopic interpretation is required to verify coating formation and persistence after washing [9].

In this work, a GPTMS-functionalized litmus precursor was synthesized via epoxy ring-opening and applied to cotton via an industry-relevant pad-dry-cure sol-gel process. The resulting halochromic textiles were evaluated for coating uptake, wash durability, surface morphology, and reversible pH response within the physiologically relevant range. By consolidating the main spectroscopic, morphological, and colorimetric outputs into quantitative results, this study provides an experimentally grounded basis for designing washable, repeatable textile pH sensors and for benchmarking against alternative pH-sensitive fibrous platforms [10].

## **2. EXPERIMENTAL STUDY**

### **2.1 Materials**

Plain-weave cotton fabric (100% cellulose; scoured and bleached) was equilibrated at  $20 \pm 2$  °C and  $65 \pm 4\%$  relative humidity before use. 7-hydroxy-phenoxazone (Litmus), (3-glycidyloxypropyltrimethoxysilane) (GPTMS), boron trifluoride diethyl etherate ( $\text{BF}_3 \cdot \text{OEt}_2$ ), buffer components, absolute ethanol, and deionised water were used as received.

### **2.2 Synthesis of GPTMS-litmus hybrid precursor**

Litmus was functionalized via epoxy ring-opening of GPTMS, catalysed by  $\text{BF}_3 \cdot \text{OEt}_2$ , in a water/ethanol solvent system (60:40 v/v). GPTMS was used at 0.3 M with a 10:1 molar ratio relative to litmus;  $\text{BF}_3 \cdot \text{OEt}_2$  was added at 12% w/w with respect to GPTMS. The mixture was refluxed for 4 h and adjusted to pH 4 with 2 M NaOH.

### **2.3 Textile finishing and wash durability**

Cotton samples (20 x 30 cm) were padded with the freshly prepared sol using a two-roll laboratory padder set to 2 kg cm<sup>-2</sup> nip pressure (wet pick-up ~75%). Fabrics were dried at 90 °C for 5 min and cured at 170 °C for 3 min to consolidate the siloxane network. Controls were processed with unmodified

litmus. Wash durability was evaluated according to EN ISO 6330:2000 under domestic laundering simulation; dry solid add-on and weight loss after one wash were calculated from gravimetric measurements.

## 2.4 Characterization

ATR-FTIR spectra (4000-550  $\text{cm}^{-1}$ , 4  $\text{cm}^{-1}$  resolution) were recorded using a Thermo Avatar 370 spectrometer equipped with a diamond ATR crystal and normalized at 1430  $\text{cm}^{-1}$ . Surface morphology was examined by SEM (Phenom ProX G6, 10 kV, low vacuum). Optical response was assessed by diffuse reflectance/absorbance measurements and CIELAB colorimetry (Datacolor Spectro 700). The total colour difference was computed as  $\Delta E^* = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{1/2}$ .

## 3. RESULTS

Coating uptake and laundering resistance are quantified in Table 1. The fabric treated with unmodified litmus exhibited only a marginal add-on (0.2 wt%) and, after one washing cycle, the indicator was effectively removed from the substrate, confirming the limitations of non-covalent fixation. By contrast, GPTMS-functionalized litmus yielded a markedly higher add-on (3.2 wt%) and retained most of the deposited material after washing, with a weight loss of 1.1 wt%, consistent with a chemically anchored hybrid layer.

**Table 1.** Add-on values and weight loss after one washing cycle (WLW 1W) for cotton fabrics treated with unmodified litmus (CO\_LTM) and GPTMS-functionalized litmus (CO\_GPTMS-LTM).

| Sample       | Add-on (wt%) | WLW 1W (wt%) |
|--------------|--------------|--------------|
| CO_LTM       | 0.2          | /            |
| CO_GPTMS-LTM | 3.2          | 1.1          |

ATR-FTIR analysis corroborated successful inorganic network formation on the cotton surface. As outlined in Table 2, untreated cotton is dominated by cellulose-related features (broad O–H stretching near 3330  $\text{cm}^{-1}$ , C–H stretching around 2900  $\text{cm}^{-1}$ , and C–O–C bands in the 1030-1060  $\text{cm}^{-1}$  region), whereas treated samples display additional silica-related absorptions ( $\approx 1100$  and  $\approx 775$   $\text{cm}^{-1}$ ) consistent with Si–O–Si connectivity. Importantly, these siloxane signatures remained detectable after one washing cycle, indicating structural persistence of the xerogel coating.

**Table 2.** ATR-FTIR bands used to verify formation of the GPTMS–litmus coating on cotton and to assess persistence after washing.

| Band / range ( $\text{cm}^{-1}$ ) | CO_UT (untreated) | CO_GPTMS-LTM (treated)                | Assignment                                 |
|-----------------------------------|-------------------|---------------------------------------|--------------------------------------------|
| $\sim 3330$                       | Broad band        | Broad band                            | O–H stretching of cellulose / bound water  |
| $\sim 2900$                       | Present           | Present                               | C–H stretching of cellulose                |
| 1030–1060                         | Present           | Present                               | C–O–C asymmetric stretching of cellulose   |
| $\sim 1100$                       | Not observed      | Distinct band (retained after 1 wash) | Si–O–Si stretching (siloxane network)      |
| $\sim 775$                        | Not observed      | Distinct band (retained after 1 wash) | Si–O–Si vibration (silica-related feature) |

As shown in Figure 1, the CO\_UT sample exhibited the typical morphology of scoured cotton, characterized by well-defined longitudinal grooves and a clean fibrillar surface. EDS analysis detected only carbon (54 wt%) and oxygen (46 wt%), which is consistent with the chemical composition of cellulose. In contrast, the CO\_GPTMS-LTM sample showed fibres covered by a continuous, more uniform layer that partially smoothed the characteristic grooves on the cellulose surface.



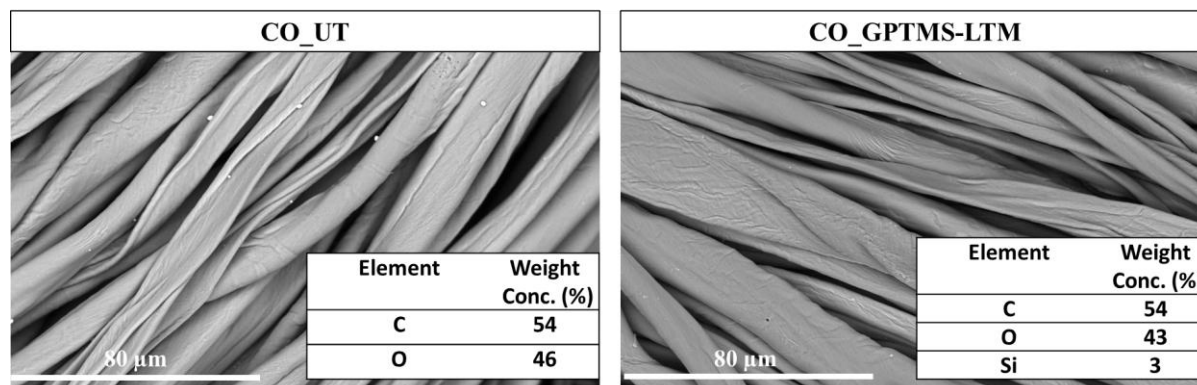


**Figure 1.** SEM micrographs (2000×) and corresponding EDS analysis of CO\_UT and CO\_GPTMS-LTM samples.

This morphological modification indicated the formation of a conformal coating. EDS confirmed the presence of silicon (3 wt%), together with carbon (54 wt%) and oxygen (43 wt%). The detection of Si, absent in the untreated sample, provided direct evidence of the successful deposition of a silane-based xerogel layer. Overall, the combined SEM-EDS results demonstrated homogeneous coating formation of the GPTMS-derived xerogel onto the cotton substrate.

