

ADVANCES IN TEXTILE SCIENCE AND TECHNOLOGY: SUSTAINABILITY, INNOVATION CHARACTERIZATION, AND PERFORMANCE

Editor:
Assist. Prof. Dr. Ayşe Özkal



BİDGE Yayınları

**Advances in Textile Science and Technology: Sustainability,
Innovation, Characterization, And Performance**

Editör: AYŞE ÖZKAL

ISBN: 978-625-5057-24-2

1. Baskı

Sayfa Düzeni: Gözde YÜCEL

Yayınlama Tarihi: 2026-10-25

BİDGE Yayınları

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Sertifika No: 71374

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PREFACE

Textile science and technology cover a wide range of subjects, from conventional manufacturing processes to the development and characterization of textile materials. Environmental concerns, developments in production technologies, and changing industrial requirements have brought new topics into textile research. Sustainability, recycling, digital manufacturing, and material performance are among the areas receiving increasing attention. This book, *Advances in Textile Science and Technology: Sustainability, Innovation, Characterization, and Performance*, consists of four chapters addressing different subjects in textile science and engineering. The first chapter discusses the relationship between sustainability and recycling in the textile industry from environmental, social, and economic perspectives. It examines resource conservation, waste management, working conditions, consumer behavior, and the economic aspects of textile recycling. The second chapter focuses on technological developments in the carpet industry. It covers advances in fiber and material technologies, developments in manufacturing equipment, digital production systems, and the use of artificial intelligence in carpet design, manufacturing, and quality control. The third chapter examines analytical approaches for textile fiber characterization, with particular attention to their relevance to the forensic examination of recycled fibers. It reviews established analytical methods, discusses studies on distinguishing recycled and virgin fibers, and considers the challenges associated with their forensic evaluation. The fourth

chapter addresses the viscoelastic behavior of textile materials, including creep, stress relaxation, and hysteresis. It describes commonly used viscoelastic models and reviews studies on the time-dependent mechanical behavior of textile structures, particularly spacer fabrics subjected to compressive loads. The chapters cover different areas of textile research, including sustainable practices, manufacturing technologies, analytical methods, and mechanical properties. The book is intended for researchers, academics, students, and professionals interested in textile science and engineering. I would like to thank all the chapter authors for their contributions to this book. I also thank the publisher for its support in preparing and publishing this work.

Editor

Assist. Prof. Dr. Ayşe Özkal P

AMUKKALE UNIVERSITY

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BÖLÜM 1

INTERACTION BETWEEN SUSTAINABILITY COMPONENTS AND RECYCLING IN TEXTILE INDUSTRY FROM ENVIRONMENTAL, SOCIAL AND ECONOMICAL PERSPECTIVES

**AYŞE ŞEVKAN MACİT¹
GONCA ALAN²
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Introduction

The textile industry represents one of the most critical manufacturing sectors globally, characterized by an extensive value chain. However, the production pathway of textiles and garments lead to severe ecological degradation spanning from primary raw material cultivation to end-of-life product disposal. Key environmental burdens unavoidable in textile processing include intensive chemical loading, excessive water-energy consumption, atmospheric emissions and solid waste generation. In applying

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corporate sustainability factors within this framework, it is essential to account for a range of interconnected variables to ensure a comprehensive approach. Crucially, formalizing these distinct variables into a cohesive model and analyzing their cross-functional interdependencies remain vital to unlocking viable corporate sustainability strategies (Jovanovic et al., 2026).

Within this network, closed-loop interventions consisting of recycling practices during both the production and post-consumption phases have emerged as a primary mechanism to mitigate resource intensity and operational costs. As manufacturers face volatile energy prices and stricter environmental regulations, mitigating textile-driven impacts and recycling textile waste is no longer optional, but a fundamental requirement for long-term industrial sustainability (Islam et al., 2022). Ultimately, navigating this industrial transition requires a comprehensive paradigm shift at the institutional, manufacturing, and consumption levels. Here, evaluating how recycling supports the environment, society, and economy is the key to understand true sustainability components in the sector (Silina et al., 2024).

Environmental Components

Textile recycling processes contribute significantly to the conservation of water, energy, and secondary resources within the broader framework of sustainability. Traditional textile manufacturing is inherently defined by intensive hydrological dependency; cotton cultivation, pre-treatment, dyeing, and printing operations serve as prime examples of processes that consume vast volumes of water. Strategically recycling a cotton product effectively eliminates the water consumption associated with both virgin fiber cultivation and the subsequent product dyeing phases. Consequently, this yield-optimized circularity offers dual benefits by conserving natural water bodies and reducing industrial wastewater treatment

expenditures. Conforming to this trajectory, a comprehensive study examining the ecological implications of large-scale textile-to-textile recycling frameworks across the EU by 2035 demonstrated that escalating the regional recycling rate to 10% yields a 92% probability of mitigating climate impacts and an almost 100% probability of reducing water scarcity stress (Sandin et al., 2025). Regarding energy conservation, recycling and reuse of textile resources inherently demands substantially lower energy inputs compared to virgin manufacturing from raw substrates. This operational efficiency holds true for both synthetic polymers and natural biomass fibers. Empirical investigations validate the net positive contribution of recycling to global energy conservation paradigms. For instance, Woolridge et al. (2006) quantified the energy savings associated with closed-loop reuse and recycling systems across the entire lifecycle encompassing resource extraction, material processing, electricity generation, garment collection, logistics, and ultimate waste disposal. Their findings indicated that substituting post-consumer garments for virgin inputs results in substantial energy savings of approximately 65 kWh per kilogram of cotton and 90 kWh per kilogram of polyester, thereby significantly diminishing the global environmental burden. Similarly, in a comparative lifecycle analysis between virgin and recycled polyester staple fibers, Li et al. (2024) determined that recycled alternatives offer definitive advantages by drastically lowering carbon emission indices, conserving thermal/electrical energy, and minimizing process water consumption. Beyond the metrics of water and energy, circular management facilitates the conservation of ecological resources. This resource preservation is achieved by reducing the total land area required for agricultural fiber cultivation, limiting the intensive application of eco-toxic agricultural chemicals, and minimizing the allocation of arable land for municipal waste disposal facilities.

