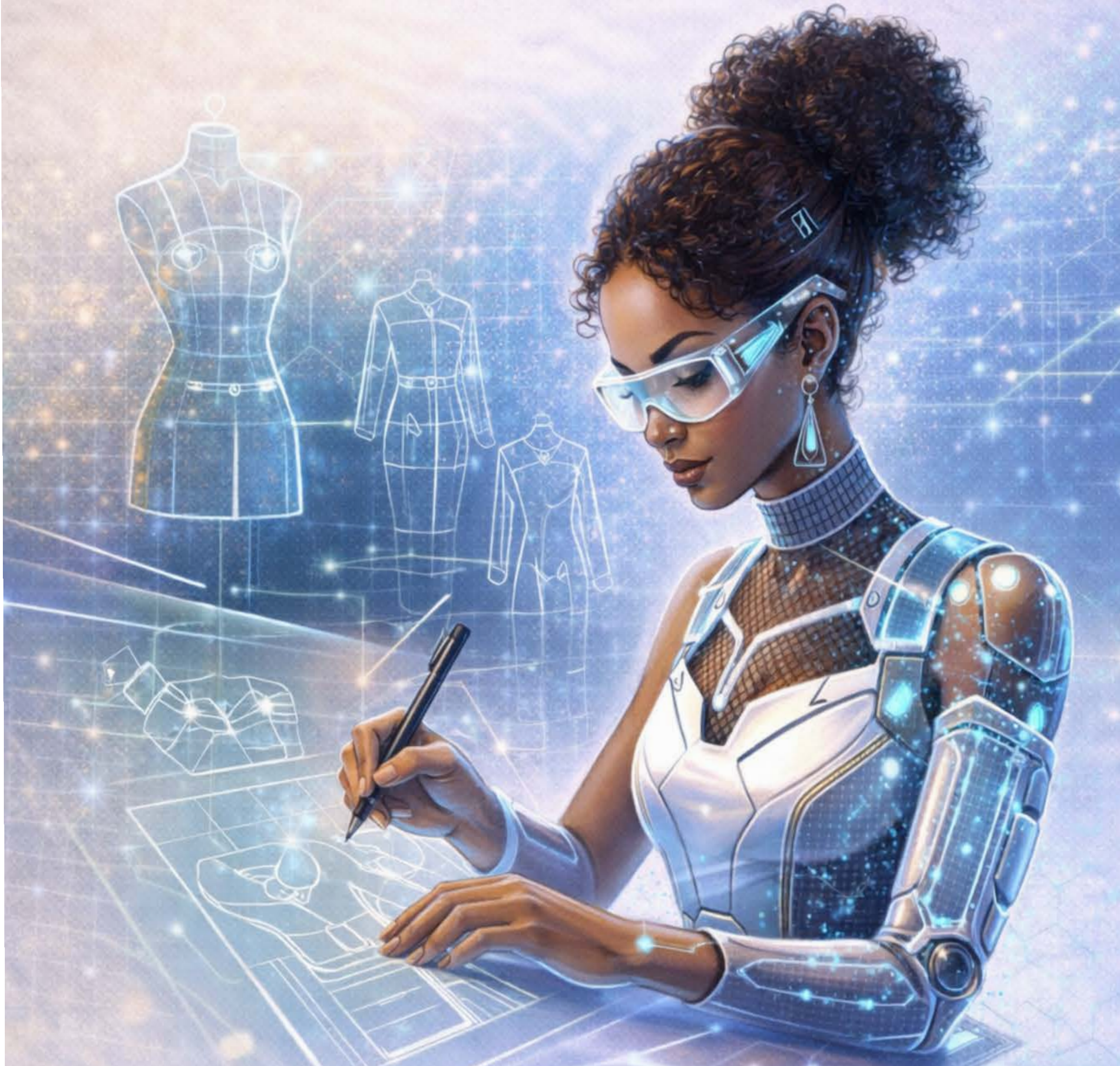
Innovative Trends in Fashion Design Practices



Editor

Assoc. Prof. Dr. Serkan BOZ

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GLOBAL ACADEMY

Preface

The implementation of this study has revealed that innovation in fashion design has moved beyond being merely a creative discourse and has become central to the survival and evolution of the industry. This makes it even more evident that designers and brands must adapt to new technological and ecological paradigms. In this sense, the need for a contemporary source exploring the intersection of design, technology, and ethics has become clear. By combining theoretical discussions on modern trends with practical applications, "Innovative Trends in Fashion Design Practices" serves as a guide for students, researchers, and practitioners alike.

The chapters in this book examine and address the multidimensional dynamics of the fashion industry from both theoretical and practical perspectives, with a particular focus on sustainability, wearable technologies, and the integration of advanced tech in fashion systems. The chapters are written with the aim of providing readers with insights from different levels of the global fashion landscape, drawing on the knowledge and expertise of the contributing authors. These examples have been carefully crafted to demonstrate how innovative design practices can contribute to a more efficient, tech-driven, and sustainable future.

In this regard, I extend my sincere gratitude to the esteemed authors who contributed to this book for their dedicated research and visionary perspectives. I would like to thank Global Academy Publishing House and the institutional representatives, who were involved in every aspect of the book's development and provided invaluable support, for their meticulousness throughout the process. I would also like to thank Esra Yılmaz, who supported me throughout the book's development and contributed to the visual identity of this work.

Innovation and sustainability hold a crucial place in today’s fashion world. The fusion of technology with design plays a crucial role in shaping the industry of the future, guiding this transformation journey through ethical values and smart solutions. Therefore, I hope this book will serve as an essential guide and an inspiration in achieving this transformation.

Editor

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CHAPTER I

SUSTAINABLE FASHION AND THE USE OF ECO-FRIENDLY MATERIALS

Hatice Kübra ÖZBEY[1]

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Introduction

The apparel industry is one of the leading sectors on a global scale, holding significant importance in terms of economic growth, employment, and cultural expression. The sector, which has a large economic share, meets consumer demands such as self-expression and keeping up with current trends. It is also easily accessible physically and materially, which encourages increased demand for the sector. The concept of "fast fashion" significantly increases resource usage, chemicals in production processes, carbon footprint, and waste amounts, which are often overlooked while responding to consumer demands. Today, the consumption frenzy and the disregard for global resources lead to productions that are neither human- nor environmentally-friendly, causing the industry to question itself. It has become necessary for design and production processes to advance by holistically addressing production-environment-human issues and integrating the waste process into the entire life cycle without neglect. Supporting the production process with sustainable approaches has become an obligation, but sustainability in the apparel industry will be achieved through consumers becoming conscious of this matter.

The fashion industry, which ranks second in water consumption, requires approximately 2,700 liters of water to produce a cotton shirt and approximately 7,500 liters for jeans (Maiti, 2025). Thirty-five percent of microplastics in the ocean originate from the washing of synthetic textiles (Boucher & Friot, 2017). This industry pollutes water by releasing water containing chemicals used in dyeing, printing, and finishing processes back into the environment, such as rivers and streams. The fashion industry accounts for 10% of global carbon emissions (Maiti, 2025). Only a small portion of clothing is recycled. A garment is worn seven to ten times before being discarded, and the number of wears has decreased by 36% over the past 15 years. Of the 100 billion garments produced each year, 92 million tons are sent to landfills as waste (Igini, 2023). In light of these facts, the extent of waste committed by unconscious consumers and producers shows that while the sector is encouraging continuous production, the damage it causes to the environment has reached a level that cannot be ignored.

When we look at the garment sector, the use of pesticides starting from fiber production, the use of chemicals especially in the production process, the use of raw materials resulting from continuous and excessive consumption with the fast fashion approach, and the fact that clothing expires in a short time and fills up landfills due to the constantly changing fashion, the sector is an environmentally polluting sector. Sustainability has emerged as a prominent concept in the sector to prevent this from becoming irreversible. Sustainability is the ability to be permanent; it means producing without depleting resources for both individuals to continue their lives and for the continuity of economic relations. It appears as a whole by addressing environmental, social, and economic issues together. The protection of the environment, ecosystem, and biodiversity is necessary in production and consumption processes. It must be economically feasible, and resources should be used efficiently in the long term. Socially, it includes issues such as fair treatment of individuals and societies, equal approach, and the elimination of poverty (Şen, Kaya, and Alpaslan, 2018).

Sustainability, which exists in many fields, began to take shape with its foundations laid at the United Nations Conference on the Human Environment held in Stockholm in 1972. The concept of sustainable development was defined in its most general terms in the Brundtland Report prepared by the World Commission on Environment and Development in 1987 as "Development that meets the needs of the present without compromising the ability of future generations to meet the needs of others." With the "United Nations Conference on Environment and Development" held in Rio de Janeiro in 1992, climate change, biodiversity, and environmental issues became priorities on the international agenda. With the World Summit on Sustainable Development (Rio+10) held in Johannesburg in 2002, social and economic development were addressed in conjunction with environmental protection, and the concept of sustainability in its current sense was established (Ağca, 2002). At the Rio+20 Conference held in Rio de Janeiro in 2012, sustainability was addressed in a broader framework at the global level, and the requirements were strengthened (Pisano, Endl, & Berger, 2012). In 2015, the 2030 Agenda for Sustainable Development and the 17 Sustainable

Development Goals were adopted by the United Nations. Accordingly, it has become a common action framework signed by 193 countries, addressing various issues such as eliminating poverty, reducing inequalities, combating climate change, promoting peace, justice, environment, and social issues (United Nations, 2015).

The textile and apparel industry, particularly in developing countries, causes environmental problems. This manifests itself in air and water pollution, noise levels, heavy metal emissions, and accumulated waste (Rahaman, Pranta, Repon, Ahmed & Islam 2024). As sustainability has become a necessity in the fashion industry, designers, manufacturers, and academics have developed different approaches to meet consumer demands while protecting the environment and human health. These approaches include reducing environmental damage through the use of eco-friendly materials, increasing recycling, and reducing waste. Current fast fashion design thinking focuses solely on the production process; designs are created with considerations such as what materials will be used, what the new season's colors and trends are, how much will be produced, what the consumer's preference is, and how long the garment will last (i.e., how long it will wear out). This process encourages consumers to buy garments that will only be worn for a short time and perhaps never be worn, thus occupying space in their closets, leading to a shift towards fast fashion.

Sustainable design requires systematic thinking encompassing the production process, consumer use, and disposal processes. When selecting materials, it is crucial to ensure environmentally and human-friendly materials; this prevents chemicals used in the production process from harming the environment and humans, irritating skin, and creating an environmental burden through non-biodegradable waste. Furthermore, advanced and innovative production systems ensure a production process that reduces carbon footprint and protects employee rights. By not following fast fashion, it prioritizes the long-term wearing of clothes by shifting from a fast-paced consumption approach to a sustainable consumption approach with sustainable fashion. With the conscious consumer, production quantities are planned accordingly, moving away from continuous consumption and increasing the lifespan of a garment. It aims to cause the least harm to the environment by planning the recycling or waste process both during production and after the consumer.

In order to establish the section on sustainability in textiles and sustainability in fashion through the use of materials and new design approaches, it is necessary to consider textiles and apparel as a whole. This chapter will explore sustainable fashion and environmentally friendly materials, addressing sustainable materials, recycling, 3R principles, new design approaches, certifications in the textile and apparel sectors, and the waste disposal process. Within the framework of sustainability, fashion will be considered not merely as a style statement but as part of a systemic transformation. The basic conceptual framework of sustainable fashion approaches, its importance for the environment, the requirements of transformation in production processes, and environmentally friendly materials will be discussed, and the components of the sustainable fashion concept will be examined.

1. Sustainable Fashion Concept and Approaches

In 2020, the European Commission published sustainable product and design principles within the "Sustainable Product Policy Framework" in the document "A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe." It is worth mentioning these principles, as understanding sustainable design will also help us better understand sustainable fashion.

- Durable, reusable, and repairable products
- Limiting the use of chemicals that are hazardous to the environment and human health
- Recycling
- Reuse
- Reducing carbon footprint and negative environmental impact
- Limiting single-use products and avoiding rapidly outdated and obsolete designs (European Commission, 2020).

These principles aim to extend the lifecycle of a product by moving away from disposable or quickly obsolete products and opting for durable and repairable products. This approach has formed the basis of slow fashion, modular clothing design, and recyclable clothing. Products that have reached the end of their useful life are recycled or reused, preventing material loss and landfills, and reintegrating them into the system for a new lifecycle. This allows unusable products to be revitalized and reused, while also preventing the need for new raw materials to produce the new product. This reduces resource consumption. This understanding has formed the basis of concepts such as 3R, upcycling, downcycling, and secondhand clothing in sustainable fashion. In all these production processes, production is carried out by taking the environment and human health into consideration, expressing the use of sustainable materials and production processes, and in fact, we encounter environmentally friendly materials such as organic textiles and design approaches such as the zero-waste design approach.

Sustainable fashion emerged as a counter-movement to fast fashion (Tekin Akbulut, 2012) and is often used interchangeably with terms such as ecological fashion, ethical fashion, and environmentally friendly fashion (Yücel & Tiber, 2018). It refers to the new fashion system that prevents waste in the use of energy and raw materials, preserves resources for future generations without harming or consuming nature and the ecosystem, protects the rights of employees, produces long-lasting clothes that are far from the concept of fast consumption, and allows for recycling after the end of their lifespan to become raw materials for a new product.

1.1.Slow Fashion

With the opening of a fast-food hamburger chain restaurant in Rome and the proliferation of these foods, a group responded to fast food with the slow food social movement. This is the inspiration for today's slow fashion. Fast fashion has transformed clothing habits with inexpensive clothing, creating a fast-consuming consumer. However, this also leads to a rapid depletion of resources. Slow fashion is taking its place as a sustainable fashion trend today, with seasonless, durable products and longer production processes (Fletcher, 2010). Sustainable fashion supports consumers in purchasing fewer but higher-quality garments by promoting the production of smaller quantities of clothing with greater added value and longer service life (Mangır, 2016).

This sustainable fashion approach, which protects the environment without overburdening or depleting resources, aims to prevent the devastation caused by fast fashion. As conscious consumers and brands turn to slow fashion, its adoption within the industry will accelerate.

1.2. 3Rs Approach

The 3Rs approach, consisting of "reduce," "reuse," and "recycle," is based on extending product life and managing waste. Reduce can be defined as reducing the use of raw materials and waste generated by consumption. "Recycle" refers to using a product that has reached the end of its useful life and would now be waste as raw materials for another product (Yücel & Tiber, 2018). This process is the one that gives life to a garment. This new product may appear as a filling material or as a new fabric. This will be discussed in more detail in the discussion of environmentally friendly materials. "Reuse" is the reuse of unused clothing. An example of this is mending a pair of pants whose seams have come undone, making them usable again. Another example is repurposing a garment that a person no longer wears and selling it as secondhand clothing, giving it a new life. In both of these examples, the garment, which was originally usable, had a small tear or simply became bored with the garment due to the fast fashion trend, and was then discarded, but its lifespan has been extended. At the same time, by eliminating waste, it avoids taking up landfill space. By finding a new user for secondhand clothing, the resource consumption required for a new garment is prevented. While "reuse" refers to reuse, it actually encompasses many ideas and interpretations, forming the basis of upcycling and downcycling approaches in fashion.