Finally, the coating exhibited a reversible optical response to pH. Across pH 4-8, the absorption maximum shifts from ~515 nm under acidic conditions to ~490 nm in alkaline media (Table 3), in agreement with the acid-base equilibria of the litmus chromophore embedded in the hybrid network. Colorimetric analysis in CIELAB space showed a strong chromatic contrast ( $\Delta E^* > 20$  between pH 4 and pH 8), which was preserved after one washing cycle. Repeated pH switching (three cycles) produced minimal drift, with  $\Delta E^*$  fluctuations below 5%, supporting short-term repeatability of the response.

**Table 3.** Summary of pH-dependent optical and colorimetric performance for GPTMS-litmus cotton fabrics.

| Metric                                  | Acidic condition | Alkaline condition | Durability / repeatability note                                                             |
|-----------------------------------------|------------------|--------------------|---------------------------------------------------------------------------------------------|
| Working interval                        | pH 4             | pH 8               | Reversible response observed across pH 4–8                                                  |
| Absorption maximum ( $\lambda_{\max}$ ) | ~515 nm          | ~490 nm            | Shift attributed to reversible protonation state changes                                    |
| Chromatic contrast ( $\Delta E^*$ )     | —                | —                  | $\Delta E^* > 20$ between pH 4 and pH 8 before washing and maintained after 1 wash          |
| Repeatability ( $\Delta E^*$ stability) | —                | —                  | $\Delta E^*$ fluctuation < 5% over 3 pH switching events                                    |
| Post-wash integrity                     | —                | —                  | Silica-related FTIR features persisted, and color response remained detectable after 1 wash |

Overall, the findings show that GPTMS-mediated covalent immobilization was key to wash stability while maintaining measurable and reversible optical pH transduction, offering a practical basis for textile-integrated sweat pH sensing.

#### 4. CONCLUSION

A sol-gel strategy based on covalent functionalization of litmus with GPTMS enabled the fabrication of wash-stable, pH-responsive cotton textiles. Spectroscopic and morphological analyses supported the formation of a durable siloxane network and the homogeneous deposition of a xerogel. The coated

fabrics retained reversible halochromic response within the physiological pH window (4-8) after laundering, supporting the potential of this approach for wearable, non-invasive sweat pH monitoring.

## ACKNOWLEDGMENT

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## **POSTURE SUPPORTIVE DENIM SHIRT DESIGN**

**Beyzanur Ulaşır<sup>1,\*</sup>**

<sup>1</sup>Eroğlu Giyim Tasarım Merkezi

\*Beyzanur.Ulasir@eroglugiyim.com

### **ABSTRACT**

Prolonged low-activity work, particularly in desk-based occupations, often leads to decreased muscle strength due to extended periods of maintaining the same posture and limited physical movement. Over time, this condition contributes to postural disorders, as well as back and lower back pain. For individuals with advanced postural deformities, various supportive products such as braces are available to help maintain proper alignment. However, preventing the progression of postural disorders and avoiding permanent musculoskeletal deformities requires not only corrective products but also muscle-strengthening exercises (e.g., Pilates) and conscious efforts to maintain correct sitting posture during work. This study aims to design a supportive wearable garment, based on denim fabric, to assist desk workers in improving and maintaining proper posture. To determine the functional requirements of the posture-support product, an extensive literature review was conducted. The design process focused on integrating both rigid and elastic fabrics within the same garment structure. Specifically, the back panel—either entirely or partially—was constructed from rigid fabric to promote an upright posture, while other sections incorporated elastane-containing fabrics to ensure comfort and mobility. In addition, technical challenges associated with combining rigid and highly elastic fabrics—such as differential stretching, seam puckering, and distortion during sewing—was addressed. In addition to this design, alternative models were also developed to enable the attachment of supportive apparatus and posture-alert devices that help desk-based workers maintain an upright posture. The ultimate objective was to develop a functional, comfortable, and structurally supportive denim shirt design that contributes to posture correction and prevention in desk-based working environments.

**Keywords:** *Denim, Ergonomic clothing, Posture, Support*

## THE ROLE OF GARMENT CONSTRUCTION IN REDUCING TEXTILE WASTE: AN ANTHROPOMETRIC APPROACH TO SUSTAINABLE PATTERN MAKING

Blaženka Brlobašić Šajatović<sup>1\*</sup>, Franka Karin<sup>1</sup>, Renata Hrženjak<sup>1</sup>, Ksenija Doležal<sup>1</sup>

<sup>1</sup> Faculty of Textile Technology University of Zagreb, Zagreb, Croatia

\* [blazenka.brlobasic@ttf.unizg.hr](mailto:blazenka.brlobasic@ttf.unizg.hr)

### ABSTRACT

Anthropometry and garment construction play a key role in contemporary pattern making, enabling the precise adaptation of garments to human body measurements. The use of accurate anthropometric data during pattern development leads to a more precise construction process and improved garment fit. In this study, a comparison was made between a standard construction pattern and an anthropometric pattern for a men's shirt, with particular emphasis on construction time and the number of required corrections. The results show that the anthropometric approach significantly reduces the number of pattern corrections and improves construction efficiency. Efficient construction and careful planning of pattern development contribute to better material utilisation and reduce the need for repeated prototype adjustments. As the textile industry is one of the largest environmental polluters, reducing textile waste has become essential for sustainable production. Therefore, anthropometry and garment construction represent not only the technical foundation of pattern making, but also important tools for improving production efficiency and reducing the environmental impact of the fashion industry.

**Keywords:** *anthropometry, intercut loss, textile industry*

### 1. INTRODUCTION

Anthropometry and garment construction play a significant role in the technological process of clothing pattern making and design. The development of the textile and fashion industry, driven by technological progress and increasing market demands, has created a need for a precise and scientifically based approach to garment design. In this context, anthropometry, the science of measuring the human body, enables the collection of accurate data on body dimensions, proportions, and variations within the population. These data form the basis for constructing patterns that ensure optimal fit, comfort, and functionality of clothing. The application of anthropometric measurements in the garment construction phase allows for the rational design of pattern pieces and their precise adaptation to different body types. This achieves not only the aesthetic and functional quality of the garment but also ensures more efficient use of textile materials. Careful planning of the marker layout and proper arrangement of pattern pieces on the marker reduce inter-pattern waste, that is, the amount of waste generated during the cutting process. Given that the textile industry is one of the largest global polluters, sustainability has become one of the key challenges of modern production. Reducing textile waste, rational consumption of raw materials, and optimisation of production processes are necessary steps towards more environmentally responsible business practices. In this regard, anthropometry and garment construction represent not only technical and aesthetic components of garment production but also important tools in reducing the negative impact of the fashion industry on the environment. This paper analyses the role of

anthropometry and garment construction in the process of modern garment cutting, with particular emphasis on their contribution to reducing textile waste and improving sustainable production [1,2].