In alignment with global efforts to establish a low carbon footprint, the textile industry as a major source of global pollution, faces increasing pressure to decarbonize, making recycling essential for this transformation. Incorporating systematic recycling pathways for both pre-consumer industrial waste and post-consumer end-of-life garments represents an essential strategy for reducing the overall carbon footprint of the apparel industry (Muthu et al., 2012). By bypassing the energy-intensive processing stages inherent in virgin material synthesis, recycling systematically decreases the volume of greenhouse gas (GHG) emissions generated during industrial transformation. This compression of the manufacturing lifecycle, coupled with the diversion of textile waste from open emissions sources, drives a net reduction in atmospheric carbon loading. Evaluating these dynamics, Zamani et al. (2015) reported that consolidating diverse recycling technologies into an integrated processing system for one tonne of textile waste yields significant ecological dividends compared to baseline linear practices. Depending on localized process efficiencies, their model demonstrated that an integrated recycling framework could achieve net savings of 10 tonnes of CO₂-equivalent and 169 GJ of energy per tonne of processed waste. Further reinforcing the environmental efficacy of these processes, Pérez et al. (2022) established that the systematic reuse of textile waste—by structurally avoiding virgin remanufacturing loops yields approximately 5.8 tonnes of CO₂-equivalent savings in greenhouse gas emissions for every single ton of recycled material.

Proper waste management and recycling are essential steps to reduce environmental pollution and save natural resources. Recycling textiles creates a highly positive shift in industrial waste management. By proactively repurposing discarded materials, enterprises can drastically downscale the volume of solid waste routed to municipal landfills, lower heavy transportation costs

associated with bulk waste logistics, and enhance their global market competitiveness through certified sustainable waste management compliance. In the end, setting up solid recycling frameworks creates multiple advantages for modern waste management ecosystems, most notably through the reduction of cumulative industrial waste and the suppression of regional environmental pollution (Oğuz, 2026; Awogbemi et al., 2022). Furthermore, these circular practices play a decisive role in reducing overall environmental degradation (Juanga-Labayen et al., 2022), serving as one of the most effective strategies for systematically eliminating textile waste streams (Shamsuzzaman et al., 2023). Within this hierarchical framework of circularity, the direct reuse of apparel emerges as an exceptionally sustainable approach to waste management, primarily because it preserves the essential value and structural integrity of the product far more efficiently than energy-intensive redesign or structural remanufacturing processes (Lee et al., 2025).

However, optimizing the macro-level governance of textile waste requires a sophisticated combination of regulatory and operational interventions. While systemic policy mechanisms including mandatory sustainability labeling, deposit-refund schemes, the scaling up of closed-loop recycling infrastructures, and stringent bans on the exportation of unsorted textile waste substantially improve waste management metrics, the most profound ecological dividend is derived from the absolute prevention of waste generation (Solis et al., 2024). This empirical insight underscores the critical necessity of minimizing waste footprints at both the source-manufacturing and post-consumer phases. Consequently, establishing solid pathways for continuous product reuse and systemic textile recycling acts as the primary vehicle for achieving this preventative, high-efficiency waste management.

Social Components

Beyond changing industrial processes, the transition of the textile sector to a sustainable configuration fundamentally interfaces with consumer psychology and socio-cognitive behavioral transformations. Traditionally viewed as a less important "second-hand" status, products incorporating recycled textile content are increasingly validated as core signifiers of a proactive, sustainable lifestyle. This evolution in consumer mindset has elevated the strategic visibility of manufacturers. Companies that base their corporate identity on verifiable circular practices and transparent eco-labeling systematically gain higher market prestige and competitive advantage. Modern consumers demonstrate an expanding awareness of resource scarcity and end-of-life pollution, viewing their purchasing decisions not purely as commercial exchanges, but as a tool for protecting the environment for future generations. However, empirical literature illustrates that this consciousness is highly stratified across distinct consumer demographics and behavioral archetypes. For instance, Weber et al. (2017) demonstrated that an individual's engagement with fashion, conceptualized as the "fashion index," directly dictates post-consumer waste management behavior. Their findings revealed that high-index "fashion consumers" engage with apparel disposal through significantly more active circular pathways such as reselling, swapping, and participating in brand take-back schemes than low-index cohorts. Paradoxically, while fashion-centric consumers generate a higher gross volume of textile waste due to accelerated consumption cycles, their net disposal rate into municipal streams remains lower, driven by their preference for these alternative redistribution channels. This new socioeconomic shift is further confirmed by Ribeiro et al. (2023), who identified a profound transformation in the global consumer mindset toward ethical consumption. Their analysis underscores that contemporary

consumers are increasingly adapted to the broader social and informational dimensions of apparel production, subsequently requiring major brands to offer clear transparency and accessibility. Yet, despite this theoretical readiness to embrace circularity, a critical attitude gap persists within specific demographic sectors. Investigating the recycling perceptions of young European consumers, Grębosz-Krawczyk and Siuda (2019) observed that while empirical participation in brand-led garment collection campaigns remained statistically low, there was a clear willingness among youth to participate in future initiatives. This gap indicates that the main barrier for consumers is not a lack of intent, but rather a shortage of institutional promotion, structural accessibility, and targeted education on circular textiles.

Achieving genuine sustainability in global trade requires a fundamental commitment to social justice and worker welfare. The textile industry represents one of the most labor-intensive manufacturing sectors globally. Considering this complex network, adopting sustainable approaches throughout the production phase has become a vital necessity, particularly regarding the optimization of working conditions and occupational health standards. When working conditions are examined specifically in the context of recycling, it is known that they have both positive (e.g., employment opportunities) and negative (e.g., difficult working conditions) aspects. A strategy must be adopted that improves working conditions in the recycling industry while prioritizing the well-being of workers and societal welfare. Faced with shifting global labor dynamics and increasingly strict international social compliance regulations, manufacturers must prioritize workplace safety and fair labor practices, spanning from upstream garment assembly to downstream logistics (Muñoz-Torres et al., 2022). The regulatory frameworks and contemporary approaches established by the International Labour Organization (ILO) and the European Union

(EU) represent a critical transformation from voluntary corporate social responsibility (CSR) toward legally binding, enforceable, and strict legal scrutiny of human rights practices (Yücel et al., 2025). In this context Gankhuyag et al. (2025), investigated work-integrated learning as insights from the textile industry in alignment with EU's Corporate Sustainability Due Diligence Directive (CSDDD). It is reported that especially supporting the social sustainability, according to the empirical outcomes, cross-functional and external partnerships constitute a vital mechanism for expanding organizational capabilities, meeting regulatory mandates, and driving experiential knowledge acquisition. Shared artifacts, such as industry certifications, formalized legal mandates, and supplier protocols, serve as conceptual conduits that promote structural harmony and mutual comprehension across institutional boundaries. Consequently, integrating economic viability with ethical labor management within operational stages is a fundamental requirement for long-term industrial resilience and corporate reputation.