The expanded versions of the classical 3Rs approach can appear as the 5Rs or even the 6Rs approach. The 5 Rs approach includes the words reduce, rewear, repair, recycle, and resell ("Slow Fashion & the 5 Rs," n.d.), while the 6 Rs approach includes the words repurpose, repair, reprocess, reduce, recycle, and recommercialize ("The 6 Rs of Fashion Sustainability," 2024).

Furthermore, as the circular economy, waste management, and the fashion industry develop a new business model together, the number of "Rs" is steadily increasing, such as rent, recovery, refurbish, remanufacture, and redesign (Zorpas, 2024).

1.3. Upcycling

It is the transformation of garments that have reached the end of their service life into new, value-enhanced products instead of becoming waste. This approach produces affordable products with high quality, aesthetics, and design value. They are often handmade and unique. Examples include creating a handmade rug from a worn-out T-shirt or sewing a girl's dress from adult T-shirts that have holes in them or are unwearable for various reasons (Vadicherla, Saravanan, Muthu Ram & Suganya, 2017). Upcycling is an approach favored by designers rather than ready-to-wear brands because it requires a design-focused approach to clothing that has become unusable. The unusable garment is prevented from ending up in a landfill and is used as a raw material for a new product. It is a sustainable fashion design approach that both prevents the filling of landfills and contributes to the reduction of resource consumption.

1.4. Downcycling

Upcycling refers to the use of end-of-life clothing as raw material for a new, high-value product, while downcycling refers to the use of clothing as raw material for a product of lower value than its original state. Virgin is valuable for sustainable approaches because it reduces resource consumption (Patel & Tiwari, 2024).

An example is the use of old or unwearable T-shirts as cleaning cloths (Vadicherla et al., 2017).

1.5. Zero-Waste

During garment production, a portion of the purchased fabric is discarded as waste during cutting due to the pattern layout; this is referred to as cutting waste. While the waste generated in this conventional production process does not pose a significant problem for a garment, considering the volume of garments produced globally, the amount of fabric discarded at the end of cutting is significant. Zero waste appears as a solution to the waste management process in the cutting process with the order in the mold layout (Özbey & Gürarada, 2022). The cutting process involves interlocking the pattern pieces that make up a garment design, creating fabric without any fabric waste. It is a movement that aims to reduce waste throughout the design, production, and use of a garment. If there are any leftover fabric pieces, they can be used for piping or decoration without wasting anything (Gupta & Saini, 2020). With a zero-waste design approach, designers can eliminate waste by developing creative designs. Traditional garments such as the chiton and peplos from ancient Greece, the Indian sari, and the Japanese kimono are examples of zero-waste designs. The zero-waste approach, whose conceptual beginnings date back to the 1970s, emerged in the 2000s as a systematic and widespread use in fashion design (Rissanen & McQuillan, 2023). Figure 1 shows an example zero-waste trouser design and pattern layout designed by Rissanen (Rissanen, 2013).

The zero-waste approach is a design approach focused on creativity and pattern-making practices, moving away from traditional design and pattern concepts to focus on the production process, where the design is created with 100% fabric efficiency in mind. It supports sustainability by maintaining the highest level of resource efficiency in the garment production process.

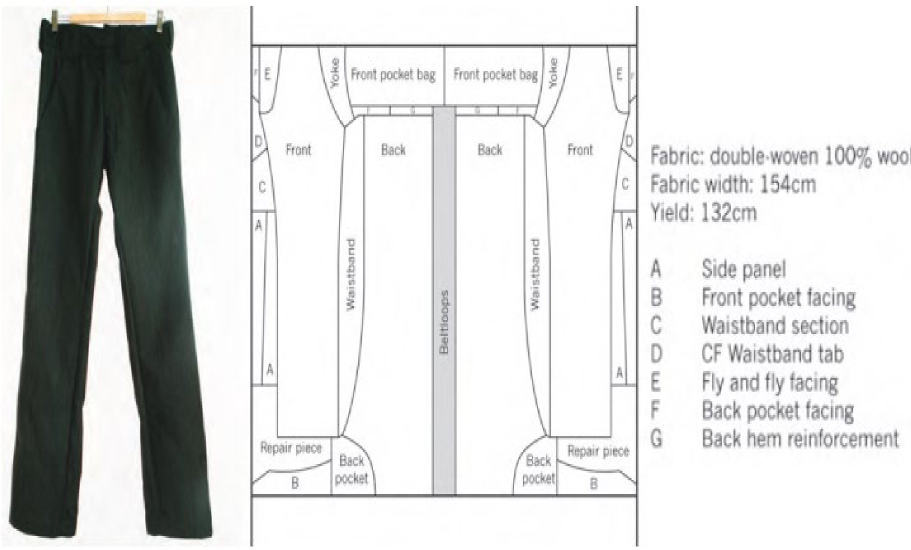

Figure 1. Zero Waste Garment Design And Pattern Layout Sample, Source: Rissanen (2013)

1.6. Modular Garment Design

In modular clothing design, clothing parts can be assembled and removed from one another. LEGO toys are a good example of this structure. Users can combine and remove these parts as desired, wearing the garment in multiple different styles (Şevkay & Bayburtlu, 2020). Modular clothing, a sustainable fashion design approach, increases variety and functionality, and allows the user to participate in choices. By offering multiple clothing options for a purchased garment, the garment's lifespan is extended. The parts are assembled together using embedded techniques, knotting, buttons, zippers, and snaps. Examples include adding and removing different collar shapes to a shirt, attaching and removing sleeve pieces to a dress, and turning a dress made up of pieces into a skirt and blouse (Li, Chen & Wang, 2018). Figure 2 shows examples of modular clothing designs (Manteco, 2025; Zhang et al., 2024).

The relationship between the fast fashion approach and the sustainable modular garment approach serves as a bridge for today’s consumers. While consumers are aware of sustainability, they are also prone to fast fashion habits. Their desire to wear something new, though not to the same extent as before, continues. With this approach, different dressing desires are met with multiple different clothing styles using the raw materials and resources used for a single garment.

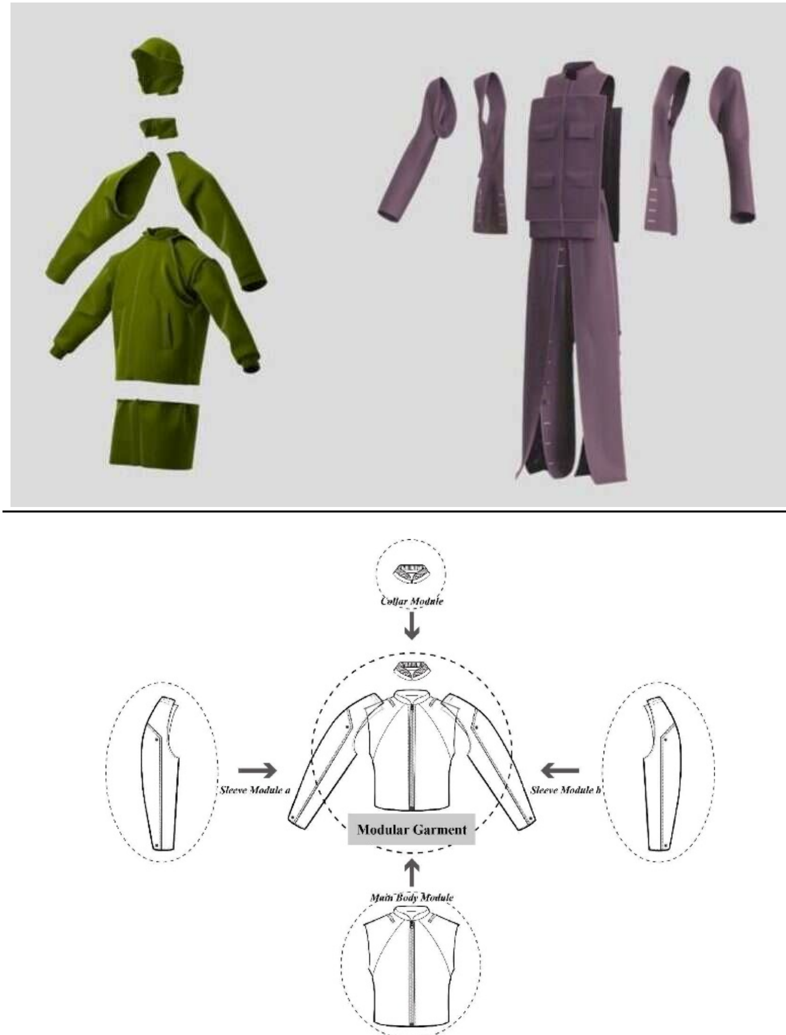

Figure 2. Modular Clothing Design Examples, (A) Manteco (2025); (B) Zhang et al. (2024).

1.7. Transformable Garment Design

Transformable clothing designs are garments that offer multiple styles through manipulative methods such as tying, folding, wrapping, or embellishment. Thus, it transforms according to the needs that vary from user to user. Similar to modular clothing designs, transformable clothing designs involve consumers in the design process and offer multiple options for users who need to wear different garments. With this sustainable design approach, the wearing process of the garment is prolonged, and the product's lifespan is extended by postponing psychological wear and tear, thereby contributing to a reduction in waste and resource use. By integrating with modular clothing designs, clothing diversity can be increased. In the example of the transformable garment design designed by Rahman and Gong in Figure 3, a garment can be used both as a dress and a skirt (Rahman & Gong, 2016).

Reversible garments are currently being sold as an example of interchangeable garment design, the most common form of clothing used by ready-to-wear companies. The transformable clothing concept, which offers the habit of wearing different clothes in a single garment, instead of the quest for wearing different clothes that comes from fast fashion, is the sustainable design concept that will be preferred by today's consumers. It is a design approach that bridges the gap between fast fashion and sustainable fashion for today's consumer, such as modular clothing design.

Figure 3. Transformable Clothing Design Example, Source: Rahman & Gong (2016)

2. Sustainable Fashion Production Process

Designers and manufacturers are often compelled to use inexpensive materials to produce affordable products for the fast fashion industry. Only by choosing sustainable materials can we truly define sustainable fashion. Garments produced using renewable resources, ecological materials, environmentally friendly production methods, and a sustainable supply chain demonstrate sustainable production practices in the fashion industry (Rahaman et al., 2024). Moreover, sustainability can be fully addressed when considered together with social and economic issues. However, even if all the criteria for sustainable production are met, we cannot demonstrate this to the other party unless it is documented. With certificates, we can prove that we produce sustainable products through sustainable production.

Transparency is required in sustainable certification processes, meaning that every step of production must be traceable. Figure 4 shows the sustainable clothing production stage and material flow in the textile and apparel industry schematically (Rahaman et al., 2024).

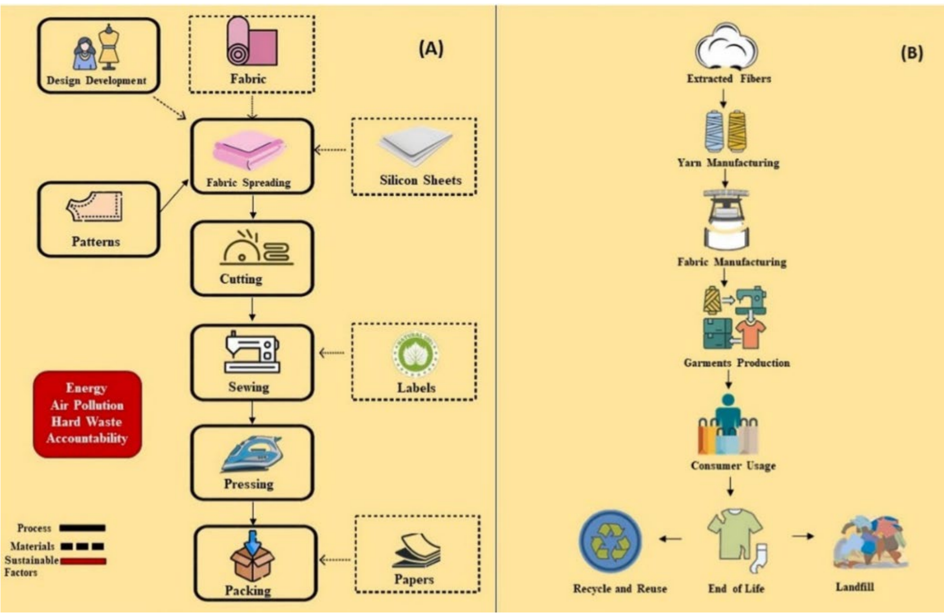

Figure 4. (A) Sustainable Clothing Production Stage, (B) Material Flow In The Textile And Clothing Industry, Source: Rahaman et al., 2024

In the literature, sustainable textile certifications and standards have been examined from various perspectives, including the traceability of raw materials, environmental impact, and the use of chemicals (Plakantonaki et al., 2023; Textile Exchange, 2022; Ziyeh & Cinelli, 2023). Based on these studies, certificates were classified into four groups, as shown in Table 1.

1- Raw material and fiber source certifications and standards: The primary focus is on ensuring that the fiber production process is environmentally sustainable. Some certifications in this group monitor the process only up to the fiber stage, while others control the entire process from fiber to garment production. These certifications include the Global Organic Textile Standard (GOTS), Organic Content Standard (OCS), Global Recycled Standard (GRS), Recycled Claim Standard (RCS), Better Cotton Initiative (BCI), Fairtrade Cotton, and Responsible Wool Standard (RWS).

2- Production process and chemical management certifications and standards: The focus is on environmental management of the production chain, safety in chemical use, and resource efficiency. Certifications in this group include OEKO-TEX® Standard 100, OEKO-TEX® MADE IN GREEN, OEKO-TEX® STeP, bluesign® SYSTEM, Zero Discharge of Hazardous Chemicals (ZDHC), and ISO 14001.

3- Social compliance and ethics certifications and standards: It focuses on the social dimension of sustainability, which is the human and total issue of sustainability, such as working conditions and fair wages. Certifications in this group include Worldwide Responsible Accredited Production (WRAP), Fair Wear Foundation (FWF) and SA8000.

4- Product and environmental performance certifications and standards: It focuses on the product's life cycle, carbon footprint, biodegradability, and ecological impact. Certifications in this group include EU Ecolabel, Cradle to Cradle Certified™ (C2C), and Higg Index (by Sustainable Apparel Coalition).

Table 1. Sustainable Certifications, Standards, And Classifications In Textiles And Apparel

Group	**Certification Name**	**Logo**	**Description**
1. Group Raw Material and Fiber Source Certifications And Standards	Global Organic Textile Standard (GOTS)		It certifies that the product has been processed in accordance with organic criteria, from the organic fiber production phase to the garment production phase. It includes criteria for chemical use, waste management, energy use, and environmental and social compliance.
	Organic Content Standard (OCS)		It verifies and ensures traceability of organic fiber content during the production process and does not include social criteria.
	Global Recycled Standard (GRS)		It monitors recycled material content, chemical restrictions, and includes environmental and social compliance criteria. Proves recycled material content.
	Recycled Claim Standard (RCS)		It verifies the amount and extent of recycled material in the product and ensures traceability throughout the supply chain. It does not include environmental and social criteria.
	Better Cotton Initiative (BCI)		It supports agricultural practices that regulate the use of chemicals such as pesticides in cotton production and that are environmentally friendly, high water efficiency, and protect soil health. It also aims to improve working conditions.
	Fairtrade Cotton		It aims to ensure that cotton producers produce under fair trade conditions and increase social welfare. It includes environmental improvement criteria such as pesticide use and waste management.