## **2. IMPORTANCE OF ANTHROPOMETRIC MEASUREMENTS**

Anthropometric measurements involve the systematic collection of data on the dimensions and proportions of the human body, with the aim of applying this information in various fields, among which garment construction is particularly important. The accuracy of these measurements is essential for developing patterns that ensure proper fit, comfort, and functionality of clothing. To develop garment patterns, it is necessary to study a large number of human body proportions. The goal of anthropometry is to quantitatively characterise the morphological and physiological features of the human body based on body measurements, which vary within and between specific populations. Through statistical processing of anthropometric measurements from a given population or country, clothing labelling systems, standard and proportional measurements are determined, and size systems for clothing and footwear are established. Increasing importance is being placed on the fit and comfort of clothing produced based on the average anthropometric characteristics of a specific population. The values of average body dimensions change significantly due to factors such as nutrition, lifestyle, climate, and others. Anthropometric measurements of subjects are performed using the conventional body measurement method with traditional measuring equipment, as well as by using non-contact body measurement systems, such as 3D body scanners. Measuring instruments and procedures for anthropometric measurements have been developed to ensure accurate and reliable measurements of populations for garment construction (within the textile, clothing, and footwear industries), as well as for other industrial sectors, medicine and paediatrics, educational institutions, and more. The basic anthropometric instruments used in the conventional measurement method include the anthropometer, stadiometer, pelvimeter, cephalometer, sliding caliper anthropometer, caliper, measuring tape, and scale. In addition to conventional measuring instruments, 3D body scanners are also used for measuring body dimensions. A 3D scanner analyses an object in the real world or its environment to collect data about its form. The collected data are used to construct digital, three-dimensional models. The standardisation of measurement points and methods ensures data consistency and enables their application in mass production. At the same time, modern technologies such as 3D body scanning further increase precision and allow for more detailed analysis of body proportions. By applying reliable anthropometric data in pattern construction, the need for subsequent corrections is reduced, thereby optimising the production process and decreasing textile waste. Disadvantages of 3D scanning compared to traditional anthropometric measurement methods include the lack of data on certain body surfaces due to shadows, light absorption caused by hair and skin colour, and differences in measurement techniques between scanners, as variations exist in the methods used to capture specific body measurements. Advantages of 3D scanning include a significantly larger amount of measured data, the possibility of analysing body shape and posture, faster measurement procedures, preservation of participant privacy since measurements are performed without physical contact, and the possibility that the obtained values may be more accurate and repeatable than conventional body measurements. For the clothing and textile industry, anthropometric measurements using conventional methods are conducted in accordance with EN 13402-3:2017 standards, while 3D scanning of subjects is performed in accordance with ISO 20685-2:2023 [1,3].

### **2.1 Garment Construction, Marker Layouts, and Inter-Pattern Waste**

Garment construction is a fundamental phase in garment production, during which pattern pieces are developed based on anthropometric measurements and the design model. The purpose of construction is to ensure proper fit, functionality, and aesthetic value, while also enabling efficient use of materials. A well-constructed pattern allows precise shaping of garment parts according to the body's contours and reduces the need for later corrections during production. After the construction phase, the marker layout is created – this is the plan for placing pattern pieces on the marker or fabric. The marker layout must

be designed to maximise the use of the material's width and length, while considering grain direction, fabric pattern, elasticity, and the technical requirements of the design. A properly planned marker layout enables optimal arrangement of pattern pieces, thereby reducing the amount of unused material. Inter-pattern waste is the portion of fabric that remains unused after cutting. It arises from improper arrangement of pattern pieces, limitations in material width, the shape of individual pieces, or specific design requirements. In industrial production, even a small percentage of inter-pattern waste can result in significant material and financial costs, as well as increased textile waste. Modern construction methods and computer-aided design (CAD) systems enable precise planning of marker layouts and simulation of different pattern placement options. This leads to more efficient material utilisation, reduced production costs, and contributes to the sustainability of the textile industry. Therefore, garment construction and marker layout optimisation are key elements in reducing inter-pattern waste and in developing an environmentally responsible production system [4-6].

### 3. EXPERIMENTAL STUDY

The International Organization for Standardization (ISO) has issued a series of standards that serve as the basis for the global system of size designation for clothing and footwear. In accordance with ISO 8559 and EN 13402:3-2017 – Size designation of clothes, research was conducted on a sample of 189 male subjects aged 22 to 35 years. Anthropometric measurements, carried out using the conventional method, included 54 body dimensions of the male population. The paper analyses the body measurements required for constructing a men's shirt. To determine body measurements using the conventional method, a complete set of anthropometric instruments was used (Table 1). For the experimental comparison of construction models, a representative subset of subjects was used to test the fitting and correction process of the shirt prototype.

**Table 1.** Basic Parameters of the Distribution of Main Body Measurements for the Construction of a Men's Shirt

| Main body m<br>(cm)            | $\bar{x}$ | s     | CV (%) | 95% CI<br>h1 | 95% CI<br>h2 | Min.  | Max.  |
|--------------------------------|-----------|-------|--------|--------------|--------------|-------|-------|
| <b>Body height</b>             | 180,1     | 6,02  | 3,3    | 179,2        | 180,9        | 170,0 | 200,5 |
| <b>Chest<br/>circumference</b> | 102,6     | 9,03  | 9,8    | 91,2         | 93,8         | 72,7  | 131,0 |
| <b>Waist<br/>circumference</b> | 81,9      | 10,36 | 12,6   | 80,4         | 83,3         | 61,0  | 130,0 |
| <b>Hip<br/>circumference</b>   | 99,1      | 7,96  | 8,0    | 98,0         | 100,3        | 82,0  | 135,0 |
| <b>Neck<br/>circumference</b>  | 40,2      | 2,99  | 8,1    | 36,7         | 37,5         | 30,0  | 46,0  |
| <b>Armhole<br/>depth</b>       | 20,8      | 2,91  | 14,0   | 20,3         | 21,2         | 14,0  | 30,0  |
| <b>Back length</b>             | 46,8      | 4,84  | 10,3   | 46,1         | 47,5         | 35,2  | 64,0  |
| <b>Garment<br/>length</b>      | 76,5      | 3,01  | 3,9    | 76,1         | 77,0         | 71,5  | 86,8  |



|                   |      |      |      |      |      |      |      |
|-------------------|------|------|------|------|------|------|------|
| <b>Back width</b> | 38,6 | 3,89 | 10,1 | 38,0 | 39,2 | 30,0 | 51,0 |
|-------------------|------|------|------|------|------|------|------|

<sup>a</sup> number of cases, <sup>b</sup> arithmetic mean, <sup>c</sup> standard deviation, <sup>d</sup> coefficient of variation, <sup>e</sup> confidence interval 95%

Anthropometric measurements were taken using the conventional body measurement method, employing standard anthropometric measuring equipment. The measurements followed standardised anthropometric procedures to ensure reliable and comparable data collection. The main body dimensions measured included body height, chest circumference, waist circumference, hip circumference, and neck circumference. In addition to these basic body dimensions, proportional and construction measurements important for pattern construction were also recorded: armhole depth, back length, garment length, and back width. The resulting statistical indicators provide insight into the average values of body measurements, their variability, and the range of deviations within the observed population. Based on these data, it is possible to define characteristic body proportions used in garment construction and pattern system development. The results of the anthropometric measurements form an important basis for garment construction. By analysing the average values and ranges of body measurements, construction parameters can be defined to enable better garment fit for different body types. The application of these data in pattern construction contributes to the optimisation of marker layouts and a more rational arrangement of pattern pieces, thereby reducing inter-pattern material loss and the amount of textile waste generated during production. Analysis of the anthropometric measurements of the subjects shows significant variability in certain body dimensions, particularly chest circumference, waist circumference, and shoulder width. The range of values in chest circumference is as much as 23 cm (from 92 cm to 115 cm), while the difference in waist circumference is 30 cm. Such differences indicate considerable diversity in body proportions within the observed group of subjects. Standard construction patterns, based on average ready-to-wear measurements, often cannot fully accommodate such a wide range of body dimensions. As a result, additional pattern corrections are required, including shifting construction lines and adjusting individual pattern pieces during garment production. For this reason, this research applied an anthropometric approach to the construction of a men's shirt, with pattern pieces defined according to the measured body dimensions of the subjects. This approach enables more precise sizing of pattern pieces and more optimal marker layout planning, which may result in a reduction of inter-pattern material loss. In the continuation of the study, the efficiency of the standard construction pattern (Model A) and the anthropometric pattern (Model B) is analysed, with particular emphasis on the number of corrections, construction time, and the amount of inter-pattern waste [1].

### 3.1 Analysis of the Efficiency of Construction Models

Based on the average anthropometric measurements of the subjects, particularly chest circumference (102,6 cm) and neck circumference (40,2 cm), the standard construction pattern (Model A) corresponds approximately to clothing size 40 according to the European clothing size designation system. This pattern is based on average measurements and represents a typical industrial approach to the construction of a men's shirt. In this study, two approaches to the construction of a men's shirt were compared: the standard construction pattern (Model A) and the anthropometric pattern (Model B). The analysis was conducted based on three key parameters: construction time, the number of required corrections, and the amount of inter-pattern waste.