Economical Components

Minimizing input costs through resource efficiency constitutes the most direct way toward achieving long-term financial feasibility and industrial resilience. Given that textile manufacturing is inherently resource-intensive, effective cost management is inseparably linked to the strict optimization of raw materials, water, and energy consumption. In the current industrial landscape, operational efficiency and ecological sustainability are mutually reinforcing objectives (Luján-Ornelas et al., 2020). From a strategic standpoint, the United Nations Sustainable Development Goals serve as a comprehensive macro-framework designed to diminish long-term operational expenses and minimize resource waste by targeting the elimination of economic inefficiencies by the 2030 deadline (Thakker and Sun, 2023). By integrating resource-efficient technologies, adopting circular economy principles, and

systematically reducing waste streams, manufacturers can decrease their environmental footprint while simultaneously optimizing operational expenses (Gheorghita and Nistor, 2024). To reach these goals across the different stages of textile production, enterprises should translate waste reduction into direct savings. Maia et al. (2013), carried out a thorough study on industrial optimization considering the components of sustainable development in the textile industry. They reported that resource consumption in manufacturing is inherently driven by the choice of substrate, equipment, and processing parameters. Analyzing this correlation allows firms to achieve high resource efficiency, enabling precise operational adjustments that simultaneously curtail water and energy consumption. Applying a cost-reduction mindset to specific textile manufacturing steps, resource efficiency in spinning and weaving avoids surplus inventory and frees up tied-up capital. Similarly, prioritizing cost control in resource-intensive wet processing and dyeing cuts down on defective batches, preventing re-dyeing cycles that heavily drain water, chemicals, and energy. Ultimately, streamlining material flows and quality controls across the entire manufacturing process enables textile enterprises to turn resource efficiency into a strategic tool for enhancing profitability and global market competitiveness.

Sustainable production relies on smart systems that eliminate waste by converting it back into valuable resources. To achieve effective sustainability, industrial systems must adopt a circular economy framework that prioritizes waste valorization. The circular economy is a developing sustainable business model that shifts production from traditional linear frameworks to closed-loop systems. Instead of following a linear model, a circular system generates continuous value by maximizing resource efficiency and eliminating material and energy waste. Under this framework, implementing reduction, reuse, recycling, and resource recovery

throughout the supply chain systematically extends the lifecycle and utility of products. In this context, waste valorization through advanced recycling has become central to the circular economy, fundamentally reshaping the financial structure of textile manufacturing. Transitioning to a closed-loop system allows material recycling to reposition sustainability as a strategic economic advantage rather than a regulatory cost. (Wiegand and Wynn, 2023). Recycling pre-consumer scraps and post-consumer textile waste into high-value raw materials provides significant micro and macroeconomic benefits (Abrishami et al., 2024). On an operational level, this transition serves to reduce waste management costs and optimizes raw material expenses. Macroeconomically, this approach decouples industrial growth from resource depletion and protects supply chains from volatile raw material markets (Desore and Narula, 2018). Grover et al. (2025), studied on a thorough review regarding the valorization of textile waste within the circular economy framework to address the global waste crisis. The study reveals a comparative analysis of mechanical, chemical, and biological recycling methodologies, evaluating their operational processes, and sustainability outcomes. Ghosh et al. (2025), in another study emphasized transformative potential of chemical and biotechnological recycling methodologies in converting blended and finished textile waste into high-value secondary resources. Consequently, integrating recycling into the textile value chain moves beyond environmental necessity; it becomes a strategic tool that reduces supply chain risks, stabilizes operational costs, and strengthens long-term competitiveness.

Conclusion

The objective of this study is to highlight the critical need for evolving the global textile and clothing industry toward sustainable development, repositioning this shift as a fundamental requirement for the sectoral outlook. By examining the multi-dimensional

components of sustainability, this study demonstrates that integrating closed-loop recycling into specific manufacturing stages serves as a key driver for both environmental and economic optimization. From an environmental perspective, structured recycling pathways across fiber preparation, spinning, and dyeing provide definitive advantages by reducing water use, optimizing energy consumption, lowering carbon emissions, and minimizing landfill waste. Similarly, from an economic standpoint, these resource-efficiency strategies function as potent tools that directly translate waste elimination into cost savings. On a microeconomic level, preventing surplus inventory and optimizing production inputs protect corporate profitability. However, maximizing these financial and ecological returns requires a comprehensive, risk-based alignment of the entire value chain from raw material sourcing to final logistics. Isolated interventions are insufficient; navigating this transformation demands a comprehensive transition that harmonizes corporate optimization with macro-level legislative mandates and emerging regional policies. From a standpoint of social components, this study concludes that institutional and technological advancements must interface dynamically with behavioral and social realities. While macro-level policies are vital for supporting a circular economy, the success of textile recycling ultimately depends on closing the gap between consumer attitudes and behaviors. To turn consumer willingness into active participation, demands for brand transparency must be supported by better infrastructure and targeted awareness campaigns. Ultimately, integrating these complex connections into a clear operational framework is essential for securing the industrial long-term future, driving sustainable innovation, and achieving global development goals.

Artificial Intelligence Usage Statement

Google Gemini was used within ethical boundaries and without replacement of the authors to support the construction of the comprehensive framework of this study.