<u>2. Group</u> Production Process and Chemical Management Certifications and Standards	OEKO-TEX® Standard 100		It tests textile products to determine whether they contain chemicals harmful to human health. It specifies prohibited substances and their limit values. It reassures consumers that the product is safe.
	OEKO-TEX® MADE IN GREEN		It provides assurance to consumers by verifying that textile products are produced in sustainable facilities and contain no harmful substances. It enables transparent monitoring of the supply chain via QR code.
	OEKO-TEX® STeP		It evaluates the environmental management, chemical use, energy, and social compliance criteria of textile companies. Proves corporate sustainability performance.
	bluesign® SYSTEM		
	Zero Discharge of Hazardous Chemicals (ZDHC)		It aims to completely eliminate hazardous chemicals from production processes in the textile and leather industry. It includes a list of banned chemicals and focuses on chemical sustainability.
<u>3. Group</u> Social Compliance And Ethics Certifications And Standards	Worldwide Responsible Accredited Production (WRAP)		It certifies compliance with ethical production, working conditions, environmental, and social responsibility principles in textile and ready-made clothing manufacturers.
	Fair Wear Foundation (FWF)		It supports the improvement of fair working conditions, worker safety, and wage policies in the supply chain of brands. It conducts complaint handling, auditing, and training programs.
<u>4. Group</u> Product And Environmental Performance	Cradle to Cradle Certified™ (C2C)		It considers the life cycle of products, assessing material cycle, material health, renewable energy, social justice, and water management. Evaluates the product's potential for reuse, biodegradability, or recycling

Certifications And Standards	Higg Index (by Sustainable Apparel Coalition)		It is an assessment system used to measure the environmental and social performance of textile and apparel manufacturers. It is a system that scores environmental and social conditions, such as carbon emissions and water usage.

Source: Global Organic Textile Standard (GOTS, 2025); Textile Exchange (OCS, GRS, RCS, 2025); Better Cotton Initiative (BCI, 2025); Fairtrade International (Fairtrade Cotton, 2025); OEKO-TEX® Association (OEKO-TEX® Standard 100, MADE IN GREEN, STeP, 2025); bluesign technologies ag (bluesign® SYSTEM, 2025); ZDHC Foundation (ZDHC, 2025); Worldwide Responsible Accredited Production (WRAP, 2025); Fair Wear Foundation (FWF, 2025); Cradle to Cradle Products Innovation Institute (C2C, 2025); Sustainable Apparel Coalition (Higg Index, 2025).

3. *Eco-Friendly Materials*

Materials obtained through conventional production methods create environmental burdens due to their use of resources such as water, energy, and raw materials, carbon emissions, waste production, and chemical use. Eco-friendly materials play an active role in reducing the environmental impact of the textile and apparel industry. Eco-friendly materials contribute positively to the circular economy by increasing sustainability performance and resource efficiency throughout the product's lifecycle. Sustainable fashion requires considering design concepts that minimize the negative impact a product will have on the environment. For this reason, it is desired that the fiber that makes up the fabric is disposed of without harming the environment or humans during production, and without harming the environment or creating a waste load at the end of the usage period, or it is desired to be used as raw material for a new material. In this regard, organic fibers, recycled fibers, ecological fibers, and biodegradable materials are expressed as sustainable materials.

According to a 2018 report published by the United Nations Environment Programme (UNEP), the textile and apparel industry must shift to sustainable materials to reduce marine microplastic pollution. In order to solve the environmental problems caused by microplastic release from synthetic fibers, material selection and production methods must be handled sustainably. The report states that using natural fibers and bio-based polymers instead of plastic-based textile materials are environmentally friendly alternatives for sustainable fashion (United Nations Environment Programme [UNEP], 2018).

A garment's sustainability performance is determined through a life cycle analysis. The sustainable performance of the garment is evaluated from an environmental perspective by measuring values such as water, energy, carbon emissions, and toxicity by considering the fiber production, production, and disposal processes (International Organization for Standardization [ISO], 2006). Life cycle studies conducted to assess the environmental impacts of various fibers, as shown in Figure 5, show that organic cotton and linen have higher sustainability values than other fibers, while virgin synthetic fibers have lower sustainability values (UNEP, 2018). The entire life cycle of the garment, namely the production phase, the user, and the waste process, should be designed as a sustainable system from the very beginning.

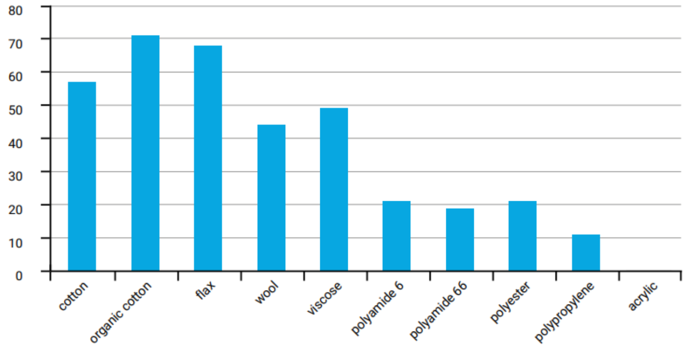

Figure 5. Comparison of Different Fiber Types in Terms of Environmental Sustainability Source: UNEP. (2018).

3.1. Ecological Textiles

Sustainable fashion is an approach that targets environmental responsibility and social issues. Ecological textiles are materials that aim to reduce the environmental impact of classical textile materials. It is desired that ecological textiles do not harm human health during use. It aims to protect the environment during both the production phase and the waste disposal process after the end of its life (Özbey & Gürarda, 2022). Recently, as consumers have become more aware of the fashion industry's resource consumption, waste, and chemical use, they have begun to turn to eco-friendly garments. Considering how polluting the fashion industry is, the fact that ecological textiles are preferred by brands and consumers is a positive situation in terms of protecting the environment (Bureekhampun & Maneepun, 2021).

The raw materials of ecological materials are desired to be easily degradable in nature or made from recycled materials. Natural fibers; cotton, bamboo, nettle fiber, linen, silk, wool, organic fibers, etc.; regenerated fibers based on natural raw materials; viscose, lyocell, modal, milk protein, soy protein fiber, etc.; recycled synthetic or naturally sourced fibers; recycled polyester (rPET), recycled nylon (Econly, etc.), recycled cotton, etc.; and bio-based synthetics fibers; Polylactic Acid (PLA), bio-based polyethylene terephthalate (biodegradable polyester, Bio-PET), etc. are referred to as ecological fibers (Textile Exchange, 2017; UNEP, 2018; Çeven & Günaydın, 2023).

The high demand for synthetic fibers in the fashion industry leads to the accumulation of microplastics, which do not degrade over time. This creates waste management problems and increases the environmental burden. Using biodegradable fibers in material selection is more environmentally sustainable, as they are compostable, have a low carbon footprint, and do not leave toxic residues. Biodegradation is the breakdown of materials by microorganisms and their return to nature in the form of carbon, nitrogen, and sulfur (Çelebi & Karagöz). Biodegradable materials should not be considered solely for use in fabrics; they can also be utilized in accessories, such as buttons. Plant-based fibers such as cotton, linen, and jute degrade more rapidly during composting. Biopolymers such as thermoplastic starch, polylactic acid (PLA), and polyhydroxyalkanoates (PHA) hold potential as compostable biomaterials. However, care must be taken to ensure that these materials do not mix with the ocean (UNEP, 2018).

Figure 6 shows the 4-week biodegradation process of conventional cotton fabric dyed with synthetic dyes and organic cotton fabric dyed with synthetic and natural dyes. It is observed that as the fabric's organic capacity increases, the biodegradation process accelerates (Özbey & Gürarda, 2025b).

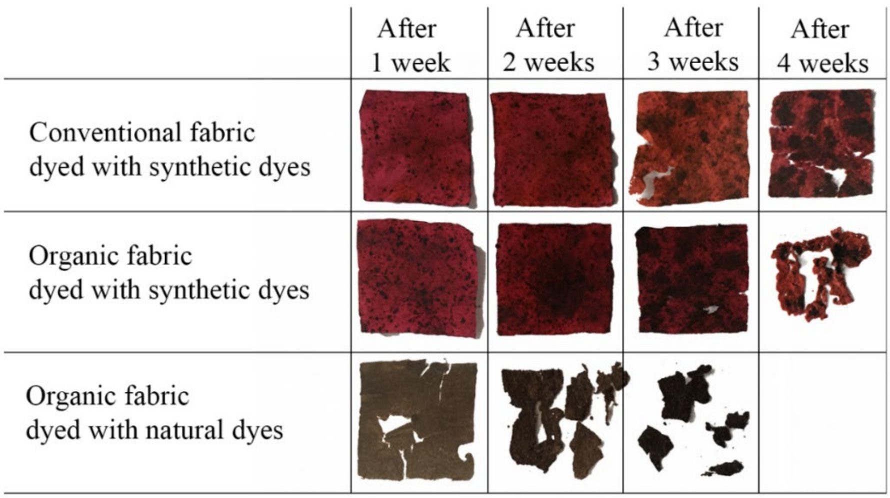

Figure 6. Conventional-organic cotton biodegradation process, Source: Özbey & Gürarda (2025b) adapted

The Preferred Fiber or Material grouping in the Textile Exchange (2017) report is shown in Figure 7. Accordingly, it indicates sustainable fibers or materials that create a lower environmental and/or social impact than their conventional counterparts (Textile Exchange, 2017).

The term ‘ecological textiles’ generally refers to a broad range of sustainable textile materials.

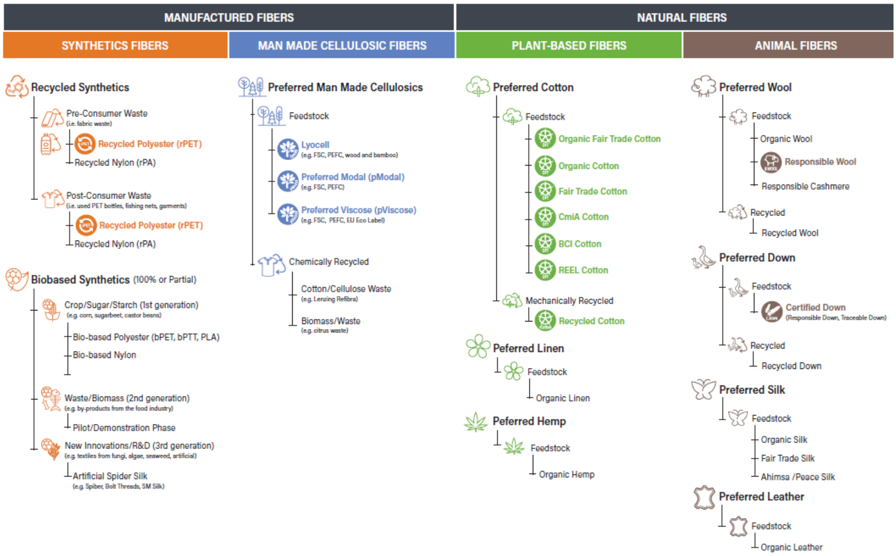

Figure 7. Sustainable textile materials, Source: Textile Exchange-Preferred Fiber & Materials Market Report 2017.

3.2. Recycled Textiles

Textile products that have reached the end of their lifespan should be reintegrated into the system for sustainability. The aim is to turn these products into raw materials for a new product through recycling processes, without going to the landfill. This reduces both waste and resource and energy consumption (Yücel & Tiber, 2018). Waste is divided into two groups: "pre-consumer waste" and "post-consumer waste." It can be encountered in the form of fiber, yarn, and fabric waste at every stage of the production process. Pre-consumer waste can be reintegrated into the system through mechanical, thermomechanical, and chemical recycling methods (Türemen, Demir, & Özdoğan, 2018). Post-consumer waste can be defined as the clothes we remove from our wardrobes because we no longer want to wear them. Twelve percent of textile products are recycled, while the rest is incinerated to generate energy or ends up in landfills. 1% of these recycled fibers, originating from recycling processes, can be used to produce yarn again. The remaining is used as cleaning cloths and filling materials. The process of turning synthetic fibers into polymers and reincorporating them into the spinning system is somewhat easier in recycling (Rahaman et al., 2024).

Waste textile materials can be converted into energy by incineration. However, in this method, the resource that could be a raw material for another product is destroyed. With the effective use of recycling, the polluting process of fashion will be made more sustainable. This will reduce the use of virgin materials and carbon footprint, bringing resource consumption to sustainable levels. Figure 8 shows the process steps for effectively reusing and recycling clothing that is no longer used by consumers. It shows the recycling of textile waste into the living process, such as recycled fiber or upcycling and secondhand clothing (Rahaman et al., 2024).

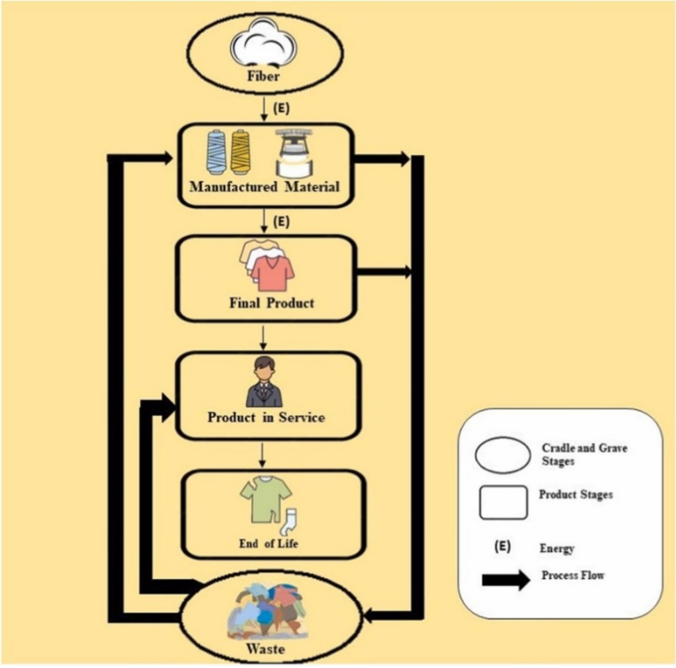

Figure 8. Methods for reusing and recycling clothing at the end of its lifespan, Source: (Rahaman et al., 2024)

Textile waste collected for recycling is separated by material type and color. If mechanical recycling is performed, the material is broken down into small pieces and converted into fibers for use in yarn production or other applications, such as insulation (Yücel & Tiber, 2018). If all recycled materials are cotton in this method, recycled cotton yarn, and therefore recycled cotton fabric, is obtained. However, considering that not every garment or fabric is 100% cotton, it can be noted that recycling cannot be applied to all products (Rahaman et al., 2024). Composite textile products containing multiple fibers can be recycled and used in different areas, such as filling material.