### 3.2 Analysis of Construction Time

The results show that the average construction time for Model B was 65 minutes, while Model A required 42 minutes. The longer construction time for the anthropometric pattern is expected, as it

involves a more detailed analysis of the individual body measurements of the subjects. However, after the first fitting, the time required for corrections in Model B was significantly shorter (10 minutes) compared to Model A (33 minutes). Consequently, the total production time for both models was approximately the same (75 minutes). Although the total production time for both models is equal (75 minutes), the time allocation differs: Model A requires more time for corrections, while Model B requires more time during the initial construction phase. This indicates that the anthropometric pattern reduces the need for subsequent adjustments (Table 2).

### 3.3 Analysis of the Number of Corrections

An initial pattern is created for Model A – a standard pattern based on clothing size – and Model B – a pattern constructed according to anthropometric measurements. The subject then wears the shirt, and the fit is subjectively analysed in the areas of chest circumference, waist circumference, shoulder position, sleeve length, armhole position, and back width. Each modification of a construction line is counted as one correction. The number of corrections is an important indicator of the quality of the initial pattern construction. For the standard pattern (Model A), the average number of corrections was 3.1, while for the anthropometric pattern (Model B) this number was reduced to 0.9. This result shows that a pattern constructed based on the actual anthropometric measurements of the subjects corresponds much better to their body proportions. Reducing the number of corrections not only improves the fit quality of the garment but also simplifies the production process (Table 2).

**Table 2.** Comparison of the Efficiency of Model A and Model B of a Men’s Shirt

| Parameter                               | Model A – Standard Fit | Model B – Anthropometric Fit | Difference / Improvement            |
|-----------------------------------------|------------------------|------------------------------|-------------------------------------|
| Average pattern construction time (min) | 42                     | 65                           | Model B requires more initial time. |
| Average correction time (min)           | 33                     | 10                           | Reduction $\approx$ 69.7%           |
| Total time (min)                        | 75                     | 75                           | Total time equals                   |
| Average number of corrections           | 3.1                    | 0.9                          | Reduction $\approx$ 71.0%           |

The analysis of the results shows that applying the anthropometric pattern reduced the average number of corrections from 3.1 to 0.9, representing a reduction of approximately 70.9%. Additionally, the time required for corrections decreased from 33 minutes to 10 minutes, corresponding to a reduction of approximately 69.7%. These results confirm the greater precision of the anthropometric approach to garment pattern construction.

The number of corrections is an important indicator of the precision of pattern construction. A higher number of corrections indicates insufficient adaptation of the pattern to the user's actual body dimensions, which may lead to repeated interventions in the construction process and increased material consumption during prototype garment development. In this study, the standard construction pattern (Model A) required an average of 3.1 corrections, while the anthropometric pattern (Model B) required only 0.9 corrections. The reduction in the number of corrections indicates greater precision in construction based on anthropometric measurements. Fewer construction interventions contribute to

more stable shaping of pattern pieces and reduce the need for repeated adjustments and the production of additional prototype garments. As a result, material consumption and the amount of textile waste generated during the garment development process are indirectly reduced.

#### **4. CONCLUSION**

The results show that using anthropometric measurements in garment construction enables more precise sizing of pattern pieces and significantly reduces the number of corrections required during production. By decreasing construction interventions, production efficiency increases, the need for additional prototype garments is reduced, and textile materials are used more efficiently. Thus, the anthropometric approach contributes to more sustainable and environmentally responsible clothing production. Although inter-pattern waste was not directly measured, the significant reduction in pattern corrections indicates improved construction accuracy and suggests a potential decrease in material consumption during garment development.

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## **UPCYCLING SOCKS PRODUCTION WASTE INTO THE ECONOMY**

**Tuğçe İşgören<sup>1</sup> , Metin Yüksek<sup>1</sup>**

<sup>1</sup>Marmara University

### **ABSTRACT**

While textile recycling has significant potential, a comprehensive recycling ecosystem has not yet been established. However, significant and rapid steps are being taken daily to establish both international validations and technological infrastructure. Textile recycling is carried out using two main methods: mechanical and chemical. Mechanical recycling is the method that receives more attention due to its low cost and low environmental impact. However, this method results in significant reductions in the mechanical properties of the resulting fibers. Recycled fibers are then recycled into lower-value-added products for new products or reintroduced into the production process by supplementing new fibers. Mechanical recycling is seen as an effective method for transforming waste textiles into new textile products with minimal environmental impact. It also helps reduce the need for primary raw materials and significantly reduces the likelihood of textile waste being incinerated or dumped in landfills. Raw materials play a significant role in production costs. In addition to raw material prices representing a significant cost, pre-consumer textile waste has no commercial value. Bringing these wastes, which are more qualified than post-consumer textile wastes, into the economy is very valuable in terms of qualified upcycling. The focus of the study is on the evaluation of pre-consumer waste socks as a high value-added product in areas requiring insulation.

**Keywords:** *Circular Economy, Textile Recycling, Textile Waste, Upcycling, Waste Management*

## USING THE VIBRATION TRANSMISSIBILITY OF KNITTED FABRICS FOR VARIOUS APPLICATIONS

Perdevară Mihaela\*, Grosu Cristina, Rusu Ioana-Otilia, Plăcintă Diana-Andreea, Blaga Mirela

“Gheorghe Asachi” Technical University of Iași, Faculty of Industrial Design and Business Management, Romania

\*mihaela.perdevara@staff.tuiasi.ro

### ABSTRACT

Weft spacer knitted fabrics can effectively reduce vibration transmission, making them suitable for protective environments where vibration may cause discomfort or injury. They are used in anti-vibration gloves, pads, and mats to reduce hand-arm vibration from machinery or tools, as cushioning layers for workstations or equipment mounts to isolate vibration and reduce noise exposure, and can be integrated into seat cushions, headrests, or armrests to dampen vibrations from engines or machinery. In medical and recovery support applications, spacer fabrics cushion joints and soft tissue while reducing mechanical vibrations transmitted to the limb, and are useful for prosthetic liners where comfort and shock absorption are critical. For rehabilitation and physiotherapy equipment, they can provide controlled vibration transmission, which may enhance muscle activation and proprioception during rehabilitation. Weft spacer knitted fabrics offer a unique combination of adjustable vibration damping, lightweight comfort, and structural stability, making them ideal for both protective applications in industrial, automotive, sports, as well as, medical contexts where vibration isolation and soft tissue protection are critical. Their 3D architecture and inlay design allow engineers and textile designers to target specific frequency ranges, optimizing performance for comfort, safety, or therapeutic outcomes. This paper analyses the vibration transmissibility of weft spacer knitted fabrics and discusses potential applications in various fields, providing a guideline for selecting and designing knitted textiles for vibration-sensitive environments.

**Keywords:** *Spacer knitted fabrics, Vibrations, Transmissibility, Applications.*

### 1. INTRODUCTION

The human body is sensitive to vibrational environments generated by electrically and pneumatically powered rotary tools and processes in mining, demolition, or road construction, which may cause discomfort and disease. For example, workers with significant exposure to hand-transmitted vibrations may develop hand-arm vibration syndromes (HAVS), such as vibration-induced white finger (VWF) and peripheral neurological disorders. To mitigate the effects of vibration on the human body, passive anti-vibration materials such as rubber and polyurethane foams have been used in car cushions, anti-vibration gloves, and similar products. However, these conventional anti-vibration materials are often uncomfortable due to poor air and moisture management.

Knitted spacer fabrics could be a suitable alternative for vibration isolation, as they can provide better thermophysiological comfort for the human body [1, 2]. Due to their layered structure, knitted spacer fabrics are appropriate for the sound attenuation, concrete reinforcement, geotextiles, thermal insulation, impact protection, and the piezoelectric effect for energy harvesting. Knitted spacer fabrics have proven effective in reducing the magnitudes of sportive and occupational vibrations because of their versatility and valuable properties, such as high compressibility, breathability, impact resistance, elasticity, and elastic recovery. These performances have been highlighted in a series of research studies by analysing the spacer fabric characteristics and parameters with the greatest influence on behaviour in a vibration environment, such as spacer yarn threading, spacer yarn diameter, yarn consumption, fabric thickness,

and raw material [3, 4]. This paper analyses the vibration transmissibility of weft spacer knitted fabrics and discusses potential applications in various fields. By characterising how fabric structure, yarn type, and thickness affect vibration propagation, the study aims to provide guidelines for selecting and designing knitted textiles for vibration-sensitive environments.