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BÖLÜM 2

VISCOELASTIC BEHAVIOR IN TEXTILE MATERIALS

GONCA ALAN¹

Introduction

The viscoelastic behavior of textile materials is a critical factor that directly influences their lifespan and performance during use. Since textiles are subjected to various forces in daily applications, researching this behavior requires a careful consideration of the actual mechanical loads these materials experience. These investigations are primarily conducted by analyzing stress relaxation and creep behaviors, which reflect how textiles respond to constant deformation or sustained weight over time. Furthermore, the inherently bulky and porous structure of textile materials, combined with their diverse application areas ranging from apparel to technical textiles, exposes them to complex combinations of mechanical loads. During everyday use or industrial operations, these structures do not merely experience simple tension; instead, they undergo bending, compression, and shearing forces simultaneously. Due to this structural complexity, the performance

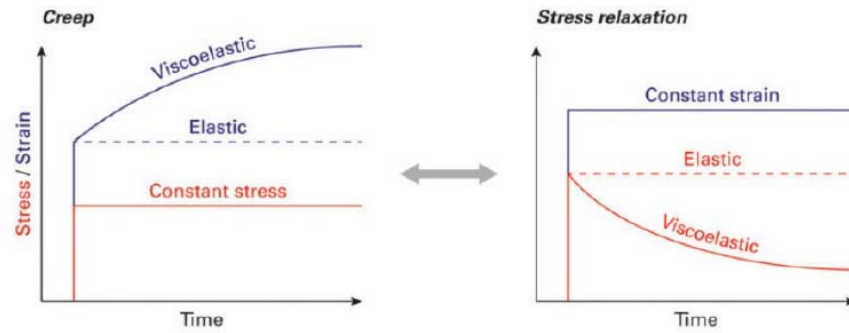
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of textiles inevitably degrades over time, leading to issues like permanent deformation, sagging, or loss of structural integrity. Consequently, understanding the concept of viscoelasticity becomes essential for evaluating these time-dependent changes. By analyzing viscoelastic properties, researchers and manufacturers can accurately assess how a material will deform under sustained stress and predict its long-term behavioral shifts, ensuring that textile products maintain their functionality and quality throughout their service life. Finally, the experimental data gathered from these tests are evaluated and supported by various viscoelastic models to accurately predict long-term material deformation and durability.

Viscoelasticity and Viscoelastic Models

Viscoelasticity is a fundamental mechanical property of materials that exhibit both viscous (liquid-like) and elastic (solid-like) characteristics under deformation. Elastic materials obey Hooke's Law in which stress is directly proportional to strain and recovery is instantaneous, whereas viscoelastic materials demonstrate time-dependent behavior. Time dependency can be explained by the terms stress relaxation, creep and hysteresis. Stress relaxation can be defined as the mechanism when constant strain is applied to a textile material, the internal stress required to maintain that deformation decreases over time. Creep occurs if a constant load (stress) is applied to a fabric, the material continues to deform progressively over time rather than reaching a fixed deformation immediately. Hysteresis refers to the energy during cyclic loading and unloading, applied to deform the textile which is not fully recovered. Some energy is dissipated as heat, creating a loop in the stress-strain curve (Banks et al. 2011, Şengül 2021, Haşçelik 2015, Hosford 2010).

Figure 1. Viscoelastic behavior over stress relaxation and creep phenomena



Reference: Zoback and Kohli, 2019

The three primary viscoelastic models widely utilized to mathematically describe and analyze the time-dependent mechanical responses of textile materials are established by combining an ideal elastic spring (representing Hookean solid behavior) and an ideal viscous dashpot (representing Newtonian fluid behavior) in various configurations.

The most common viscoelastic models employed in academic research include:

The Maxwell Model

The Maxwell Model is constructed by connecting a spring and a dashpot in series. Upon the application of an instantaneous load, the spring deforms immediately to exhibit an elastic response, whereas the dashpot begins to displace gradually over time, demonstrating viscous flow. This model is highly effective for characterizing stress relaxation behavior. It accurately simulates how internal stress within a textile material dissipates over time when held at a constant strain. However, it is generally inadequate for predicting long-term creep deformations.

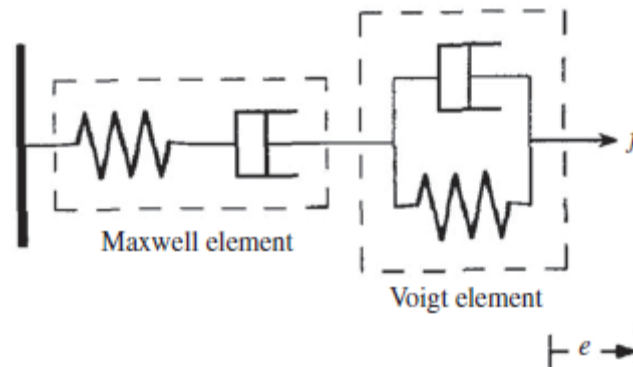
The Kelvin-Voigt Model

The Kelvin-Voigt Model features a spring and a dashpot connected in parallel. Due to the parallel alignment, both components are forced to experience the identical amount of strain. The spring suppresses the sudden movement of the dashpot, causing the material's deformation to develop progressively rather than instantaneously. This model is exceptionally well-suited for modeling creep and subsequent elastic recovery. It illustrates how a textile structure deforms under a sustained, constant load and how it reverts to its original dimensions once the load is removed.

The Burgers Model

This model is known as the four element model and a combination of two others; the Maxwell model and the Kelvin-Voigt model connected in series.

Figure 2. Four unite viscoelastic model



Reference: Terzopoulos and Fleischer, 1988 , Martins et al., 2015

Spacer Fabrics and Recent Studies on Their Viscoelastic Properties

Spacer fabrics are defined as advanced three-dimensional textile structures comprising two distinct outer layers interconnected by a spacer layer, typically composed of monofilament yarns. Spacer fabrics can be manufactured using nonwoven, weaving, weft knitting, or warp knitting techniques. Among these, warp knitting is the predominant method due to its cost-effectiveness, high production efficiency, and superior structural versatility (Wen et al., 2022, Wan et al., 2025). These fabrics are characterized by a three-dimensional architecture consisting of two distinct surface layers joined by monofilament spacer yarns. The functional performance of a spacer fabric is primarily determined by key design parameters, including the choice of raw materials, the surface geometry of the outer layers, the specific interlacing patterns, fabric thickness, and the diameter of the monofilament yarns (Qu et al., 2022, Chen et al., 2017, Vassiliadis et al., 2018). The unique tri-dimensional architecture of these textiles provides distinctive functional advantages; as superior alternatives for high-performance sports helmets Muthu Kumar et al. (2022), protective applications, (Asayesh&Amini, 2021). Beyond thermal comfort, they offer superior compressive strength and kinetic energy dissipation, which are vital for impact-related application fields (Kwan et al., 2024). Spacer fabrics represent a highly sustainable alternative to conventional polyurethane foams, characterized by waste-minimizing production processes and significant time and energy savings. Beyond their eco-friendly profile, advancements in raw material selection and structural configurations have expanded their utility far beyond traditional applications (Matsouka et al., 2020, Caronna et al., 2022). Since the cushioning effect is majorly related to the response of the textiles structure under pressure, mechanical compression behavior of spacer fabrics have been studied by the