Synthetic fibers such as polyester and polyamide can be recycled through mechanical or chemical means. For example, recycled polyester (rPET) fiber can be obtained from textile waste or by using PET bottles (Eser, Çelik, Çay, & Akgümüş, 2016). The letter "r" in the fiber's name indicates that it is recycled. Such as rPET, rNylon, r-Nylon, rCotton. There are also trade names, such as Econyl, for nylon obtained by recycling industrial waste, including fishing nets and carpets (Aquafil, n.d.).

The Levi’s Eco® collection is created with fabrics made from Levi’s brand’s organic and recycled cotton. Another example is Levi’s Waste-LessTM collection, which consists of fabrics recycled from PET bottles, which comprise 29% of post-consumer waste. In the fashion industry, led by global brands such as Nike, Lindex, Puma, and Esprit (Yücel & Tiber, 2018), the use of recycled materials is preferred by many brands today within the framework of sustainability.

3.3. Organic Textiles

Organic fibers are plant fibers such as cotton, linen, and hemp or animal fibers such as wool, cashmere and silk. These fibers must have certifications such as GOTS and OCS to distinguish them from conventional fibers. They are produced using non-GMO seeds, agricultural practices that prohibit the use of pesticides and chemicals, or animal husbandry processes that promote animal health, natural nutrition, and avoid chemical processing (Global Organic Textile Standard [GOTS], n.d.). They are textile materials that protect the environment, human, and animal health.

While clothing with organic certification is labeled, they are labeled "organic" if they contain 95% or more organic fibers, or "organic blended" if they contain less organic content (varies by certification) (Özbey & Gürarda, 2025b).

There has been an increase in global cotton production, shifting from conventional to organic cotton production (Textile Exchange, 2022). The global organic fabric market is expected to grow at an annual rate of around 5.4% from 2024 to 2033 (MarketGrowthReports, 2025). While 4,500-7,000 tons of water are used to produce 1 kilogram of conventional cotton, water-saving methods in organic farming can save up to 62% (Atalık, 2013; Şimşek Yeşil, Dal, Öztürk & Kitiş, 2023). It is stated that there are more than 8000 chemicals used in the production stages of a garment. These chemicals return to nature as waste, causing environmental damage (Akbulut, 2012). At the same time, chemicals found on clothing can cause various skin problems. Organic certified cotton clothing is clothing that minimizes the use of chemicals. It is a sustainable alternative, especially for people with sensitive or allergic skin and for babies (Azizağaoğlu, Aksu, 2018).

Today, organic clothing is colored with synthetic dyes for various reasons, including the dyeing recipes companies are accustomed to and the test results of which are known. As an alternative to synthetic dyes, there are natural dyes. These are obtained from materials such as leaves, plant peels, and fruit waste. In the comparison of the conventional-organic state of the same fabric with synthetic dyestuff and natural dyestuff, it was seen that the color resistance of the naturally dyed organic fabric, that is, the fastness results, were similar to the conventional state and gave satisfactory high results for the customer. Natural dyes offer an alternative to synthetic dyes because they are non-toxic, non-carcinogenic, and environmentally friendly, leaving no chemical waste (Özbey & Gürarda, 2025a).

Clothing sent to landfills must decompose quickly to avoid occupying landfills for extended periods. Cotton fiber is biodegradable. The biodegradability of organic cotton fabric is higher than that of conventional cotton fabric. Similarly, the biodegradability of organic cotton fabric dyed with natural dyes is higher than that of fabric dyed with synthetic dyes (Özbey & Gürarda, 2025b).

The environmentally and human-friendly approach of organic fiber production and the low use of chemicals in the yarn, fabric, and apparel stages increase its preference among sustainable materials. Consumers' preference for organic fiber clothing provides a significant competitive advantage for brands in the market.

3.4. Biobased Synthetic Fibers

Biobased synthetic fibers are derived from natural raw materials such as corn, sugarcane, and potato starch. They are sustainable alternatives to conventional petroleum-based synthetic fibers, featuring a lower carbon footprint and environmentally friendly production and waste management practices. Polylactic acid

(PLA) and polyhydroxyalkanoates (PHA) fibers are the most commonly used biobased fibers (Hottle, Bilec, & Landis, 2017; Álvarez-Chávez et al., 2012). Biobased fibers are seen as innovative solutions in the textile industry with the correct production chain and disposal method.

Polylactic Acid (PLA) fiber is a bio-based polyester fiber produced from plant starch such as corn. It is similar to conventional polyester fiber, but its biodegradability and natural origin of the raw material make it a sustainable fiber (Üner & Koçak, 2012). Textiles produced from thermoplastic PLA fiber are lightweight, with good strength and thermal properties. PHA fiber is a biopolymer obtained by synthesizing sugars or fatty acids using microorganisms. They are used in textile applications in coating, packaging, and fiber form. They are rapidly biodegradable, leaving no toxic residue (Öztürk & Eroğlu, 2025). Milk protein fiber is derived from the casein protein in milk. The fabric produced from this fiber is antibacterial and breathable. It has a shiny appearance and a silky soft touch. It is stated that 2 million tons of milk are thrown away every year. Milk protein fibers from companies like QMILK and Duedillate extract casein from industrial waste, such as whey. By integrating waste generated in the dairy market into the textile industry, it is a good example of the intersection of sustainability principles in two different sectors (QMILK, 2025; Duedilatte, 2025). The vegetal leather, commercially known as Pinatex, is produced by mixing PLA and pineapple leaf fiber, which is obtained from the leaves remaining after the pineapple harvest. It provides an alternative to animal leather and synthetic leather. It is a strong and flexible surface that resembles skin texture. It is an important alternative as a sustainable textile material, utilizing agricultural waste, reducing CO_2 emissions, and being an environmentally friendly material (Ananas Anam, 2025). Mycelium skin is a new alternative to conventional leather, produced by growing the root structure of a mushroom in a controlled environment. It is a lightweight, flexible, and biodegradable material (Öztürk & Eroğlu, 2025). Figure 9 shows samples produced from the mycelium skin produced by MycoWorks (MycoWorks, 2025).

Figure 9. MycoWorks miselyum derisinden ürettiği ürünler
Source: MycoWorks, 2025.

Conclusion

Today, as a result of fast fashion, excessive resource consumption, and high waste amounts have turned the textile and ready-made clothing industry into a polluting sector that causes environmental problems. To reduce the fashion industry's negative impact on the ecosystem, choosing environmentally friendly materials has become imperative. Environmentally conscious material selection will form the basis of responsible fashion design.

Among sustainable fashion approaches, approaches such as slow fashion, upcycling, transformable clothing design, and modular clothing design stand out. These approaches foster conscious consumer behavior. They offer effective strategies for reducing the environmental impact of the fashion industry. Clothes produced with sustainable fashion are long-lasting clothes that do not wear out quickly, can be repaired, and do not become outdated quickly. Sustainable fashion is an adventure that starts with sustainable materials and continues with sustainable design approaches, is preferred by conscious consumers, and minimizes waste.

Sustainable fashion addresses the three dimensions of sustainability: environmental, social, and economic issues. Environmentally friendly production is achieved with eco-friendly materials and design approaches that address the waste system. It has a production process that respects people from a social perspective by protecting employee rights in accordance with the criteria set in the standards. Both sustainable material selection and sustainable fashion approaches reduce waste, reduce resource use, conserve water and energy, increase production efficiency, and reduce costs. This enhances the company's competitiveness in the market. Sustainable fashion is not just a design approach, but also a system that addresses environmental protection, social responsibility, and economic sustainability in a holistic way.

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CHAPTER II

CIRCULAR ECONOMY AND FASHION: REUSE, RECYCLING, AND DESIGN

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Abstract

In recent years, the notion of circularity has rapidly gained traction in design and fashion discourses, increasingly positioned as the successor to sustainability. Within fashion, the circular economy envisions a system without a clear beginning or end, a continuous loop inspired by the geometry of the circle itself. It refers to processes by which materials and products can be returned to production cycles without losing their physical or chemical properties. Examples include transforming plastic bottles into polyester fabric or converting a worn denim jacket into a handbag. When adopted on an industrial scale, such methods can form a circular fashion system. As an alternative economic model, circularity aims to break the linear production–consumption–waste cycle by keeping materials in a closed loop through recycling, upcycling, reuse, and repair, thereby extending the lifespan of resources through multiple regenerations.

This vision aligns with the philosophy of Cradle to Cradle (C2C), developed by William McDonough and Michael Braungart as a response to the "cradle to grave" logic of linear production. C2C proposes that products should circulate within two systems: the biological cycle, where materials safely decompose and return to nature, and the technical cycle, where non-biodegradable materials are continuously reused or upcycled.

By situating circularity within broader debates on sustainability, material flow, and design ethics, this chapter adopts a critical and comparative methodology to examine how circular principles are translated into fashion practice. It analyses theoretical frameworks such as C2C and regenerative design, while also questioning how these concepts are interpreted, appropriated, and sometimes diluted within contemporary fashion discourse. Through a combination of historical review, conceptual analysis, and critical reflection, the chapter explores how circular design can move beyond the symbolic loop to embrace ecological, social, and poetic dimensions that reconnect fashion to its material and ethical origins.

Keywords: circular economy, circular fashion, sustainable fashion, cradle to cradle, regenerative fashion

1. Introduction

Circularity derives from the formal characteristics of the circle, articulating a system without a beginning or an end. The concept describes the transformation of products and materials with distinct properties into new ones without any loss of their physical or chemical integrity. Practices such as producing polyester fabrics from recycled PET bottles or, at an individual scale, converting an old denim jacket into a bag exemplify this logic; when implemented at an industrial scale, such practices signify the formation of a circular fashion system. The circular economy seeks to disrupt the linear production–consumption–waste sequence by keeping products in a continuously closed loop (Geisendorf & Pietrulla, 2018). It promotes the repeated utilization of waste and by-products through strategies such as recycling, downcycling, upcycling, reuse, and repair.

In 1966, American economist Kenneth Boulding proposed a paradigmatic shift from a "cowboy economy," characterized by the unrestricted consumption of resources, to a "spaceship economy," in which all materials are continuously recycled and reused. This metaphor foregrounds the notion that the Earth constitutes a single, finite system. Boulding's proposition is widely regarded as one of the conceptual cornerstones of circular economy thinking. The circular economy thus rests on the study of non-linear systems that contrast with the linear production logic institutionalized during the Industrial Revolution (Boulding, 2013).

Within the field of design, circularity is further articulated through the Cradle to Cradle (C2C) framework, which draws from this economic paradigm. Developed by architect William McDonough and chemist Michael Braungart, this approach challenges the conventional "cradle to grave" model by insisting that product life cycles must not follow a one-directional trajectory (McDonough & Braungart, 2002, 2013). According to the C2C approach, products should be conceived within two principal cycles: the biological cycle, which allows materials to safely decompose and return to the environment as compost at the end of use; and the technical cycle, which reintegrates non-biodegradable materials into production through recycling or upcycling.

At this point, the distinction between *waste* and *discard* becomes crucial. Waste denotes chemical, industrial, domestic, or medical materials generated during production and consumption that have lost their function, are no longer usable, or have become hazardous. In the context of textile production, dye residues, chemical waste, and contaminated wastewater fall under this category. One of the central challenges of textile waste is that most materials are not inherently biodegradable. Biodegradability refers to a material's capacity to be broken down by microorganisms in nature into harmless components (McDonough & Braungart, 2002). However, this process requires specific conditions—appropriate temperature, moisture, and microbial activity. In the absence of these conditions, even materials classified as “biodegradable” may persist in the environment for extended periods and pose ecological risks. In contrast, discard refers to materials that emerge during production or consumption but remain suitable for reuse, repurposing, or further transformation (Brown, 2013).

In the field of fashion and textiles, residues typically take the form of fabric offcuts, end-of-season stock, or garments and textiles discarded or no longer preferred by individuals. When these materials are directed to landfills, they contribute to carbon emissions and the formation of greenhouse gases (Gwilt, 2013). Moreover, the prolonged degradation time of synthetic fibers exacerbates environmental burdens, as these materials can persist in ecosystems for decades or even centuries. Consequently, the effective management and reintegration of textile residues into circular systems have become critical priorities within sustainable fashion discourse.

The growing engagement of governments, industry, and academia with circular fashion reflects its emergence as a key strand within the broader discourse of sustainable fashion (Cooper& Claxton, 2022). The environmental impacts of the fashion industry, ranging from greenhouse gas emissions and excessive water consumption to fossil fuel dependency, pesticide pollution, and microplastic release, have intensified calls for systemic transformation. Within this context, the lifespan of garments has become a central concern. Despite being physically intact, many garments are discarded due to shifting trends, changing body shapes, or aesthetic preferences (Cooper& Claxton, 2022). According to WRAP (2012), extending the average active life of clothing by nine months could reduce the carbon, water, and waste footprints by approximately 20–30 percent. Furthermore, the average duration of garment use was found to be 3.3 years in a large-scale survey of UK consumers (WRAP, 2013). Materials can be granted a second life through downcycling, recycling, and upcycling. *Downcycling* denotes the transformation of a material into a new form with reduced quality, functionality, or value (McDonough & Braungart, 2002). For instance, converting used paper into cardboard exemplifies downcycling. In such cases, the resulting material has diminished value and fewer applications than the original product. *Recycling* refers to the conversion of post-consumer materials into new materials or products (McDonough & Braungart, 2002). This process reduces the demand for virgin resources, conserves energy, and mitigates environmental pollution. Nevertheless, recycling is constrained by material composition; multi-component composite materials, for example, are particularly difficult to process. In the textile sector, recycling typically occurs at the fiber level, with cotton and polyester being the most commonly reprocessed materials. A common example involves converting plastic bottles into polyester fibers. Despite such efforts, textile-to-textile recycling accounts for only 1% of global material recycling, highlighting its limited role in sustainability discourse (European Parliament, 2020). Furthermore, blended fabrics cannot be chemically separated into pure fibers, and recycled polyester continues to release microplastics during production and use, thereby perpetuating environmental pollution.

In contrast, *upcycling* involves reintroducing a material or product into circulation through processes that preserve—or actively enhance—its value (McDonough & Braungart, 2013). As a design-led, creativity-driven strategy, upcycling plays a significant role in sustainability and circular economy practices. Re-evaluating existing materials in innovative ways not only reduces waste but also extends product life cycles (Gwilt & Rissanen, 2012). Within the fashion context, upcycling enables surplus materials, discarded garments, or textile remnants to be reworked into novel and distinctive designs (Brown, 2013). This method reduces material waste while supporting the production of items that carry heightened aesthetic, symbolic, and cultural value.