## 2. EXPERIMENTAL STUDY OF KNITTED MATERIALS TRANSMISSIBILITY

Knitted materials are characterised by internal damping (the behaviour of a damper, due to internal friction) and stiffness (the behaviour of a spring). Internal damping refers to the ability of a material to dissipate modal mechanical energy or to irreversibly convert modal energy from vibration into heat. Internal stiffness refers to the magnitude of reversible deformation under a compressive force and is defined as the ratio between the compressive force and the resulting deformation. One of the best and simplest methods to estimate the damping and stiffness properties of a knitted fabric is to use a single degree of freedom (SDOF) vibration system – a spring-mass-damper (SMD) system – placed on a mobile support S, as shown in Fig. 1 [1].

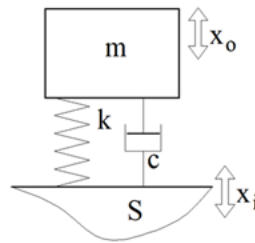


Figure 1. SDOF vibratory system [1]

The role of the suspension in the mass-spring-damper system is typically fulfilled by a spring (with *stiffness k*) and a damper (with *damping ratio c*). In this case, the suspension is replaced by the material tested specimen. Under these conditions, the mass-spring-damper system functions as a vibration isolator. The isolator’s transmissibility, *T* is defined as the ratio of the displacement amplitudes, *X<sub>o</sub>* and *X<sub>i</sub>* of the mass *m* and the support S (Equation 1):

$$T = \frac{X_o}{X_i} \quad \text{Eq.1}$$

Thus, *T* is defined as the ratio of the output (transmitted vibration) amplitude to the input (source vibration) amplitude. The crossover point occurs when *T* = 1, corresponding to the condition where the transmitted vibration amplitude equals the input amplitude. This frequency is commonly referred to as the crossover frequency (*f<sub>c</sub>*) or the unity transmissibility point [5], [6]. Figure 2 presents an example of the simulation of *T*, determined for a knitted material, as part of extensive research carried out on spacer knitted materials, produced on automatic flatbed knitting machines.

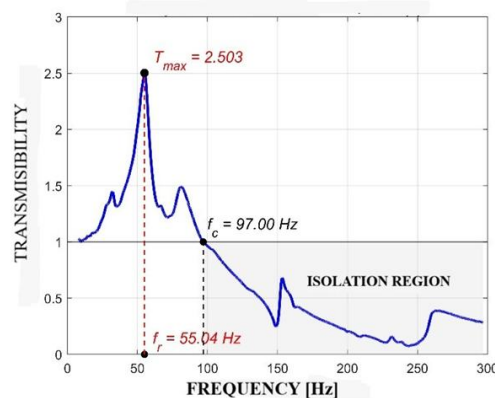


Figure 2. Simulation of spacer knitted materials vibration transmissibility



For transmissibility values less than unity ( $T < 1$ ), the system attenuates the input vibration, indicating effective vibration isolation region. Conversely, for transmissibility values greater than unity ( $T > 1$ ), the system amplifies the input vibration, resulting in an increased transmitted response. Thus, the crossover points at  $T = 1$  represents the boundary between amplification and isolation regions in the system's dynamic response.

The resonance region occurs when the excitation frequency approaches the system's natural frequency,  $f_r$ , that is, when the frequency ratio  $r \approx 1$ . In this region, the system exhibits a pronounced dynamic response characterized by a peak in transmissibility,  $T_{max}$ . Physically, resonance arises because the external excitation is in phase with the system's natural motion, allowing energy to be efficiently transferred into the system. As a result, even relatively small input vibrations can produce large output amplitudes. From an engineering perspective, operation within or near the resonance region is generally undesirable, as it can cause excessive vibrations, reduced performance, or structural failure. Consequently, systems are typically designed either to avoid excitation frequencies near the natural frequency or to include sufficient damping to reduce the severity of the resonance peak.

### 3. EXPERIMENTAL PART

Knowing that the raw material, binding yarn ratio and the NP setting influence vibration behavior, a set of spacer knitted fabrics was produced on a Stoll CMS 330 TT, E7.2 automatic flatbed knitting machine. From these, several representative structures (one example shown in Figure 3) were selected for further evaluation in practical applications. The fabrics were manufactured with two outer layers made from Cotton Nm 50/1 (code X) and Cotton Nm 50/1 plus polyester/elastane, 237.3 dtex (code Y). The layers were connected using a PES monofilament with a diameter of 0.10 mm and a fineness of 108 dtex, at a 1:15 binding ratio (coded A), while the stitch cam position was set at two values: NP11 and NP13 (codes 1 and 3). The samples were tested in both raw and finished states (F).

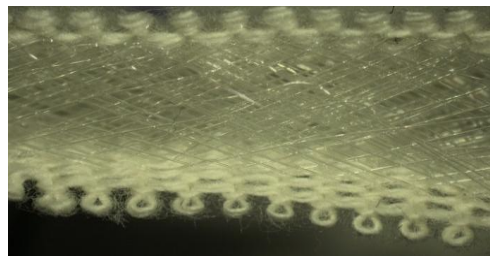


**Figure 3.** Spacer knitted fabrics with 1:15 connecting ratio

## 4. APPLICATIONS OF SANDWICH KNIT FABRICS IN VIBRATION CONTROL

### 4.1. Applications of anti-vibration insulation

The theoretical evaluation of the vibration transmissibility for the selected knitted fabrics followed the experiment described in Section 2 and was conducted in accordance with ISO 13753, which is dedicated to anti-vibration glove material testing. Based on experimentally determined dynamic parameters, namely specific stiffness  $k_s$  and specific damping factor  $c_s$ , the obtained values of  $T(f)$  were less than 0.6 across the 50–500 Hz frequency range, coded as  $T(50)$ – $T(500)$ . These results highlight the potential for use as resilient materials integrated into the palm area of anti-vibration gloves, as well as for covering the handles of vibrating tools, in accordance with the requirements of the standard.

The results are presented in Table 1.

**Table 1.** Vibrations transmissibility of spacer knitted fabrics

| Fabric Code | $T_{(50)}$ | $T_{(63)}$ | $T_{(80)}$ | $T_{(100)}$ | $T_{(125)}$ | $T_{(160)}$ | $T_{(200)}$ | $T_{(250)}$ | $T_{(315)}$ | $T_{(400)}$ | $T_{(500)}$ |
|-------------|------------|------------|------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| A-1-X       | 0,049      | 0,033      | 0,020      | 0,013       | 0,008       | 0,006       | 0,006       | 0,005       | 0,004       | 0,003       | 0,002       |
| A-1-X (F)   | 0,059      | 0,040      | 0,025      | 0,016       | 0,010       | 0,007       | 0,008       | 0,007       | 0,005       | 0,004       | 0,003       |
| A-3-Y       | 0,076      | 0,049      | 0,030      | 0,019       | 0,013       | 0,009       | 0,009       | 0,007       | 0,005       | 0,004       | 0,003       |
| A-3-Y (F)   | 0,112      | 0,070      | 0,042      | 0,017       | 0,012       | 0,011       | 0,008       | 0,006       | 0,004       | 0,004       | 0,004       |

#### 4.2. Applications of Vibration Amplification

Apart from the aforementioned case, in specific applications vibration transmission ( $T=1$ ) or controlled vibration amplification ( $T>1$ ) may be desirable. In the vicinity of resonance frequency, elastic systems can exhibit transmission values exceeding unity, resulting in amplified motion. This phenomenon can be exploited in applications involving vibrational energy transfer, mechanical stimulation, and vibration energy harvesting [7-10].