researchers (Liu et al. 2024, Sadretinova et al. 2025, Alan 2025, Hossain et al., 2026). Viscoelastic properties of textile products have been investigated by researchers through numerous studies. Analyzing their complex structure and time-dependent behavior when utilized in usage areas specifically exposed to compressive loads, has been the main issue in the majority of the studies. Jafari Horastani et al. (2023), have studied time dependency of a kind of shape memory fabric. They investigated the stress relaxation behavior of the knitted shape memory fabric considering viscoelastic models. Finally the researchers revealed that the Kelvin-Voigt-Maxwell model demonstrated a higher and more acceptable regression coefficient among others. Marzougui et al. (2023), applied cyclic loading to knitted cotton fabric in alignment with the assumptions of the structure while in use. Following the test procedure an energy model was described by the researchers from the viscoelastic terms of Burger's model. The researchers stated that, cyclic loading significantly affected the elastic, plastic and viscoelastic responses of the knitted fabric. Since they focused on the the energy dissipation, their energy model was convenient to have a knowledge on the knitted fabric to recover. Walther et al. (2026), studied on warp-knitted spacer fabrics and nonwoven sandwich structures, considered as alternatives to polyurethane foams in terms of environmental benefit and sustainability. Quasi-static compression and vibration were applied to these structures to analyze their performances. Main objective of the study was to determine the potential of the warp-knitted spacer fabrics and nonwoven sandwich structures to be used as alternatives to polyurethane foams. In this context the researchers reported that the knitted spacers and the nonwoven sandwich structures exhibited significantly remarkable performance under vibration and a lower isolation frequency in comparison with the selected foams.

Mirakhorli and Asayesh (2022), emphasized the importance of managing the stress relaxation in textile structures in terms of durability. From this stand-point of view, they conducted viscoelastic analysis on weft knitted fabrics with intentionally miss stitches to determine the stress relaxation by assessing strain levels. Considering the examined viscoelastic models, the three component Maxwell model with a nonlinear spring was found to be suitable to clearly state the stress relaxation behavior of all selected fabrics. Zadekhast and Asyesh (2023), conducted a study on the creep duration of the warp-knitted fabrics. They have analyzed Kelvin (voigt) model, Eyring three element model, Standard linear solid model, Kelvin model in series with spring, and Kelvin model in series with dashpot to determine the creep behavior of various warp knitted fabric structures. In the result, the creep behavior of the aforementioned fabrics could be accurately predicted utilizing Kelvin model in series. Sadoughi et al. (2024), manufactured different types of woven spacer fabrics to study on their compressional behavior. By changing the manufacture process and structural parameters, they aimed to have a large scale of data on the compressional behavior of these fabrics with selected properties. In conclusion, they correlated the compressional behavior of woven spacer fabric with viscoelastic models namely (Kelvin model, Maxwell model, and also the Van Wyk Theory. The researchers revealed that the three-component model with nonlinear spring well fitted with the experimental data. Jamshidi et al. (2026), stated that searching mechanical behavior of textile materials in terms of viscoelastic perspective provide deep knowledge about their endurance and dimensional stability. For this purpose they examined creep mechanism of multi-layered technical textiles utilized in insulation applications. These structures had seam zones and seamless control groups as well. They proceeded by using the Burgers model to evaluate the creep process. The researchers observed a non-linear correlation between the number of layers and viscoelastic mechanism of the materials.

As it can be observed clearly from the latest literature review, viscoelastic components, fundamentally known as stress relaxation and creep phenomena attract great attention from the researchers to be investigated. Since these components are related to the time-dependency, they represent the response mechanisms of the textile structures under loading exposure in alignment with the usage field. Analyzing these mechanisms through viscoelastic models and evaluating the results to predict future manufacturing and usage conditions constitutes a highly significant area of study for researchers.

Conclusion

In conclusion, understanding the viscoelastic behavior of textile materials, particularly advanced three-dimensional structures like spacer fabrics, is essential for predicting their long-term performance and durability. This study highlights that time-dependent properties such as stress relaxation, creep, and hysteresis directly influence how these fabrics respond to continuous mechanical loads in daily applications. By utilizing viscoelastic configurations like the Maxwell, Kelvin-Voigt, and Burgers models, researchers can mathematically evaluate the balance between elastic recovery and viscous flow. Recent academic literature confirms that these models provide precise regression coefficients and energy dissipation analyses, which are crucial for characterizing the deformation behavior of complex knitted and shape-memory textile structures under sustained pressure.

Furthermore, warp-knitted spacer fabrics have emerged as a highly functional and sustainable alternative to conventional polyurethane foams. Owing to their unique three-dimensional structure comprising two surface layers connected by monofilament yarns, these fabrics offer excellent compressive strength, thermal comfort, and kinetic energy dissipation. Consequently, combining

these advanced structural designs with accurate viscoelastic modelling allows for the development of eco-friendly, high-performance textiles that are perfectly optimized for technical branches such as; protective equipment, sports wear, cushioning applications and medical textiles.

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BÖLÜM 3

FROM FIBER TECHNOLOGIES TO AI-BASED PRODUCTION SYSTEMS IN THE CARPET INDUSTRY

SEVCAN ÜSTÜN ¹

Introduction

Carpet weaving one of the oldest crafts in human history is a deep-rooted art form that originated from the fundamental human need for warmth and shelter and evolved over centuries into a symbol of aesthetics, power, and status. Traditionally reliant on manual craftsmanship, patience, and a master-apprentice relationship passed down through generations, the sector transitioned to mechanical production with the Industrial Revolution, paving the way for mass manufacturing. As one of the most deeply rooted crafts possessing significant socio-cultural depth, carpet weaving is a strategic industry that reflects the evolution of societal needs, aesthetic sensibilities, and production capabilities throughout history. However, the technological changes brought

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about by the 21st century, along with the concepts of Industry 4.0 and digital transformation, have transformed the carpet industry from a mere manufacturing sector into a high-tech industry where materials science, automation, data analytics, and artificial intelligence converge.