2. Systems Thinking in Relation to Regenerative Fashion

In the study conducted by Dan and Østergaard (2021), the theme of *systems thinking* emerged prominently in the perspectives of designers and key stakeholders. The authors emphasize that such an approach requires a holistic design mindset that encompasses not only internal organizational processes but also external actors, including suppliers, customers, and broader value networks. Within this framework, design is no longer confined to the activity of formulating a product; instead, it becomes a function deeply embedded in value chains and closely aligned with the customer value proposition (Dan & Østergaard, 2021). In this discussion, systems change refers to a profound, radical transformation in the characteristics of interconnected systems that shape an entity, a component, or a whole. As Meadows (2008) argues, systems are inherently multi-layered and dynamic, often comprising systems within systems that interact through reinforcing or balancing feedback loops. Systems change, therefore, necessitates understanding these complex interdependencies and implementing interventions that shift paradigms, perceptions, and practices—rather than producing isolated or superficial adjustments (Meadows, 2001; Richmond, 1994).

Within the context of sustainable fashion, systems change is among the most pressing and debated topics. Fletcher (2010) argues that slow fashion invites engagement with systemic transformation by challenging the logic of speed, volume, and disposability embedded in industrial fashion systems. From this perspective, examining what constitutes the fashion system itself and designing its transformation requires analyzing the production–consumption relationships and redefining how constructive and regenerative economic systems might operate within fashion. This process implies that existing structures and mindsets must undergo fundamental and generative transformation. Transitioning to circular fashion requires a systemic perspective that actively involves all stakeholders-designers, manufacturers, suppliers, retailers, and consumers, and a fundamental shift in mindset across each group. Every organization within the supply chain should develop its own tailored strategies. Local production and consumption must advance alongside the circular economy to ensure transparent and efficient reverse flows while minimizing global resource use and pollution. This transformation can be further strengthened through supportive global, regional, and national policies (Dissanayake & Weerasinghe, 2022).

As Meadows (1999) notes in her seminal work "Leverage Points: Places to Intervene in a System", change within complex systems is most effective when interventions target the deeper layers, such as goals, paradigms, and information flows, rather than surface-level processes. However, as Richmond (1994) cautions, changing systems is rarely simple; efforts focused on smaller subsystems often create the illusion of transformation while leaving larger systemic issues untouched and failing to address macro-level frameworks. Such changes risk reinforcing fragmentation or instability.

In this sense, genuine transformation in the fashion sector requires systems thinking—a holistic, reflexive mindset that considers the interdependencies among material, social, and economic flows (Meadows, 2008; Fletcher, 2010). Through this lens, sustainability is not achieved through isolated design solutions but through reconfiguring the relationships and feedback loops that define the system itself.

Considering the environmental and chemical problems generated by recycling processes, the terminological ambiguities surrounding circularity, and the superficiality observed in many of its applications, regenerative fashion emerges as a more holistic and advanced approach. Originally a biological term, *regeneration* refers to the capacity of living organisms and ecosystems to repair or renew themselves following damage or loss (Goss, 2013). In nature, many organisms sustain their life cycles through self-renewal; regenerative design and fashion practices draw inspiration precisely from these natural processes.

Regenerative fashion moves beyond circularity by focusing not only on the reuse of materials but also on aligning production practices with the natural balance of ecosystems (Fletcher & Grose, 2012). Grounded in the self-repairing capacities of living organisms and ecological systems, this approach aims to integrate fashion into nature’s own cycles of renewal. It emphasizes agricultural and livestock practices that support the regenerative capacities of soil, water, and biodiversity; the development of non-toxic, biodegradable materials; and the transformation of waste into productive processes. In this respect, regenerative fashion seeks not merely to mitigate the damage created by the production–consumption–waste chain, but to design a system that works in tandem with the ecosystem’s inherent cyclical capabilities (Fletcher, 2013; Fletcher & Grose, 2012; Minney, 2022). Through this lens, fashion is redefined not simply as a sustainable production practice, but as an ethical and ecological mode of restructuring that operates in harmony with nature’s own reparative processes.

Within this broader conceptual landscape, regenerative fashion offers a critical reframing that expands the possibilities of sustainability beyond circularity alone. Yet, while regeneration emphasizes ecological reciprocity and the restoration of natural systems, circular design practices continue to shape the dominant discourse in contemporary fashion due to their operational feasibility, infrastructural compatibility, and market-driven adaptability. In other words, regenerative approaches outline an aspirational horizon grounded in ecological renewal. In contrast, circular fashion represents the mechanisms currently available to restructure material flows, reduce waste, and extend product lifecycles. Examining concrete examples of circular fashion, therefore, becomes essential not as an alternative to regeneration but as a means of understanding the industry's existing tools, strategies, and limitations. Such an exploration offers insight into how current circular practices can evolve—or be reoriented—toward more regenerative and ecologically attuned futures.

3. Systemic Approaches to Circularity in Fashion Brands

Against this conceptual backdrop, it becomes necessary to examine brands that have operationalized circular principles within real-world industry contexts. Doing so allows for a clearer understanding of how circularity is interpreted, implemented, and negotiated within existing market structures, and how these practices align—or fail to align—with regenerative ambitions. Among contemporary fashion companies, certain brands stand out for their attempts to embed durability, repairability, and material recirculation into their organizational models. Patagonia, in particular, offers a compelling case: its long-standing commitment to repair culture, product longevity, and responsible resource use positions it as a significant reference point for evaluating the practical possibilities and inherent constraints of circular fashion systems. Patagonia is considered one of the strongest examples of circular economy practices worldwide. The brand's "Worn Wear" program stands out as a pioneering initiative that redefines the culture of repair within fashion design at an institutional level. Through Worn Wear, Patagonia encourages users to keep their garments in use for as long as possible, offering free repair services, online repair guides, and on-site repair events. Within the program's scope, users can have their old garments repaired and worn again, exchanged, or returned to the brand for resale. Patagonia also adopts a material-conscious approach to circular fashion by using low-impact materials such as recycled polyester and organic cotton in its products. The brand's approach directly intersects with concepts such as "repair aesthetics," "sustainability ethics," and the "garment–subject relationship," as it redefines the connection between clothing and the wearer through responsibility, care, and circularity.

MUD Jeans is one of the most innovative examples of developing a circular business model in the fashion industry. The "Lease a Jeans" rental system allows users to lease a pair of jeans for one year instead of purchasing them and, at the end of the year, either exchange them for another model or return them for recycling. Returned jeans are broken down into fibers and used to produce new denim fabrics, enabling genuine "fibre-to-fibre recycling." This approach not only reduces waste but also establishes a systemic paradigm that requires designers to consider a product's entire life cycle. MUD Jeans stands out as a strong case that embodies concepts such as extending product lifetimes, material memory, rethinking, and re-establishing value within a practical model.

MUD Jeans' core strategy focuses on prolonging product life through the rental system, offering free repairs during the first year, and sharing care guidelines to slow the loop. At the same time, the company applies closed-loop recycling practices that reintegrate materials into new production. Its business model is based on a "pay-per-use" principle; the brand retains ownership while providing customers with access, and collects products after use. Through awareness-raising campaigns, a seasonless and long-lasting design approach, repair services, and Black Friday counter-campaigns that question consumption, MUD Jeans also supports "sufficiency" strategies. The company is B Corp-certified and regularly reports its environmental impact through life-cycle analyses.

Eileen Fisher is one of the most established brands embracing the principles of slow fashion, simplicity, and responsible production. The brand's "Renew" program allows users to return their old Eileen Fisher garments for repair and resale, or to be redesigned through methods known as "creative reuse." Damaged or worn pieces are not treated as waste; instead, they are transformed into new designs using reconfigured panels, patches, hand-stitching, and patchwork techniques. This process creates a new aesthetic opening through both design and care practices. Eileen Fisher's focus on visible mending and reuse is the reanimation of garments, because the brand offers a calm yet profound aesthetic that embraces aging, traces, and the lived memory of clothing.

Known as Türkiye's first circular fashion brand, Nivogo continues its journey under its renewed identity, nivo. This transformation signifies more than a conventional brand restructuring; it represents a redefinition of how the idea of circularity interacts with everyday practices. Aiming to make the circular economy accessible to all, nivo restores out-of-use fashion items in its Renewal Center and reintroduces them into circulation, thereby adopting the extension of product lifespans as a core value. This approach disrupts the linear flow between production and consumption, positioning fashion as a system that is re-evaluable, transformable, and open to continuity. The brand's initiative "Circuverse" extends beyond the constraints of the linear economy, outlining a holistic circular ecosystem in which products are revalorized before becoming waste and where collaborations generate shared value. Circuverse repositions circularity not merely as an economic strategy but as an ecological ethic grounded in the principles of repair and resource continuity rather than depletion. In this respect, nivo offers an example not only of circular fashion practice but also of a restorative economic model that operates in synchrony with natural systems.

Circular fashion gains meaning not only through educational practices within academic environments but also through direct engagement with nature, production processes, and local communities. This approach supports a design pedagogy grounded less in the transmission of information and more in experiential and observational learning. At this point, circular fashion intersects with regenerative fashion, as both perspectives emphasize that production should not be limited to waste reduction alone; instead, they advocate for systems aligned with nature's inherent capacity for renewal.

In this context, the transition from a linear to a circular economy introduces new roles, responsibilities, and modes of interaction for fashion designers within institutional structures. Dan and Østergaard (2021) argue that this transformation requires designers to develop and integrate new knowledge concerning circular design strategies, contextual factors, and design dimensions. They further highlight the importance of strengthening collaboration among different departments and stakeholders within an organization. Such interdisciplinary engagement supports creativity by enabling the exchange of expertise on materials, production processes, and supply chain management. Until designers acquire the requisite skills, knowledge, and authority to lead these processes, external facilitators can help implement co-design approaches and foster a circular mindset within institutions (Dan & Østergaard, 2021).

Drawing on this understanding, the Döngüsel Moda Kolektifi was established through a collaboration between Brother Türkiye and the Devridaim Enstitüsü to cultivate an upcycling-oriented perspective in design and production processes and to contribute to ecological continuity. The program frames fashion not merely as a consumption-driven industry but as a system capable of being regenerated in interaction with nature.

Throughout the three-month program, which brought together designers, entrepreneurs, and students aged 18–50 who work in or are interested in the field of fashion and textiles, topics such as circular economy, sustainable fashion, ethical production, clean supply chains, and upcycling were addressed both theoretically and practically. During the trainings held in Istanbul, Cappadocia, and Hatay, participants directly experienced the relationship between production and nature through workshops on flax cultivation, wool spinning, natural dyeing, weaving, and creating new products from textile waste. This process aligns with the core principles of regenerative fashion: it promotes an approach that respects the renewing capacities of soil, water, and materials, and integrates nature's cycles into the design process.

The program aims to rethink production processes in fashion and textiles through the principles of circular economy and regenerative design, and to position participants as active agents of this transformation. In the long term, the objective is to cultivate brands that are clean, ethical, and aligned with nature's restorative capacities—brands that raise awareness of limited natural resources, focus on material efficiency, and operate with ecological integrity. In this sense, the Döngüsel Moda Kolektifi materializes the philosophy of regenerative fashion, offering a foundation not only for transforming fashion but also for repairing and healing it.

Conclusion

Design has been characterized as the earliest expression of human intent (McDonough, 2014), and in the context of the fashion industry, it constitutes a fundamental leverage point for establishing closed-loop systems. When examined collectively, downcycling, recycling, and upcycling constitute a hierarchical system of material transformation. Downcycling reduces material quality, whereas upcycling enhances value. Thus, these methods should be assessed not only in terms of directional flow within material cycles but also in terms of their qualitative, functional, and symbolic distinctions. Through decisions that prioritize longevity, durability, and aesthetic continuity, design enables garments to remain in use for longer periods while also facilitating the recovery, recirculation, and multi-cycle recycling of raw materials (Niinimäki, 2017).

Although the consistent, measured, and resource-conscious approach of circular design to materials and objects is compelling, the boundaries of the concept have become increasingly blurred. In the absence of a shared definition, standardized assessment criteria, or a verifiable evaluation framework, the field remains open to broad and often ambiguous interpretations. As a result, many brands describe themselves as “circular” without undergoing any certification process, and the notion is frequently reduced to a superficial marketing rhetoric. The relationship established through material revalorization often manifests as little more than the addition of a “circular” label. At the same time, the number of actual cycles a product completes, whether it is genuinely reintegrated into the system or whether it maintains a meaningful place within material flows, remains unclear (Odabasi, 2024). Even manufacturers who develop new products from surplus textiles cannot guarantee that these items will not eventually become waste again or that they will ensure a continuous, uninterrupted flow of materials. This situation demonstrates that circularity cannot be achieved through a single act of production or a simple gesture of reuse; rather, it requires sustained responsibility, long-term monitoring mechanisms, and a structural infrastructure operating at institutional and industrial levels.

Another critical issue evident in contemporary discourses on circular design is the way the concept is simplified in practice and detached from sustainability. While sustainability encompasses a broader framework that includes not only environmental but also social and ethical dimensions, circular design frequently drifts away from this holistic perspective (Odabasi, 2024). Many current practices disregard the principle of "designing less" emphasized by Papanek (1972), failing to engage in an ethical inquiry into what is genuinely necessary. Moreover, circular processes at times fall into the paradox of "creating waste from waste," resulting in merely a formal transformation rather than extending the material's actual life cycle.

The circular economy has yet to incorporate degrowth meaningfully into its agenda, and approaches such as regenerative agriculture or restorative production remain largely overlooked. In this context, the core problem lies not in the concept itself but in its rapid popularization and its uncritical application across various domains. Just as labels such as "sustainable," "organic," or "green" have gradually become commercial slogans, the term "circular" demands a similar degree of caution (Odabasi, 2024).

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CHAPTER III

THE ENVIRONMENTAL PERFORMANCE OF NATURAL FIBERS IN SUSTAINABLE FASHION

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Abstract

The fashion industry has become one of the sectors most visibly affected by environmental and social impacts due to accelerated production models and consumption habits over the past twenty years. The fast fashion approach has been shown to engender a number of issues, including intensive water and energy use, chemical waste, microplastic emissions, short-lived product structures and an ever-growing volume of waste. In addition, it has been demonstrated that this approach can lead to unfair working conditions in different links of the supply chain. Conversely, the notion of sustainable fashion is progressively being addressed within a more extensive framework, necessitating a holistic approach encompassing all aspects from raw material selection to design, production processes, consumer behavior, and recycling infrastructure.

While conceptual discussions on sustainability emerged in the 1990s within the context of reducing environmental risks, circular economy principles now play a decisive role. It has become increasingly evident that design-focused decisions, such as durability, repairability, reuse and recyclability, have a significant impact on the overall environmental performance of a product. This is not only due to the material used, but also the usage habits of the product. The incorporation of eco-design rules, producer responsibility models and digital product passports within policy documents signifies an emergent imperative for enhanced transparency and accountability within the sector.

However, when assessed using a life cycle approach, the environmental impacts of natural fibers present a different picture. Cotton has been identified as the most dominant fiber in terms of water footprint, primarily due to its substantial production volume and the irrigation requirements of its cultivation. Despite the benefits offered by flax and hemp, due to their low agricultural inputs, it should be noted that fiber separation processes can entail additional energy and water consumption. Wool and silk, despite their disadvantageous position due to high greenhouse gas emissions and land use during cultivation, have the capacity to mitigate their impacts under certain conditions through long-term use and low maintenance requirements.