The knitted sandwich structures developed in this study, characterized by relatively low stiffness and predominantly elastic behaviour, may therefore also be suitable for such applications. Potential areas of application include:

- Portable and electronic devices, such as casings for mobile phones and other portable electronics, where controlled vibration transmission may enhance the perceptibility of notification signals.
- Sports equipment, e.g., elastic materials used in the construction of sporting surfaces or equipment, such as billiard table cloths, tennis ball coverings, or related components, where efficient impact energy transmission is required to maintain velocity and trajectory.
- Sports and biomechanical accessories, for example, elastic elements integrated into joint support systems (e.g., sports knee braces) and other biomechanical devices, which may facilitate the storage and subsequent release of elastic energy during movement.
- Vibration stimulation and wellness devices, such as massage chairs, handheld massage devices, and whole-body vibration platforms used in fitness and rehabilitation, where mechanical vibrations are transmitted to the human body for therapeutic or training purposes.
- Industrial and agricultural applications, i.e., systems that exploit vibrational motion to support technological processes, including industrial screening equipment and mechanical harvesting systems based on controlled trunk or structural vibrations.

#### 5. CONCLUSIONS

This study recommends the use of weft-knitted spacer fabrics for vibration isolation. With appropriate fabric structure design, vibration risks in various working environments, such as during transportation and from hand-arm vibration when operating hand-held power tools, may be reduced. This research can be extended to other textile structures for anti-vibration purposes, including weft-knitted and warp-knitted spacer fabrics, as well as 3D woven and nonwoven fabrics, which can also be designed as vibration isolators.

This work provides a foundation for future studies on developing new textile materials that can function as either insulators or transmitters of vibrations. The investigated knitted sandwich structures demonstrate potential not only for vibration isolation applications, but also for applications requiring controlled vibration transmission.

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## VALORIZATION OF ANATOLIAN ACORN CUPS FOR ECO-CONSCIOUS DYEING OF POLYAMIDE SPORTSWEAR WITH ANTIMICROBIAL FUNCTIONALITY

Elif Nihan Yıldız<sup>1\*</sup>, Büşra Erkömek Ateş<sup>1</sup>, Göksu Ögütçü<sup>1</sup>, Recep Karadag<sup>2,3</sup>

<sup>1</sup>Flo Mağazacılık ve Pazarlama A.Ş., Mahmutbey Merkez Mahallesi Taşocağı Caddesi No:24 Kat: 3 Bağcılar İstanbul-Turkey

<sup>2</sup>Faculty of Fine Arts, Department of Fashion and Textile Design, Istanbul Aydın University, Istanbul, Turkey.

<sup>3</sup>TCF, DATU Cultural Heritage Preservation and Natural Dye Laboratory, Umraniye, Istanbul, Turkey.

\* elifyildiz@flo.com

### ABSTRACT

The growing demand for sustainable and high-performance sportswear has emphasized the importance of integrating natural resources into functional textile design. This study investigates the application of Anatolian acorn cups (*Quercus ithaburanis*) as a novel natural dye source for polyamide-based sports fabrics, aiming to achieve both eco-conscious coloration and enhanced antimicrobial protection. To strengthen microbial resistance, gallnut extract (*Quercus infectoria*) was incorporated into the dyeing process. The acorn cups, together with gallnut extract at specific weight ratios, were extracted in water, and the resulting dye solution was applied to polyamide sports fabrics under varying concentrations, dyeing times, pH levels, and temperatures. The dyed samples were analyzed using HPLC-DAD (High-Performance Liquid Chromatography with Diode Array Detection), SEM-EDX (Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy), FTIR (Fourier Transform Infrared Spectroscopy), and CIEL\*a\*b\* (International Commission on Illumination L\*a\*b\* Color Space) methods, and their color performance as well as wash, rub, and perspiration fastness were evaluated according to international standards. Furthermore, antibacterial activity (*Staphylococcus aureus*, *Escherichia coli*) and antifungal activity (*Candida albicans*) were tested in accordance with AATCC 147 (Antibacterial Activity of Textile Materials: Parallel Streak Method), AATCC 100 (Assessment of Antibacterial Finishes on Textile Materials), ISO 20743 (Textiles Determination of antibacterial activity of textile products), and ISO 13629-2 (Textiles Determination of antifungal activity, Part 2: Mixed culture test). The findings demonstrate that Anatolian acorn cups not only provide an environmentally friendly alternative for sportswear coloration but also impart functional antimicrobial properties, particularly when combined with gallnut extract. This work highlights the potential of natural dye-based waste valorization in the development of sustainable, health-conscious, and performance-oriented sports textiles.

**Keywords:** Anatolian acorn cup, Polyamide sportswear, Natural dye, Antibacterial, Antifungal, Sustainable textiles, Gallnut, Eco-friendly dyeing

## 1. INTRODUCTION

The global textile industry is increasingly seeking sustainable and environmentally responsible alternatives to conventional dyeing processes. Synthetic dyes, although widely used due to their reproducibility and broad color range, are associated with several environmental and health concerns such as toxic effluents, high energy consumption, and potential allergenic effects on human skin [1,2]. In response to these challenges, natural dyes derived from plant-based resources have gained renewed attention due to their biodegradability, low toxicity, and compatibility with sustainable production principles [3].

Natural dye sources such as bark, leaves, fruits, seeds, and galls have historically been used in textile coloration across different cultures. Comprehensive studies on natural dyes demonstrate that plant-based colorants contain various polyphenolic compounds, flavonoids, and tannins that can interact with textile fibers and produce stable coloration when appropriate mordanting systems are applied [4]. In recent years, research has also focused on valorizing agricultural and forestry waste materials as natural dye sources, which aligns with circular economy strategies and sustainable material management. Among these resources, acorn cups derived from oak species represent an underutilized biomass rich in polyphenolic compounds, particularly hydrolysable tannins. Tannins are known not only for their dyeing capabilities but also for their antimicrobial and antioxidant properties, making them attractive for functional textile applications [5]. Previous studies have demonstrated that extracts obtained from oak species can produce durable coloration on textile fibers and can be analyzed using chromatographic techniques such as HPLC-DAD to identify their phenolic dye components [6,7].

The oak species *Quercus ithaburanis*, widely distributed in Anatolia, produces acorns with cup structures that are generally discarded as natural waste after harvesting. However, these acorn cups contain significant amounts of hydrolysable tannins and phenolic compounds that may contribute to both coloration and bioactive functionality in textiles [8,9]. Another tannin-rich natural material frequently used in natural dyeing is gallnut (*Quercus infectoria*), which has historically served as a natural mordant and antimicrobial agent in textile dyeing processes due to its high tannin content [10].

In sportswear textiles, particularly those made from polyamide fibers, antimicrobial functionality is highly desirable. Polyamide-based fabrics are widely used in sportswear due to their durability, elasticity, and moisture management properties. However, their relatively hydrophilic surface can promote microbial growth, leading to unpleasant odors and potential skin irritation during prolonged use [11]. Therefore, incorporating natural antimicrobial agents into dyeing processes represents a promising strategy for producing functional sportswear textiles.

Recent studies have explored plant-derived dyes with inherent antimicrobial activity for functional textile applications. Polyphenol-rich natural dyes have been shown to inhibit the growth of common pathogenic microorganisms such as *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans* while simultaneously providing coloration to textile materials [12,13]. Despite these advances, limited research has focused on the use of acorn cup extracts as both a dye source and antimicrobial agent for synthetic sports fabrics such as polyamide.

Therefore, the present study aims to investigate the valorization of Anatolian acorn cups (*Quercus ithaburanis*) as a sustainable natural dye source for polyamide sportswear fabrics. In addition, gallnut extract (*Quercus infectoria*) was incorporated into the dye bath to enhance antimicrobial functionality. The dyed fabrics were characterized using advanced analytical techniques including HPLC-DAD, SEM-EDX, and FTIR to determine chemical composition and fiber-dye interactions. Color properties were evaluated using the CIEL\*a\*b\* color system, while wash, rub, and perspiration fastness were assessed according to international standards. Furthermore, antibacterial and antifungal performances were

examined against *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans*. The results demonstrate the potential of acorn cup waste as a sustainable dyeing resource capable of imparting both aesthetic and functional properties to polyamide sportswear fabrics.