Figure1. Hereke Carpet Factory - Looms / 1914



Reference: *Eskitürkiye.net*

To remain competitive and meet global market demands, the industry today must integrate a wide spectrum of innovations ranging from polymer chemistry to artificial intelligence systems into its manufacturing processes. The initial and most prominent phase of this transformation has occurred within fiber and material technologies. The types of fibers preferred in carpet production have undergone significant changes over time, driven by technological advancements, economic conditions, and consumer habits (Üzümcü and Sarı, 2025). Functional synthetic fibers which either replace or complement traditional natural fibers such as wool, cotton, and silk have introduced "smart textiles" to the sector, offering features such as stain resistance, ease of cleaning, flame retardancy, and antimicrobial properties. In modern manufacturing facilities, fiber technologies are being redefined not merely based on aesthetic

considerations- but also in alignment with criteria for functional performance and environmental sustainability (McCann et al., 2005). Eco-fibers derived from recycled polymers and biodegradable materials reduce the environmental footprint and create added value within the green product segment of modern carpet design. Regenerated fibers—modified at the molecular level and fully compatible with recycling loops—are replacing polymers such as nylon and polypropylene (Ignatyev et al., 2014). The integration of circular economy models into the textile sector through this process has necessitated the recovery of carpet waste as a raw material. In this context, expectations for carpets extend beyond mere visual appeal and comfort to include environmental responsibility and long-lasting performance. Therefore, the aim should be to ensure that materials used in carpet production are free from toxicity and capable of re-entering biological or technical cycles at the end of their service life.

Figure 2. Carpet weaving machine



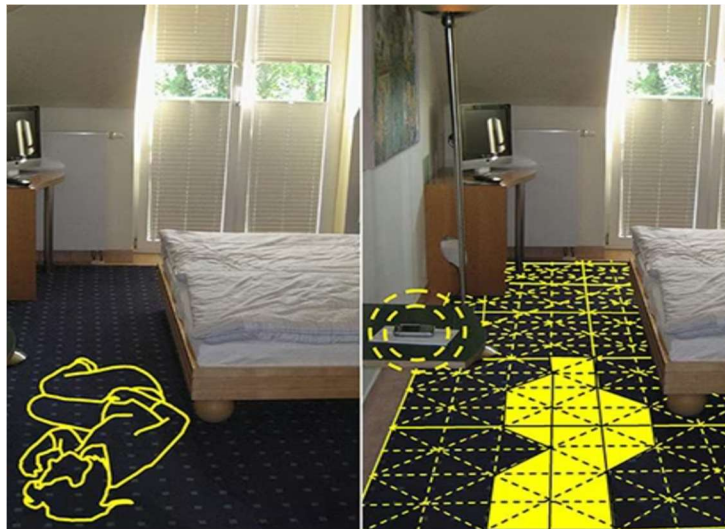
Reference: Wandewiele, 2026

On the other hand, the digitalization of production processes has ushered in a radical new era for carpet design and weaving technologies. While Computer-Aided Design (CAD) and

Manufacturing (CAM) systems have reduced design processes that once took months to mere hours, modern high-speed electronic Jacquard weaving machines and advanced tufting systems enable error-free production with infinite variations (Aykaç et al., 2017). However, the industry has now reached a new milestone with the introduction of Artificial Intelligence based production systems. Today, AI analyzes consumer trends to offer automated design alternatives that align with market demands.

Blockchain technology, utilized in logistics and supply chain management, enables the traceability of carpets from raw material to the end user. Within the framework of the "smart carpet" concept, sensors integrated into the fibers transform floors into interactive, data-generating surfaces, thereby opening up new possibilities for the health and safety sectors.

Figure 3. Home automation with the SensFloor smart carpet system



Reference: Digitaltrends, 2014

For instance, SensFloor can detect people walking on it by sensing changes in the electric field via specialized sensors embedded in every square meter and can transmit real-time data to designated centers using its integrated radio modules (Digitaltrends, 2014).

This study aims to analyze the innovation chain that extends from fiber Technologies to AI-driven systems from both technical and economic perspectives. The technological transformation facing the industry is not merely a process of mechanization but a vision of holistic digitalization. Ultimately, by placing innovation at its core, the carpet industry aims to maintain its position in the global market while respecting the planet's ecological limits.

Recent Developments in Fiber Technologies and Material Innovation

In carpet manufacturing, fiber selection plays a decisive role in the final product's mechanical strength, aesthetic value, and environmental sustainability. Conventionally used fibers such as Nylon (PA 6 and PA 6.6), Polypropylene (PP), and Polyester (PET) have achieved superior performance characteristics owing to chemical modification processes. In particular, regenerated nylons such as Econyl, derived from ocean waste and abandoned fishing nets via advanced recycling methods, exhibit physical properties identical to those of virgin polymers and meet industrial standards (Kim et al., 2026). Biodegradable fibers, such as PLA (derived from corn starch) and bamboo fibers, are gaining market share as sustainable alternatives that reduce reliance on fossil fuels (Çelebi and Karagöz, 2019; Koyuncu, 2024). These bio-based fibers fully decompose during industrial composting processes at the end of their service life (Henninger et al., 2020). Yarn structures developed to prevent microplastic release serve as a critical barrier in reducing environmental toxicity (Biswas et al., 2025).

Figure 4. *Nanotechnological carpet*



Reference: Özemek, 2022

Fiber dyeability is optimized during the spinning stage using solution-dyeing technologies, thereby reducing water consumption (Jahan and Islam, 2025). Advanced extrusion methods modify fiber cross-sectional geometries, enhancing their light-reflecting properties and, consequently, their soil-hiding capabilities (Liu and Wang, 2012). These technological improvements boost the stain resistance of carpet surfaces while protecting user health by minimizing the need for chemical cleaning. Plasma treatments that enhance the affinity of bio-based dyes for fibers are considered revolutionary in textile dyeing.

Modern fiber technologies enable carpets to function not merely as floor coverings but also as active filters that regulate indoor air quality. Innovations in yarn twisting technologies prevent flattening during prolonged use by maintaining the carpet's pile height and bulk (Dayiary et al., 2010). Laser processing of the fiber surface roughness strengthens the bond between the dye and the fiber, effectively eliminating color fading. The UV resistance of carpet pile yarns is maximized for outdoor and balcony carpets through the use of polymer stabilizers.