The concept of sustainable fashion is one that encompasses a multitude of variables, rendering it difficult to be explained by the superiority of a singular fiber. A comprehensive strategy encompassing raw materials, technology, supply chain structures, and consumer behavior is imperative for achieving sustainable enhancement.

Keywords: Sustainable fashion, natural fibers, life cycle assessment (LCA), water and energy use, global warming potential (GWP)

The Necessity of Sustainable Fashion

The fashion industry, which is one of the cornerstones of the textile sector, has, since the beginning of the twenty-first century, become visibly involved in the emergence of large-scale environmental and social problems (Niinimäki et al., 2020). Dynamics such as supply chains accelerated by the effect of fast fashion, short product cycles, and low pricing policies have triggered the mass production of goods while causing the shortening of product lifetimes (Ellen MacArthur Foundation, 2017; Quantis, 2018). The resource consumption frenzy created by high production volume has brought along not only the irresponsible use of basic inputs such as water and energy, but also subsequent problems such as increased chemical pollution, physical waste and gas emissions (UNEP, 2020; Sandin & Peters, 2018). An examination of 2017 data shows that the sector consumes nearly 98 million tons of non-renewable resources and 93 billion m^3 of water each year, yet recycles only about 1% of the products it generates (Ellen MacArthur Foundation, 2017). In addition to all this resource consumption and the waste crisis, the social dimensions such as the conditions of workers in production, the unequal situations of regions, traceability problems in the production chain and legal accountability mean that the concept of sustainability has become an indispensable solution option for the fashion industry (OECD, 2018).

The risks created by the sector are presented in detail in reports issued by various institutions. In the 2020 Report of the United Nations Environment Programme (UNEP), it was stated that the production activities of the fashion industry constitute approximately 10% of global greenhouse gas emissions, a share greater than the total impact of international flights and maritime transport (UNEP, 2020). In addition to this impact, the fact that synthetic fiber wastes are the primary cause of microplastic pollution and threaten marine life brings with it an even more dramatic deadlock (European Environment Agency [EEA], 2019; Boucher & Friot, 2017). All these negativities do not only express pollution created by the products themselves, but at the same time contain an increasing effect that arises from intertwined relations such as production lines like yarn and fabric, dyeing–finishing subsequent processes, logistical obligations and retail sales processes (Sandin & Peters, 2018; Quantis, 2018). Even the first ring of the chain, namely agricultural production or synthetic fiber production, contains ecological risks on a global scale, and the concept of sustainable fashion should be seen not as a slogan-like design preference, but as a broad systemic set-up extending from the micro level to the macro level (Kirchherr et al., 2017; Ellen MacArthur Foundation, 2017).

In addition to reducing environmental destructiveness, sustainable fashion must also cover the social dimension. In this labor-intensive sector, the social rights of workers, who are one of the rings of the supply chain, are among the most neglected (OECD, 2018). Problems such as production techniques based on labor exploitation in low-income supplier countries, the failure to eliminate risks related to occupational health and safety, wage differences, and the lack of protection of trade union rights are frequently expressed in OECD reports (OECD, 2018). Stronger defense of labor rights and the fact that social justice is valid for every part of the supply chain constitute another dimension of sustainability (Gardetti, 2014). Under the shadow of these negativities, there are also reports indicating that there is awareness among consumers towards sustainability. According to the NielsenIQ 2018 report, approximately 70% of consumers stated that they tend towards purchasing behaviors that prioritize environmental awareness (Nielsen, 2018). According to the 2021 PwC report, it is also stated that especially consumers known as Generation Z see sustainability as a purchasing criterion (PwC, 2021). In addition, according to UNEP 2020 data, although sustainability is expressed as a goodwill intention on the part of consumers, pricing, ease of access and purchasing habits are seen as more influential factors (UNEP, 2020).

The Concept and Evolution of Sustainable Fashion

At the beginning of the sustainable fashion process, ideas aimed at eliminating ecological risks in production were dominant, and the idea that was generally intended to be expressed was to reach products that had the label of “environmentally friendly production" (Fletcher, 2008). This pattern, which emerged at the end of the 1990s, expanded over the years and turned into a broad model that also covered different issues such as design, the materials used, production tools and the management of consumer expectations (Niinimäki & Hassi, 2011). Modernization practices, which constituted the first step of this evolution and were aimed at eliminating concerns arising from ecological damage, were carried out in order to improve production processes and to reduce the waste and energy–water use created by the sector (Bocken et al., 2014). The report "Well Dressed?", published by the University of Cambridge in 2006, mentions the necessity of changing user purchasing decisions through features such as product lifetime and ease of use, the importance of using recycling processes for every resource, and the need for public policies and commercial agreements from an environmental and social perspective (Allwood et al., 2006). In the report, it is shown from different points that simply improving processes cannot be a sufficient solution.

By the 2010s, besides the improvements in the production steps, the emergence of a life cycle idea took place (Bocken et al., 2014; Kirchherr et al., 2017). In this process, Fletcher (2008) stated that design decisions have quite strong effects at all stages of production from raw material selection to waste management, and that a pluralistic design idea in dialogue at each step of the supply chain is important for sustainable fashion. In addition, in this period, it was determined that the effects that the production and use processes of the product would create were connected both with ecological raw material choices and with the needs at the moment of use (Niinimäki & Hassi, 2011). Concepts such as long durability during use, repairability and reuse were revealed to be important for sustainable fashion (WRAP, 2017). In the Mistra Future Fashion 2015 report, it was mentioned that tripling the lifetime of a garment would reduce environmental impact by around 70%, that changing consumer behavior to design more than one life cycle for garments is important, that consumer education is necessary for long-term use, and that public policies are needed for regulations in the supply chain (Östlund, Westin, & Quistgaard, 2016). In this period, it was emphasized that it is an incomplete definition for sustainable fashion if only the material or production processes are sustainable, and that there must also be a sustainable mode of use after production (Fletcher, 2008; Niinimäki & Hassi, 2011).

From around 2015, the policies needed became more widely known through circular economy approaches (Kirchherr et al., 2017; EEA, 2019). In these periods, studies stated that it is necessary to reduce waste in production processes and the use of raw material sources, to extend product life cycles, and to establish suitable closed-loop recycling systems (Ellen MacArthur Foundation, 2017). Along with the prominence of environmental impacts, issues of social rights and responsibilities in the supply chain were also mentioned in various reports. According to the report of the International Labour Organization (ILO, 2014), it is stated that in all supply chains included in the textile sector, a certain level of traceability is required in issues such as remuneration for labor, responsible working hours and occupational health and safety, while according to the 2018 OECD Report, it is revealed that for responsible supply systems in the textile sector, it is important to identify risks and to establish complaint mechanisms and feedback for eliminating possible risks (OECD, 2018). In the 2019 EEA report, it was emphasized that circular models in the textile sector exist at a certain level, that especially models in repairability–reuse processes are insufficient, that recycling capacity is limited, that there is a lack of safety and standards in chemical processing stages, that trainings that will change consumer behavior should be encouraged, and that there are transparency problems in the global supply chain (EEA, 2019). In the 2022 Strategy for Sustainable and Circular Textiles of the European Union, it was explained as the 2030 vision that textiles in the EU market should be long-lasting, repairable and recyclable, contain a high proportion of recycled fibers, be purified from hazardous chemicals and comply with social and environmental standards in production (European Commission, 2022). It was especially emphasized that fast fashion should be declared “out of fashion” and that reuse should be promoted instead (Textile Exchange, 2023b). In the report, where recycling is prioritized, it was stated that there should be mandatory eco-design rules, enhanced extended producer responsibility (EPR) rules, and, within the scope of producer responsibility, a basic waste management fee that is reduced or increased according to the environmental performance of the product, that is, an eco-modulated fee meaning “better design = lower fee”, “more problematic product = higher fee” (European Commission, 2022).

Natural Fibers and Their Relationship with Sustainability

Natural fibers, which are among the oldest fibers in human history, are assumed to create a positive impression in the fashion sector in relation to the theme of sustainability because they are sourced from nature. However, an assessment must be made by taking into account many interrelated conditions, starting from where and how they are cultivated, through which production processes they pass, and how they perform during and after use. As stated in the ISO 14040/44 standard, the process that begins with cultivation conditions in the field or on the farm should be considered in the form of a life cycle (LCA) that also includes stages such as yarn–fabric production, dyeing–finishing, use and disposal–recycling (ISO, 2006/2018; Guinée, 2002). For fibers, the life cycle system is defined as the calculation of the total impact by evaluating many comprehensive conditions, primarily climate (greenhouse gas) impact, water use, land use and chemical methods in the production process, as well as conditions of use and care (washing temperature and frequency, drying, repair) and reuse–recycling (Sandin et al, 2019).

As the most widely consumed natural fiber, cotton reveals a clearly defined life-cycle structure upon detailed assessment. Making an assessment based on average water-use values for the production process reported in earlier studies provides a narrow perspective. In water footprint assessments for cotton, by breaking the water used into its components as “blue” irrigation water, “green” rainfall-derived irrigation water and “grey” water associated with the recovery of polluted water, or by considering the agricultural practices applied in producing countries and regions, very different water-use outcomes are obtained (Mekonnen & Hoekstra, 2011; WRI, 2019). In addition, by including the water–chemical–energy loads used in the dyeing and finishing of cotton fabrics and user habits such as washing and drying frequency in the equation, it is clear that the total impact will be affected in a positive or negative direction (IFEU, 2022; Laitala, Klepp, & Henry, 2018).Other frequently preferred cellulosic fibers, flax and hemp, exhibit better climate adaptability and lower water and field-input requirements compared with cotton (Kozłowski, Mackiewicz-Talarczyk & Allam, 2012). Although flax and hemp fibers, which are suitable for cool–temperate climates, are in an advantageous position in assessments due to their properties, the water and energy required in fiber separation and yarn production processes, arising from the fact that they are bast fibers, can neutralize this advantage (Angulu & Gusovius, 2024).

In considering wool, the most widely consumed protein fiber, the facts that wool products are washed less frequently during use and offer a long service life emerge as advantages in terms of water and energy use (Laitala et al., 2018). From another perspective, however, the enteric methane emitted by animals during rearing contributes to climate change through its greenhouse gas effect, and the large land areas required also create negative impacts (FAO, 2013). Like wool, silk is also in an advantageous position as a fiber because of its long service life and the tendency to wash silk products at low temperatures (Babu, 2012). The fact that silk is a fiber preferred for niche and high-value products creates problems in terms of data traceability. For both fibers, evaluating data in terms of garment and service life rather than fiber-per-kilogram comparisons may provide a better perspective (Roos et al., 2019).

In addition to process-related impacts during cultivation and processing, scenarios relating to conditions of use and care are also highly influential within the life cycle framework. For garments with similar end uses but made from different fiber profiles, sustainability impacts change dramatically depending on parameters such as washing frequency and temperature, drying method and service life (Laitala et al., 2018; Roos et al., 2019). Under some conditions, properties such as the ability to be washed at low temperatures or high repairability can lead to more positive outcomes than the process impacts occurring at the production stage (Sandin & Peters, 2018). Rather than speaking of a single "most advantageous fiber" among natural fibers, the most appropriate choice will be to refer to a design and supply chain that best define the conditions under which the fiber is obtained, the production processes used and the characteristics in use, and that additionally offer reuse and recyclability potential in terms of service life (Guinée, 2002; Sandin & Peters, 2018).

Cotton

Among natural fibers, cotton ranks first in terms of volume of use and economic value, and is frequently preferred, especially for everyday applications, due to its comfort and care properties. This widespread use also brings sustainability-related concerns. Considering the destructive effects of the processes applied in agricultural cultivation in past decades, it has become necessary to evaluate cotton from different perspectives in terms of sustainability. In light of these evaluations, there is broad agreement that it is impossible to speak of a single cotton fiber profile that, in every respect, meets all needs. From an environmental assessment perspective, cotton must be evaluated differently depending on where and how it is grown, how it is processed, and how it is used in the final consumption phase. Within the life cycle system approach described in ISO standards, aspects such as water use, climate impact, land use, and indicators related to chemicals and wastewater should be taken into account (ISO, 2014; Guinée, 2002).

One of the most problematic areas for cotton in terms of sustainability is its water footprint. Water footprint assessments should be approached in two dimensions. First, from the perspective of the volumetric water footprint, which expresses the type and quantity of water used, assessments show that the growing region, climate and irrigation method have a very significant influence. Using the same amount of water in different growing regions leads to very different outcomes. In a region with abundant water resources the use of irrigation water may be tolerable, whereas in a region with high water scarcity, using a scarce and critical resource for cotton cultivation can mean that insufficient water remains for other uses, triggering a critical situation. For this reason, the second assessment system, the scarcity-weighted water footprint (AWARE: Available Water Remaining), provides a better adjustment to regional variations (Pfister, Koehler, & Hellweg, 2009; Boulay et al., 2018; Boulay et al., 2020). Under the AWARE criteria, the method calculates the remaining water after deducting the amount needed by humans and ecosystems, and by including regional characteristics in the equation, comparisons can be made more accurately. As seen in a China-focused study, evaluating factors such as regional rainfall, water potential, climate characteristics, soil properties, and irrigation efficiency shows that the water requirements and irrigation needs of plants differ significantly between regions and with improvements targeted to the specific requirements of each region, water-use efficiency can rise by up to 45% (Zhang et al., 2021; Demeke et al., 2024). Similar studies have stated that by using more efficient irrigation systems and selecting fiber types appropriate to local conditions in cotton production, reductions have been measured in the water footprint associated both with green water (rainwater) and with blue water (agricultural irrigation) (Mekonnen & Hoekstra, 2011; Chapagain et al., 2006; Ahmad et al., 2021).

For the greenhouse gas footprint of cotton fiber, a wide range (1.3–4.1 kg CO2e/kg) appears in assessment data (IFEU, 2022). The main reasons for this variability include the need to incorporate different factors into calculations, such as the fertilizers used in the field (nitrogen fertilizers triggering N2O emissions), differences in irrigation energy (electricity/diesel/solar energy), choice of system boundaries (agricultural production phase/yarn phase/fabric phase/product phase), and the allocation basis for the product assessment (economic allocation or mass-based allocation between lint and seed) (IFEU, 2022; Cotton Incorporated, 2016). Changes in these assessment criteria can significantly alter the resulting figures. Basing decisions on emission values for cotton using only a single category such as CO2 can therefore be misleading. For this reason, attention should be paid to multiple categories, such as scarcity-weighted water footprint and indicators for phosphorus use on land (Pfister et al., 2009; Boulay et al., 2018). For example, in the case of cotton grown under organic farming practices, the absence of burdens associated with synthetic fertilization appears effective in terms of greenhouse gas footprint; however, due to the possibility of lower yields compared with conventional production, the impact per unit of product may not change as expected (Vitale, 2025).