## EXPERIMENTAL STUDY

### 2.1 Materials

In this study, a 100% polyamide (PA) sportswear fabric with a weight of 120 g/m<sup>2</sup> was used as the substrate material. Acorn cups of Anatolian oak (*Quercus ithaburanis*) and gallnut (*Quercus infectoria*), used as dye sources, as well as the pure standard compounds used in the analyses, were obtained from the DATU (Cultural Heritage Preservation and Natural Dyes Laboratory).

#### 2.1.1 Preparation of Natural Dye Extract

Acorn cups (50% owf) and gallnut (10% owf) were extracted in process water using a liquor ratio of 1:20. The extraction was carried out at 90 °C for 60 minutes.

#### 2.1.2 Dyeing Process

Polyamide fabric samples were dyed with jet machine. The fabrics were dyed at 100 °C for 40 minutes, and subsequently washed at 50 °C for 20 minutes using a nonionic soap.

#### 2.1.3 Color Measurements

Color measurements of the dyed fabrics were carried out using a spectrophotometer based on the CIELab\* color system. The color parameters L\*, a\*, b\*, K/S, chroma (C\*), and hue angle (h) were recorded to evaluate the lightness and chromatic characteristics of the dyed samples, as illustrated in Figure 1.

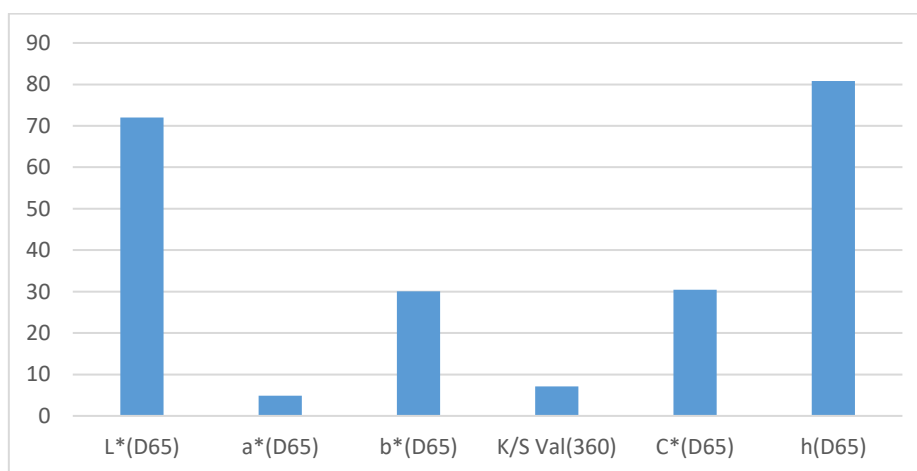


**Figure 1.** Color appearance of polyamide fabrics dyed with acorn cup and gallnut extracts corresponding to the CIELab\* color measurements.



#### 2.1.4 Fastness Tests

The color fastness properties of the dyed fabrics were evaluated according to international textile testing standards. Wash fastness was assessed in accordance with ISO 105-C06, rubbing fastness according to ISO 105-X12, and perspiration fastness according to ISO 105-E04. The obtained results were evaluated using the standard gray scale rating system, and the corresponding results are presented in Table 1.

**Table 1.** Color fastness properties of polyamide fabrics dyed with acorn cup and gallnut extracts.

| Light Fastness | Wash Fastness | Dry Rub Fastness | Wet Rub Fastness | Perspiration (Acid) | Perspiration (Alkali) |
|----------------|---------------|------------------|------------------|---------------------|-----------------------|
| 4-5            | 5             | 5                | 4-5              | 4                   | 4                     |

#### 2.1.5 SEM-EDX Analysis

The surface morphology of untreated and dyed polyamide fabrics was examined using Scanning Electron Microscopy (SEM) to observe the distribution of dye molecules on the fiber surface. The SEM images revealed that untreated polyamide fibers possessed a relatively smooth, uniform surface, whereas the dyed fabrics exhibited a thin layer of dye molecules deposited on the fiber surface, indicating successful interaction between tannin-rich compounds and the polyamide polymer matrix (Figure 2). This interaction contributes to both the coloration and the functional antimicrobial properties of the fabric.

In addition, the elemental composition of the samples was analyzed using Energy Dispersive X-ray Spectroscopy (EDX). The obtained spectra provide the percentage composition of the elements detected in the samples, offering information about the elemental distribution on the fiber surface (Figure 3).