Photocatalytic coatings applied to fiber surfaces purify air by breaking down volatile organic compounds in the environment under the influence of light (Abdelkader et al., 2025). Smart fibers provide thermal comfort by regulating the ambient temperature using phase-change materials incorporated into their structure (Kuru and Aksoy, 2012). The development of conductive fibers suitable for sensor integration forms the basis of interactive flooring compatible with smart home systems (Söker and Güney Yüksel, 2024). Carbon fiber-reinforced hybrid yarns offer high conductivity and safety standards in industrial facilities (Keskin, 2020).

Fiber structures endowed with anti-allergenic properties prevent the accumulation of house dust mites, thereby creating safe environments for asthma patients (Hassan and Sunderland, 2015). Nanotechnological additives are integrated into the molecular structure of the fibers, imparting permanent antimicrobial and antistatic properties (Joshi and Bhattacharyya, 2011; Perera et al., 2022). Processing natural wool fibers with nanotechnology enables them to acquire moth-resistant and flame-retardant qualities without compromising their inherent advantages (Wang et al., 2021). The moisture absorption capacities of the fibers are balanced through specialized hydrophilic treatments, preventing the carpet from generating static electricity. Short fibers derived from recycled textile waste are used as insulation layers in carpet backings, contributing to the circular economy. Studies indicate that the use of recycled polymers reduces energy consumption during the raw material production stage (Blackburn, 2009).

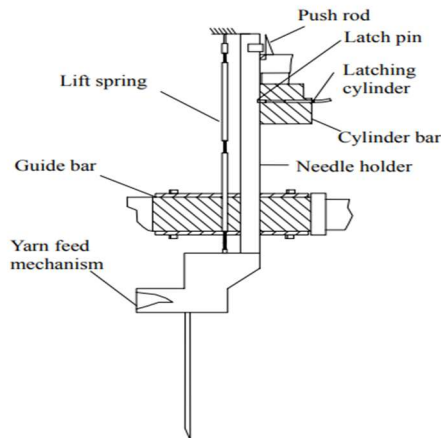
Recent developments focus on making the recycling loop for polymers used in fiber production limitless. These innovations protect the carpet industry from raw material crises while minimizing the product's total life-cycle cost. Advanced technologies such as blockchain, soft computing, and AI technologies have ushered in a new era of textile manufacturing

characterized by enhanced efficiency, optimized processes, improved product quality, and reduced resource consumption throughout the textile production life-cycle. This labor intensive industry is shifting toward a digital and automated model, presenting both significant opportunities and challenges (Amjad and Joshi, 2025).

Production Processes and Next-Generation Machine Technologies

Artificial intelligence holds the potential to drive innovation in the field of carpet design through areas such as automated collection development, creation of personalized designs based on customer preferences, and optimization of production processes (Sarioğlu Şahin et al., 2025). Alongside material innovation, mechanical processes on production lines are giving way to digital automation systems (Cohen et al., 2019). For instance, independent needle control systems used in tufting and weaving machines offer limitless design flexibility while minimizing yarn waste (Gokerneshan, 2023).

Figure 5. Mechanism of the individually controlled needle



Reference: Zhao et al., 2006

On the production line, tufting and weaving machines have evolved from traditional mechanical setups to high-precision robotic and digital systems. This transformation has been driven by the replacement of cam systems and mechanical linkages with Computer Numerical Control , robotic arms, AI-linked sensors, and digital Jacquard systems integrated with CAD/CAM (Hu et al., 2026). Independent motor-driven needle control systems (INC) employed in next-generation tufting machines enable precise management of the height and density of each individual loop (Matale, 2026). This technology allows designers to render complex geometric patterns on carpet surfaces.

Tufting and digital jet printing Technologies have elevated flexible manufacturing capabilities to the highest level. The ability to produce high resolution, intricate patterns with minimal error and maximum speed exemplifies the operational dimension of this innovation. Consequently, the carpet industry is transforming into a smart factory ecosystem driven by data and optimized by artificial intelligence without losing the spirit of traditional craftsmanship

Figure 6. Modern carpet CNC tufting machine



Reference : Hu et al., 2026

When the wide variety of Jacquard designs available for tufted carpets and rugs are combined with a compact creel, a flexible system capable of rapid color changes and low-volume production runs can be created. Colortec and ICN technologies deliver higher efficiency through Individual Control Needle (ICN) capabilities. Cobble pioneered the Colortec machine, which utilizes ICN tufting needles mounted on a single sliding needle bar; it is capable of tufting full-width cut-pile carpet patterns with up to six colors (Zhao et al. 2006). Colortec technology can be integrated with an IPD system for active yarn feeding purposes. This enables superior pile control, resulting in a cleaner fabric surface and allowing a wider range of yarn types and counts to achieve distinct aesthetics, textures, and pile heights. By utilizing TexConnect software, precise individual yarn consumption can be calculated, thereby minimizing yarn waste. TexConnect is a nonprofit technology platform focused on sustainable technologies and clean practices in the textile and garment industry (Texconnect, Textilegence 2019).

Real-time defect detection and quality control are performed using cameras and deep learning algorithms integrated into production lines. Predictive maintenance scenarios allow for the early detection of machine failures, thereby minimizing downtime and waste rates.

Digital twin technology, a component of industrial automation, maximizes operational efficiency by creating virtual replicas of production lines (Angelova, 2025). Internet of Things based sensor networks enable real time monitoring and control of machine operating parameters. This technological leap has gained a new dimension through the integration of artificial intelligence into quality control processes. Deep learning algorithms and computer vision systems can detect weaving defects invisible to the human eye within milliseconds (Hariharan and Sivaraman, 2024). AI plays a critical role not only in defect detection but also in optimizing design

processes by analyzing market trends (Başar, 2025). Inkjet printing technologies—another outcome of digitalization contribute directly to sustainability by reducing water and chemical consumption in carpet dyeing (Tkalec et al., 2022). Waterless techniques, such as dyeing with supercritical CO₂, are particularly regarded as revolutionary innovations in textile finishing (Wang et al., 2025). Some studies argue that personalized production is an emerging value in the carpet industry and that digital printing is the most efficient tool for meeting this demand (George et al., 2022).