In addition to improvements in agricultural processes, the dyeing and finishing processes, in which chemical treatments are applied to cotton fiber, are also highly important in terms of chemical load and wastewater generation. Highly colored effluents with a high chemical content, the high chemical oxygen demand required to purify such water, and the high biological oxygen demand needed for micro-organisms to biodegrade pollutants are all parameters that represent strong negative environmental impacts (Laursen et al., 2007). Through techniques such as advanced oxidation processes, in which dyestuffs are degraded by strong oxidants, membrane systems that filter water more efficiently, and hybrid systems in which pollutants are broken down by chemical processes and then treated biologically, wastewater from processes can be recovered for reuse (Holkar et al., 2016; Al-Tohamy et al., 2022). Studies show that processes in which less water and lower temperatures are used per unit of fabric, rinsing systems where clean water is used only at the final stage, the use of enzymes in desizing processes, heat and chemical recovery in processes, and cold pad-batch dyeing with low temperatures can reduce the impacts associated with energy, heat and chemical use (Karthik & Gopalakrishnan, 2014). In cases where dyeing and finishing operations are carried out, closed-loop water systems in which the water used is appropriately treated and reused, the reuse of chemicals, and efficient application recipes are as important as good agricultural practices (Laursen et al., 2007; Holkar et al., 2016).

Flax and Hemp

Flax and hemp fibers, which are the two most important members of the bast fiber group, require lower cultivation inputs in terms of production costs compared with cotton fiber (van der Werf & Turunen, 2008). Their ability to grow in the more widespread temperate–cool climates of the world, their capacity to be cultivated with low water use, their need for lower nitrogen and pesticide inputs, and their rapid growth and short cultivation period offer the potential for lower environmental impacts (EEA, 2019; Alliance for European Flax-Linen & Hemp, 2023). Although these agricultural advantages result in lower water and chemical impacts, the need for additional processing steps in fiber extraction, which is a general issue for bast fibers, can create negative effects for flax and hemp from a sustainability perspective (Gómez-Campos et al., 2021). Considering that the mechanical and chemical processes used to separate fibers from the stem require water, energy and chemicals, and that quality losses in fibers may also occur during these operations, it can be concluded that the environmental impacts of flax and hemp fibers need to be evaluated in a more comprehensive way (van der Werf & Turunen, 2008; Dey et al., 2021).

Because cotton cultivation requires specific climatic and geographical conditions, it can be grown only in limited areas in production regions such as Europe. Thanks to the broader climatic adaptability of flax and hemp, the fact that these crops can be cultivated in such regions with reliance on rainfall is highly advantageous in terms of reducing the water footprint associated with agricultural irrigation (EEA, 2019). Owing to their rapid growth and fast canopy closure, flax and hemp cover the field without allowing weeds to develop, thereby reducing the need for herbicide use for weed control (Alliance for European Flax-Linen & Hemp, 2023). However, the fact that sowing areas may present harsher conditions than cotton fields can make stable yields more difficult to achieve. For this reason, particular attention must be paid to aspects such as controlling sowing density and correctly timing the harvest (van der Werf & Turunen, 2008).

One of the steps that most strongly affects fiber quality for flax and hemp is retting, the stage in which fibers are separated from the stem (Angulu et al., 2024). Retting processes, in which pectin and similar binding substances that hold the fiber bundles together within the stem are broken down by biochemical or chemical methods, create environmental impacts (Dey et al., 2021). Water retting in rivers or controlled pond–canal systems can yield good-quality fibers; however, high water consumption and the volume of wastewater containing organic load from the decomposition process constitute important risks (Dey et al., 2021; Angulu et al., 2024). In particular, the heavy metal content of wastewater and the high chemical and biological oxygen demand make water treatment challenging (Dey et al., 2021; Harsányi et al., 2025). Another retting method is dew retting, which consists of spreading plant stems in open fields and allowing them to ret through the combined effects of dew and micro-organisms (van der Werf & Turunen, 2008; Reda et al., 2024). Although the very low volume of water used in this method reduces the water burden, the fact that the control of the retting process depends on climatic conditions can lead to reductions in fiber quality (Reda et al., 2024). In addition to classical methods, modern systems can also be used, in which parameters such as temperature, pH and oxygen content are controlled in closed tanks, and retting is carried out using selected micro-organisms or enzymes (De Prez et al., 2018; Angulu et al., 2024). In modern systems that provide more homogeneous fiber extraction, water use, process time and waste management can be managed more efficiently (Harsányi et al., 2025). The drawbacks of modern systems, however, include the energy used in the processes and the difficulty of monitoring complex process chains (Gómez-Campos et al., 2021). In evaluating all retting methods, rather than speaking of a single correct method from a sustainability viewpoint, it is important to choose the option that is most appropriate to local conditions (van der Werf & Turunen, 2008; European Commission, Joint Research Centre [JRC], 2023). For example, dew retting or enzyme-based systems may be ideal in regions with high water scarcity, whereas water retting or controlled systems may be more suitable in situations where fiber quality is a priority (Angulu et al., 2024). After the retting of flax and hemp, mechanical operations such as breaking and scutching/hackling are required to obtain spinnable fibers. The mechanical steps that make up the preparatory phase of yarn production entail additional energy consumption and risks of fiber loss (Gómez-Campos et al., 2021). A life cycle study on flax fibers has indicated that the carbon emissions associated with the energy used in mechanical processing, the efficiency of mechanical systems and the proportion of low-quality fibers generated by breakage are all highly important parameters in terms of environmental impact (van der Werf & Turunen, 2008; Gómez-Campos et al., 2021).

Wool and Silk

Among natural fibers, the protein-based fibers wool and silk have, throughout human history, been counted among the primary raw materials preferred for textile products (Kozłowski & Mackiewicz-Talarczyk, 2012). Although their consumption volumes have decreased over time with the spread of cellulosic fibers such as cotton and flax following the agricultural revolution, and with the inclusion of synthetic fibers in modern periods, they are still preferred today for certain design areas thanks to properties such as thermal comfort, aesthetic value and long service life (Kadolph & Marcketti, 2015). In addition to the intrinsic properties of wool and silk, the process stages specific to these fibers from production to end use contain various impacts in terms of sustainability (Wiedemann et al., 2020). For wool, which is the most widely used animal fiber, land use and methane emissions during rearing are striking issues, while for silk the risks posed by cultivation techniques and the fiber extraction process attract attention (Wiedemann et al., 2016; FAO, 2013; Wu et al., 2025). For both fibers, parameters such as water, energy and chemical use, the potential for wastewater generation and ethical aspects of animal use are key issues that must be evaluated separately from a sustainability perspective (Textile Exchange, 2021–2023; ZQ Merino, 2025).

For wool fiber, the most prominent environmental risk factor is enteric methane emissions resulting from digestion and manure management in the production region, and the fact that most enteric methane, which is a far more potent greenhouse gas than CO_2 in the short term, is generated at the farm stage (FAO, 2013; Wiedemann et al., 2016). Studies have indicated that, in assessing the sustainability risks associated with enteric methane during sheep rearing, local factors such as type of feed, climatic conditions and flock productivity play a major role (Wiedemann et al., 2020). A similar assessment challenge arises in relation to product allocation criteria. In production areas where sheep are raised, not only wool but also meat, milk and hides are obtained, and calculating environmental impacts solely for wool production is highly complex (IWTO, 2016). If allocation is based on economic value, the more expensive product will bear a larger share of the impact; if it is based on mass, the product with the higher weight will have the larger impact share (Wiedemann et al., 2015). Taking all these parameters into account is necessary in order to reach sound conclusions.

Greasy wool contains sweat salts, wool grease (lanolin) and solid contaminants. In order to obtain spinnable fiber, these impurities must be removed through scouring (Halliday, 2002). In addition to the wastewater impacts arising from the chemicals used in scouring, the mixing of organic substances such as lanolin and dirt into the wash water leads to effluents with high chemical and biological oxygen demand. To minimize these risks, the EU's 2023 updated Textile BREF/BAT document recommends, for wool-processing lines, scouring techniques with counter-current water use, applications that enable the recovery of heat and lanolin from the wash water, and advanced treatment systems that combine biological, chemical and membrane processes (JRC, 2023). It is stated that through the use of these techniques, the pollution load of wastewater is reduced and water and energy use can be lowered. With applications for lanolin recovery, a by-product such as lanolin, which is used in various sectors especially cosmetics, is obtained, and at the same time the removal of grease from wastewater makes treatment easier (Aissani et al., 2022).

For silk fiber, sustainability impacts begin at the fiber extraction stage. In the case of fibers obtained from conventional Bombyx mori silkworms, cocoons are placed in hot water at the pupal stage before emergence, and the pupa is killed at this stage (Babu, 2013). Instead of this practice, which leads to ethical debates in terms of animal welfare, approaches such as ahimsa/peace silk allow the moths to emerge from the cocoon, and the piercing of the cocoon causes breaks in the filament and a reduction in fiber quality. Broken filaments make reeling or weaving more difficult and can increase energy use (Tamta & Mahajan, 2021). There are very few life cycle studies on silk fiber. Some studies conducted in China have indicated that energy use in the stages of sericin removal and reeling, which are key steps in silk production, and the agricultural impacts of cultivating mulberry, the main feed source of silkworms, are important parameters (Wu et al., 2025).

Another risk area for silk fiber arises in the process of removing sericin, the gummy protein layer on the fiber. The wastewater generated from this process contains sericin as well as various organic substances, colour and salts, and different treatments are required for its purification (Gaviria et al., 2023). Studies on sericin removal have reported that, with advanced treatment techniques, the chemical oxygen demand required for water purification decreases, a large portion of the water used can be recovered, sericin can be recovered as a valuable by-product, and that in processes using heat and pressure without added chemicals, defective cocoons and silk waste can be reused (Çapar et al., 2022; Gaviria et al., 2023). For advanced systems, process-line design is highly important, and in poorly designed processes, the chemical and energy loads required may lead to negative environmental outcomes.

Comparative Analyses of Natural Fibers

Water use

Water use during the cultivation of natural fibers is one of the most distinct aspects of their environmental impacts. Water consumption arises both from agricultural irrigation (green water) and from the water used in processing stages (blue water) (Chapagain et al., 2005). As indicated in the graph, the amounts of water consumed per unit of fiber lie within wide ranges. In conventional cotton production, agricultural water use is striking and constitutes a large share of total water use. Various reports state that, on average, approximately 6–10 m^3 of water are used globally to produce 1 kg of cotton (Chapagain et al., 2017; ICAC, 2024). This value, which reflects global consumption, is influenced by regional differences such as climate characteristics, irrigation technologies and soil fertility.

For organic cotton production, some reports have indicated that lower water consumption values are required (Mikucioniene et al., 2024). Water consumption data for flax fiber are reported to be at around one third of those for cotton production (Stavropoulos et al., 2023). Especially in regions such as Europe, where rain-fed cultivation and rainfall-dependent irrigation techniques are applied, low water consumption values are observed (Alliance for European Flax Linen & Hemp, 2023). Another bast fiber, hemp, shows water consumption values in the range of 2–2.7 m^3/kg (Hoekstra, 2019; Mikucioniene et al., 2024). Owing to the deep root system of the hemp plant, soil moisture can be captured more effectively, and thus environmental impacts are reduced through low irrigation requirements (Thevs & Nowotny, 2023).

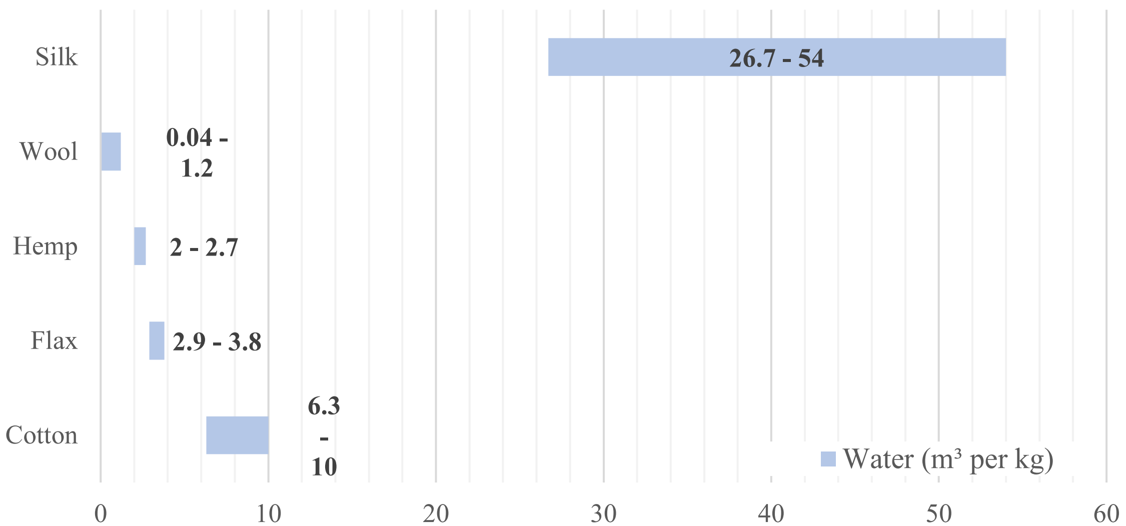

Figure 1. Water use ranges of natural fibers

For protein fibers, the ranges of water consumption are variable (Sandin, Roos, & Johansson, 2019; Plonka, 2024). In the case of wool, there are two types of water use: water used at the farm stage (green water) and water used in processes such as scouring and dyeing (blue water). Some studies report that water use is more intensive at the farm stage, while others state that greater water use occurs during scouring and dyeing processes (Russell, 2009; Dougherty, Place & Mitloehner, 2018). Regional factors such as the share of rainwater, grazing intensity and climatic conditions change the range of water use (IWTO, 2016). Silk fiber is, under most conditions, the most water-demanding fiber among natural fibers (Sandin et al., 2019). Water use stems from mulberry cultivation, which is the primary food source of silkworms, as well as from processes such as sericin removal and reeling (Astudillo et al., 2014). In terms of water footprint, silk fiber stands out as the natural fiber with the highest values, and because different production conditions are influential, its water consumption data cover a wide range (Hogeboom & Hoekstra, 2017).

Land use

Land use is an unavoidable input for the production of natural fibers. For plant-based fibers, this takes the form of agricultural land, while for animal fibers it corresponds to grazing land or land required to produce the feed they consume (Rana et al., 2014; FAO, 2016). The land-use data used in the comparison express the area required for one year of production per kilogram of fiber and are derived by taking fiber yields into account. In terms of land use, plant-based fibers generally require low to medium levels of land per unit of fiber, whereas animal fibers stand out with a high land requirement.