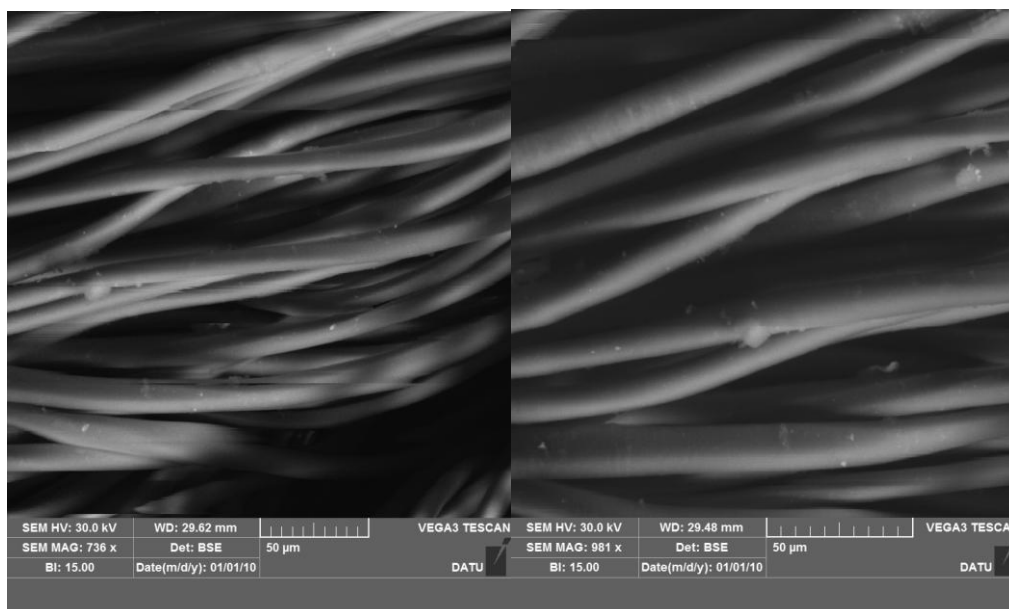


**Figure 2.** SEM images showing the surface morphology of the dyed fabrics.

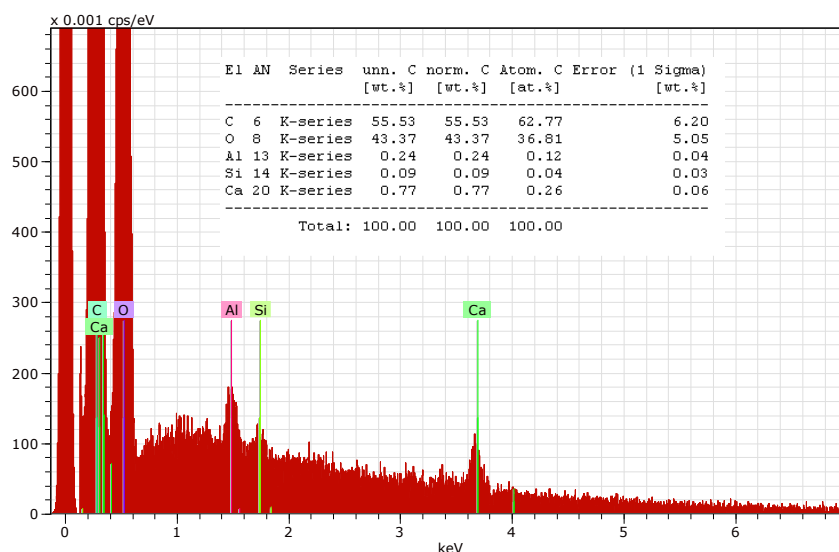


**Figure 3.** Elemental composition of dyed polyamide fabric obtained from EDX analysis.

### 2.1.6 HPLC-DAD Analysis

The chemical composition of acorn cup and gallnut extracts was investigated using High-Performance Liquid Chromatography with Diode Array Detection (HPLC-DAD). Chromatographic separation was performed on a C18 column using a gradient elution system consisting of water and acetonitrile as the mobile phase. The chromatographic analysis revealed the presence of several phenolic compounds responsible for both dyeing performance and antimicrobial activity. The major compounds identified were gallic acid, ellagic acid, and tannin derivatives, which are known for their strong affinity toward polyamide fibers and their bioactive functionality. In addition, the chromatographic profiles indicated that the incorporation of gallnut extract increased the concentration of hydrolysable tannins in the dye solution. The chromatogram, together with the major phenolic compounds identified in the dyed fabrics, is presented in Figure 4.

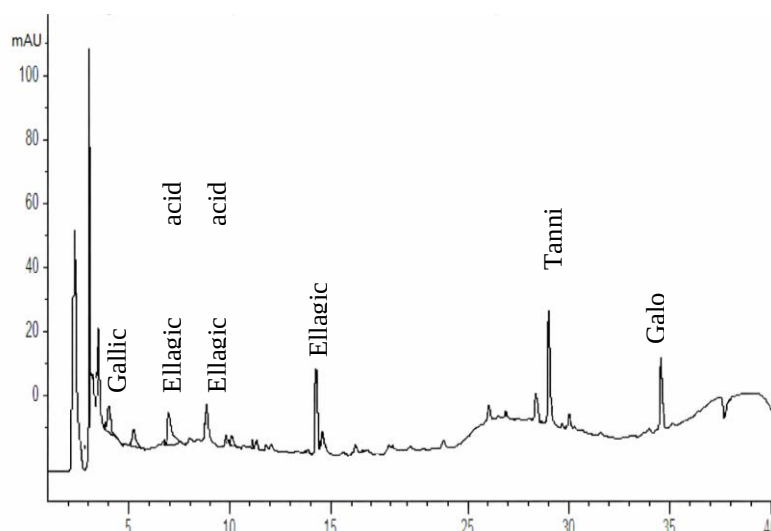


**Figure 4.** HPLC–DAD chromatogram of the dyed fabric and the identified major dye compounds.

### 2.1.7 Antibacterial and Antifungal Tests

The antimicrobial activity of the dyed fabrics was evaluated against *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans*. Antibacterial and antifungal performances were determined according to international standards, including AATCC 147 (Parallel Streak Method), AATCC 100 (quantitative antibacterial assessment), ISO 20743 (determination of antibacterial activity of textile products), and ISO 13629-2 (determination of antifungal activity). The results showed that fabrics dyed with acorn cup extract exhibited moderate antibacterial and antifungal activity; however, the incorporation of gallnut extract significantly enhanced antimicrobial performance due to the high concentration of hydrolysable tannins. As presented in Table 2, the antibacterial activity increased markedly with increasing extract concentration, reaching up to 96% reduction against *Staphylococcus aureus* and 92% against *Escherichia coli* for the AC+GN sample. Similarly, the antifungal activity against *Candida albicans* improved substantially, with the highest growth inhibition value of 88% observed for the AC+GN sample, as shown in Table 3. These findings indicate that the combined use of acorn cup and gallnut extracts significantly improves both antibacterial and antifungal properties while maintaining effective dyeing performance on polyamide sports fabrics.

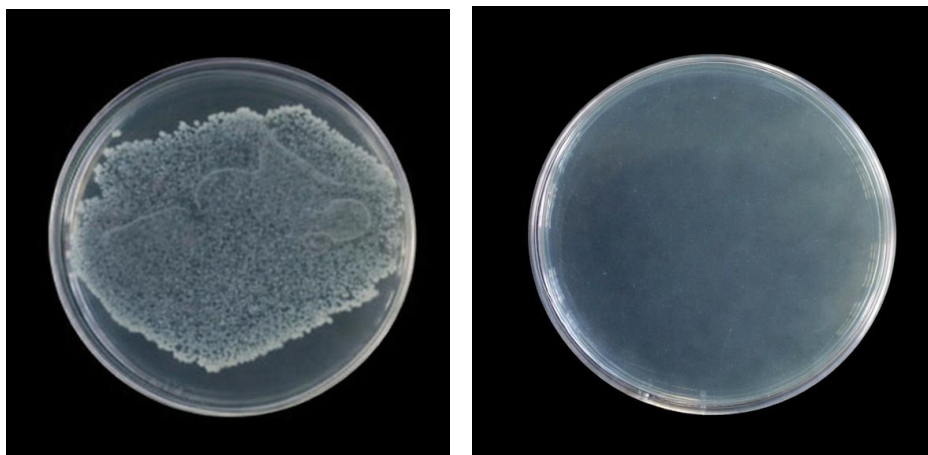


**Figure 5:** (a) undyed fabric, (b) dyed fabric

**Table 2.** Antibacterial activity of dyed fabrics [(% reduction) (a) Control sample (undyed fabric), (b) Dyed sample (treated fabric).

| Sample  | <i>Staphylococcus aureus</i> (%) | <i>Escherichia coli</i> (%) |
|---------|----------------------------------|-----------------------------|
| Dyed PA | 96                               | 92                          |

**Table 3.** Antifungal activity against *Candida albicans*.

| Sample  | Growth Inhibition (%) |
|---------|-----------------------|
| Dyed PA | 88                    |

## RESULTS

The experimental results demonstrated that Anatolian acorn cup extracts successfully dyed polyamide sports fabrics, producing natural brown to dark beige shades depending on dye concentration and processing parameters. Colorimetric analysis indicated that increasing dye concentration resulted in

higher K/S values, reflecting greater color strength. The incorporation of gallnut slightly deepened the color tone due to its high tannin content. Fastness tests demonstrated satisfactory performance, with light fastness values of 4–5, wash fastness of 5, dry rubbing fastness of 5, and wet rubbing fastness of 4. The dyed fabrics also exhibited good resistance to both acidic and alkaline perspiration, with fastness ratings of 4. In addition, antimicrobial tests confirmed that the dyed fabrics showed noticeable antibacterial and antifungal activity, which increased with the incorporation of gallnut.

## CONCLUSION

This study investigated the potential of Anatolian acorn cups (*Quercus ithaburanis*) as a sustainable natural dye source for polyamide sportswear fabrics. The results demonstrated that acorn cup extracts can effectively provide natural coloration while simultaneously imparting antimicrobial functionality. The incorporation of gallnut extract (*Quercus infectoria*) further enhanced antibacterial and antifungal performance due to its high content of hydrolysable tannins. Analytical techniques, including HPLC-DAD, SEM-EDX, and FTIR analyses, confirmed the presence of phenolic compounds responsible for both dyeing performance and antimicrobial activity.

The dyed fabrics exhibited satisfactory color strength and acceptable fastness properties, indicating the practical applicability of this natural dyeing approach for polyamide-based sportswear textiles. Furthermore, the valorization of acorn cup waste represents a promising eco-friendly alternative to synthetic dyes while contributing to circular economy practices in the textile industry. This approach supports the development of sustainable, functional, and health-conscious sports textiles. In addition, the dyeing materials and processes used in this study comply with the principles of the Natural Organic Dye Standard (NODS), which emphasizes the use of renewable plant-based dye sources and environmentally responsible processing methods [14]. Future studies may focus on optimizing dye extraction efficiency, expanding the achievable color range, and evaluating the long-term durability of antimicrobial effects under real usage conditions.

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