In modern weaving machines, traditional techniques such as Axminster and Wilton have been equipped with Industry 4.0 components, thereby increasing production speeds. Ultrasonic welding technologies have begun to replace traditional latex adhesives in the joining of carpet sections and backing materials (Kara, 2024). This innovation enhances recycling efficiency by enabling carpets to be easily separated into their constituent parts at the end of their service life. Digital twin technology, utilized in production processes, creates a virtual replica of the physical line to identify operational bottlenecks in advance (Kumbhar et al., 2023). Through virtual simulations, machine energy consumption and yarn waste rates are optimized before production commences (Ferro et al., 2021). The integration of robotic arms into palletizing, roll handling, and automated storage processes has eliminated heavy workloads and elevated occupational safety standards (Karaca, 2020). Internet of Things sensors monitor the operational status of individual machine components in real-time and transmit this data to a central hub. This data flow tracks wear and tear on machine parts, offering a management model that completely eliminates the risk of unplanned downtime (Ceyhan and Kasapbaşı, 2022). Advanced yarn tension control systems maximize production efficiency by minimizing breakages during the weaving process (Fyitester, 2026). Computer-aided design (CAD) and manufacturing (CAM) software

bridge the gap between design and production through digital connectivity (Gulay and Lucero, 2019). Social responsibility and environmental constraints are compelling manufacturers to adopt more transparent and accountable production models. The factories of the future are envisioned as fully autonomous, self-managing structures where human-machine interaction is optimized (İlhan, 2019).

Modern machinery enables mass customization through "flexible manufacturing" capabilities that make small-batch production economically viable. Automated pattern-changing systems prevent downtime by allowing transitions to different designs without stopping the machine. Autonomous guided vehicles used in in-plant logistics synchronize the flow of raw materials with production speeds. Machine interfaces allow operators to manage complex systems via simple touchscreens. Advanced machinery can now produce not only flat surfaces but also raised textures. Modern production lines are equipped with closed-loop control systems that minimize the margin of error. Automation in yarn distribution systems prevents color mixing, thereby maximizing pattern clarity. Sustainable thermoplastic applications used in carpet backing processes increase machine processing speeds while reducing drying times. Tension sensors in yarn winding machines ensure uniform winding of bobbins, thereby preventing tufting defects.

Autonomous color dosing systems ensure color consistency by eliminating human error in dyehouses. Digitalization fosters transparency in supply chain management, enabling the tracking of raw materials from the field or recycling center to the end user. Digitalization efforts have completely eliminated the costs associated with screen and template preparation required by traditional printing methods. Digital printing systems ensure that the dye penetrates deep into the fiber structure. Studies have demonstrated that considering fiber morphology in digital printing

applications is critical for enhancing print quality and final product performance. Furthermore, detailed analysis of the textile product's structure proves to be a decisive factor in optimizing printing parameters (Kara et al., 2026). Centralized dust extraction systems protect worker health by continuously monitoring air quality on the production floor. These technological advancements have reduced the reliance on labor-intensive systems in carpet factories. Factory managers can monitor the real-time status of production lines from anywhere in the world via mobile applications.

Quality Control and Artificial Intelligence Applications

Quality control mechanisms in carpet manufacturing have evolved from traditional, labor-intensive methods to AI-based automated inspection systems. Owing to AI integration, the margin of error stemming from human factors such as fatigue and lapses in concentration inherent in the classical approach is being minimized. Today, high-resolution line-scan camera systems analyze carpets on the production line by scanning thousands of frames per second (Kalkan, 2026). These systems can detect even the slightest loop defect, yarn breakage, or foreign matter contamination on the carpet surface within milliseconds. AI not only identifies the defect but also classifies its type and source, sending real-time alerts to machine operators. Analyzing fiber structural irregularities via digital microscopes enables quality control at the microscopic level. Sensor-based yarn tension monitoring prevents potential surface undulations during weaving before they even occur.

Systems used for color management analyze spectrophotometer data to measure color deviations with a precision beyond the capability of the human eye. This technology ensures product standardization by minimizing shade variations between dye batches. AI-driven systems implemented in smart factories automatically mark defective areas, thereby reducing waste during

the cutting and packaging stages. Production data is continuously recorded in cloud systems, facilitating long-term efficiency analyses. Owing to learning algorithms, defect detection systems improve their accuracy rates over time as they encounter new patterns and textures. Virtual reality (VR) and Augmented reality (AR) are among the technologies that enable customers to virtually experience carpets within their own spaces. This development minimizes physical sample production processes, thereby saving time and preventing raw material waste. Blockchain technology ensures the reliability and verifiability of carpet recycling certificates. Digital libraries can store thousands of antique patterns in high resolution, allowing them to be brought back to life using modern digital printing machines.

The quality control process is no longer merely a final stage of production but an inspection network active at every step, from raw materials to packaging. Modern quality control systems streamline certification processes by automatically reporting compliance with ISO and other international standards. Customer complaints and return data are integrated into AI systems to ensure that future production is improved based on this feedback. Quality control data is relayed directly to suppliers as feedback, ensuring the consistency of raw material quality.

Conclusion

This study presents a holistic view of the carpet industry's comprehensive transformation from traditional weaving to a digital and technological production ecosystem. The sector's trajectory has evolved from advanced fiber Technologies shaped by innovations in polymer chemistry toward AI-driven smart manufacturing systems that optimize production processes and enable full automation. Alongside micro-level advancements such as antibacterial, stain-resistant, and recycled hybrid fibers, the integration of machine-

assisted quality control and deep learning-based AI applications has accelerated progress in product quality, operational efficiency, and sustainability.

In the final stage of this technological evolution, the direct integration of generative AI models into weaving looms will facilitate the transition from mass production to personalized and autonomous manufacturing. Simultaneously, AI algorithms will automatically sort fiber types from end-of-life products, thereby securing a circular economy and sustainability.

Ultimately, the carpet industry will transcend its identity as a mechanical weaving trade to become a high-tech industrial sector shaped by the convergence of materials science, artificial intelligence, and green transition. Stakeholders who embrace this transformation and combine R&D investments with digitalization will secure a global competitive advantage in the smart textile ecosystem.

Artificial Intelligence Usage Statement: AI-based tools (Paperpal by Editage and Gemini by Google) were utilized to a limited extent during the preparation of this book chapter to review the text for language and expression. The scientific content, evaluations, and final responsibility for the chapter rest with the author.

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