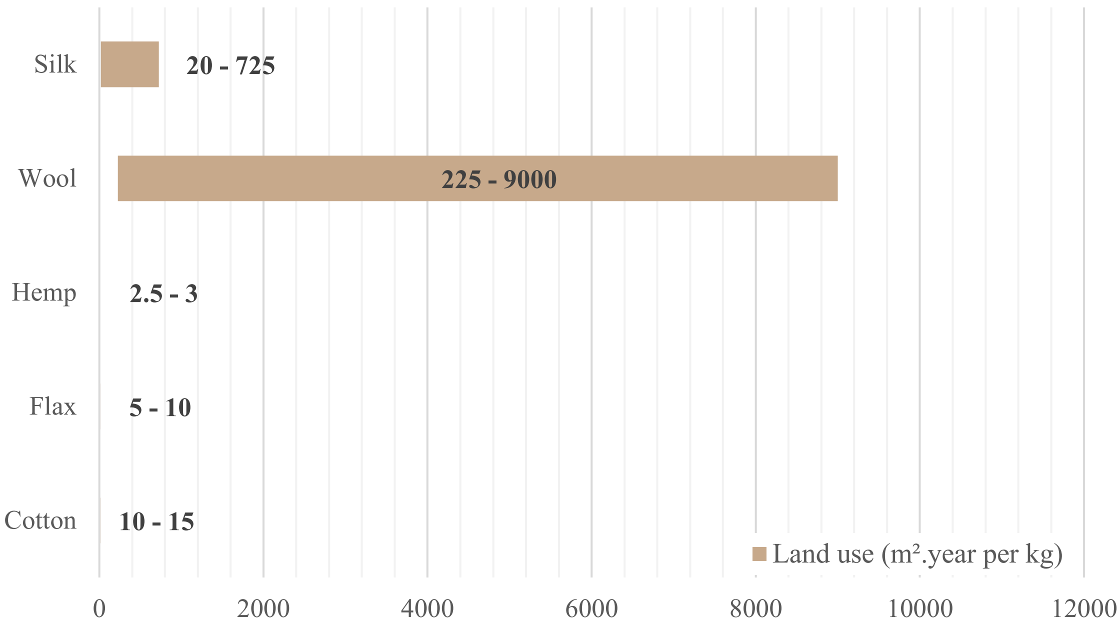

Figure 2. Land use ranges for natural fibers

It should not be overlooked that land use will result in soil contamination through fertiliser and pesticide inputs (FAO & UNEP, 2021). For cotton fiber, once different environmental factors such as climatic conditions and the use of agricultural technology are taken into account, it becomes clear that there is no single stable yield value that applies across all regions. According to FAO/FAOSTAT data, the global average yield for 2022–2024 is around 1 t/ha, while in China this value is approximately twice as high (OECD & FAO, 2025). Overall, cotton has the highest land use among plant-based fibers, yet its high area productivity is noteworthy. For flax, land-use values are reported at approximately 5–10 m^2 per kilogram of fiber per year, and global average yields lie in the range of 1–2 t/ha (Pinsard et al., 2023; Hue et al., 2024). Considering that irrigation in many European regions is largely rainfall-based and that the crop has a short vegetation period, flax offers better area productivity than cotton (Arslanoglu et al., 2022). Yield values for hemp fiber have increased in recent years. While yields in EU countries are in the range of 7–8 t/ha, the 2017 global average fiber yield is reported as around 4 t/ha (Mariz et al., 2024). For both bast fibers, the retting processes used in fiber extraction are critical factors for obtaining good-quality fibers.

Animal fibers require land for grazing and rearing, so land use values can vary significantly. Wool fiber has the highest land use among natural fibers due to factors such as grazing area, flock productivity and meat–fiber allocation systems (Harle et al., 2007). Because some studies take the entire grazing land into account, while others restrict the system boundary to the farm area, land use per kilogram of greasy wool shows a very wide variation (Wiedeman et al., 2016). Land-use data for silk fiber are evaluated based on mulberry cultivation and the yield of raw silkworm cocoons. The studies revealed that land use remained low when evaluated in terms of mulberry cultivation, whereas it became very high when assessed in relation to the annual yield of silk fiber (Astudillo et al., 2014; Hogeboom & Hoekstra, 2017; Bhatia et al., 2013).

In terms of land use for natural fibers, it is observed that plant-based fibers generally exhibit high yields with relatively low land requirements. However, because land use is inherently linked to crop cultivation, it should not be considered independently of fertilizer and pesticide inputs. In particular, factors such as advances in agricultural technology and plant breeding that increase yield may enable further improvements in land-use efficiency in the future (OECD & FAO, 2025). Despite their relatively low consumption volumes within the group of natural fibers, the high land use associated with animal fibers is striking (Textile Exchange, 2023b). Especially for wool, the need for extensive grazing areas means that the enteric methane emissions from sheep are distributed over large land areas (Fashion Industry Charter for Climate Action, 2023). Because the evaluation criteria for animal fibers are not as clear-cut as those for plant-based fibers, it may be more appropriate to conduct LCA assessments not solely on the basis of fiber mass but in relation to the product or its service life.

Energy use

For natural fibers, one of the important parameters that must be assessed in terms of environmental impact is energy use. Energy consumption arises both in agricultural production/rearing stages and in textile manufacturing processes (Cotton Incorporated, 2016). Cumulative energy demand can vary according to fiber type, as well as depending on factors such as the region of cultivation and the process technologies employed (Fu et al., 2024; Munasinghe et al., 2021). In addition, some studies recommend that energy use should not be evaluated only in this direct sense, but that the energy required to produce inputs such as chemicals and machinery used throughout all stages should also be taken into account (Bhalla et al., 2018). The energy demands presented in the graph cover cradle-to-gate (primary energy demand) processes for the fibers.

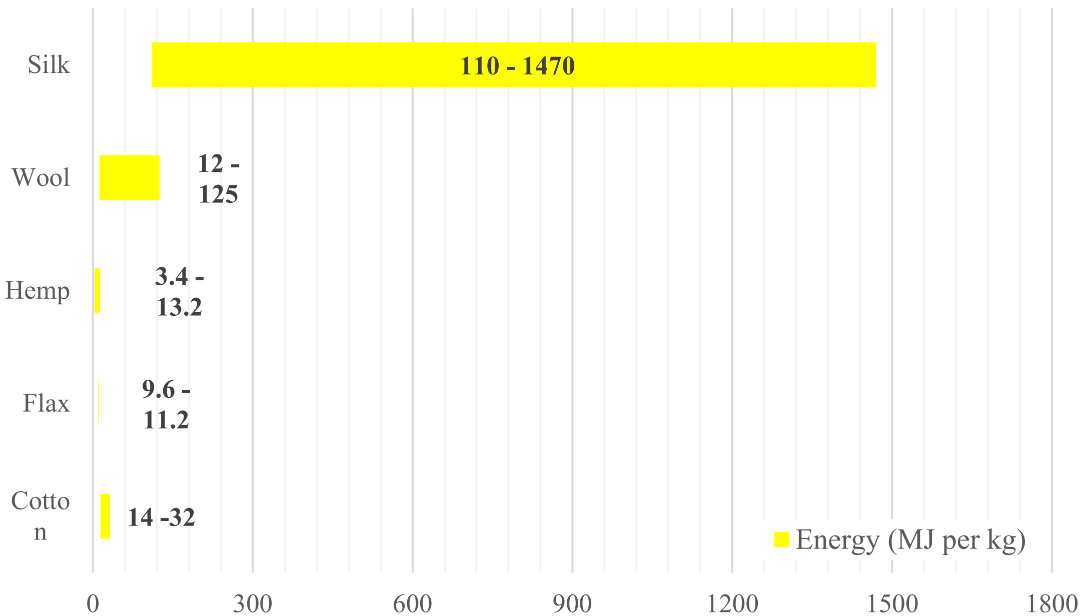

Figure 3. Energy use ranges for natural fibers

For cotton fiber, the energy-demand range varies due to regional conditions and differences in the processes applied (Mehmedi et al., 2024; La Rosa & Grammatikos, 2019). In the cultivation stage of cotton, fertilization – particularly nitrogen fertilization – is a major factor, and the irrigation technique used constitutes the most energy-intensive part of the system (Cotton Incorporated, 2016). The use of modern agricultural technologies has a positive effect in terms of energy efficiency. For example, in organic cotton cultivation, where fertilization and pesticide applications similar to those in conventional cotton can be eliminated, PED values remain at around 6 MJ per kilogram of fiber (Textile Exchange, 2014). If the processes up to the stage where the fiber is converted into fabric are included, the energy demand for cotton can increase by approximately a factor of ten (Cotton Incorporated, 2012).

In terms of energy demand, flax and hemp fibers fall within a similar range. For flax, a large share of energy consumption arises not only from agricultural operations, but also from retting and scutching/hackling processes (Le Duigou et al., 2011; Dissanayake et al., 2009). In regions where rain-fed cultivation and modern fiber-separation systems are used, energy demand is lower, whereas traditional methods tend to increase energy requirements (Rana et al., 2014). Owing to the rapid growth of the hemp plant and its low field-input requirements during cultivation, hemp fiber exhibits a lower energy-consumption profile than cotton (Shahzad, 2012;

Duflou et al., 2012). As in the case of flax, modern retting and scutching techniques can further reduce these values (van der Werf & Turunen, 2008). With its low-input, low-energy characteristics, hemp fiber is particularly noteworthy (Textile Exchange, 2023a).

For animal fibers, the energy required for production processes is generally higher than for plant-based fibers. The energy-demand range for wool fiber arises both from differences in rearing conditions and from variability in scouring processes (Wiedemann et al., 2016). Overall, the largest share of energy use is associated with the need for hot water in scouring and with the energy consumed by the process equipment (Bianco et al., 2022). Differences in scouring recipes, as well as the type and amount of energy consumed in drying (for example, line drying versus tumble drying), can significantly affect total energy demand (European Commission, 2011–2015). Among natural fibers, silk has the highest energy use in its production stages (Astudillo et al., 2015). Energy consumption begins with the cultivation of mulberry leaves, the main feed for silkworms, and increases through processes such as hot-water sericin removal and reeling (Vollratt et al., 2013). Most of the energy used in silk production is associated with these two hot-water-based processes (Astudillo et al., 2014; Wu et al., 2025). Some studies have reported that using modern systems instead of traditional methods in the reeling stage can reduce energy consumption by approximately half (Kathari et al., 2011).

Eutrophication potential

It is quite difficult to compare the chemical loads associated with textile fibers (Klöpffer & Grahl, 2014). There are many different chemical impact parameters arising during cultivation and production processes (Henry et al., 2015). In this study, in order to compare chemical impacts, freshwater eutrophication potential (EP), which is also frequently used in other studies, was selected as the indicator (JRC, 2023). It is known that the cultivation of natural fibers depends on water-based systems, and that agricultural practices transport nitrogen (N) and phosphorus (P) compounds, thereby polluting freshwater resources (Jawjit et al., 2006). In LCA studies, EP is usually reported in kilograms of phosphate equivalents (kg PO_4-eq) (Klöpffer & Grahl, 2014). However, in studies on wool and silk, values are reported in kilograms of phosphorus equivalents (kg P-eq) (Wiedemann et al., 2016; Astudillo et al., 2014). In order to compare fibers, a conversion was applied as described in example studies in the literature (van der Velden et al., 2014).

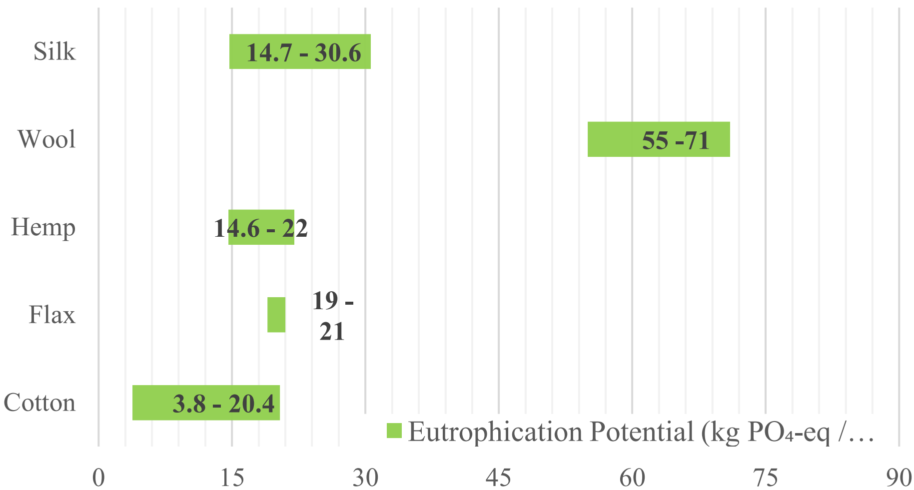

Figure 4. Freshwater eutrophication potential ranges for natural fibers

In evaluating the eutrophication impacts associated with plant-based fibers, it is observed that all fibers fall within similar ranges, and in some studies relatively low EP values are reported for cotton (La Rosa & Grammatikos, 2019). In the production of plant-based fibers, fertilizer use in agricultural processes and the transport of nitrogen and phosphate through irrigation water are the main causes of eutrophication (Cotton Incorporated, 2016). In regions such as Africa, where traditional production methods are used, intensive use of nitrogen fertilizers and the discharge of field drainage into freshwater bodies lead to upper-range EP values (PE International AG, 2014). For organic cotton practices, it has been reported that soil management can result in EP values as low as about 2.8 kg PO_4-eq/1000 kg (Textile Exchange, 2014). Studies conducted for flax and hemp fibers show similar ranges (van der Werf & Turunen, 2008). The high nitrogen-retention capacity of hemp reduces the need for fertilizer, but as observed in the studies, this has not translated into a marked reduction in EP (Lopez-Arraiza et al., 2025; Gonzáles-Garcia et al., 2010). In studies on flax that also include the yarn-spinning stage, it has been reported that dew retting can yield about 40% lower EP values compared with chemical retting (González-Garcia, 2010).

EP values for animal fibers are higher than for plant-based fibers, and wool stands out with the highest EP values (Bianco et al., 2022). High EP values arise from leakage associated with manure produced in sheep farming and from scouring processes (Wiedemann et al., 2016). Some reports state that, in wool production, most of the impact comes from nitrogen and phosphorus at the farm stage, while the scouring stage makes a smaller but still significant contribution (Henry et al., 2015). For silk fiber, EP has two dimensions, associated with mulberry cultivation and silkworm rearing (Astudillo et al., 2014). In regional studies conducted mainly in countries such as India and China, it has been reported that fertilizer use in agricultural stages and hot-water use in sericin removal and reeling are the main contributors to EP, and that good agricultural practices can improve the situation (Astudillo et al., 2014; Wu et al., 2025).

Freshwater eutrophication potential is an indicator that summarizes the chemical load arising at the cultivation stages of fibers (Sandin,et al, 2019). In the studies reviewed, cotton fiber generally appears with the lowest EP values. However, given that cotton is the most widely produced natural fiber, the environmental risks it may create should not be overlooked. In regions where conventional agricultural practices are applied, cotton can impose a comparable environmental burden to other plant-based fibers (Baydar et al., 2015). Flax and hemp, owing to their cultivation and processing characteristics, fall into a medium-risk group (van der Werf & Turunen, 2008; González-García et al., 2010). For animal fibers, the impacts are higher. In the case of wool, manure management during rearing and scouring processes place it in the highest risk group (Wiedemann et al., 2016). Silk fiber, on the other hand, is generally evaluated as a medium risk due to agricultural fertilization and thermal processes (Astudillo et al., 2014; Wu et al., 2025). For all fibers, modern practices such as controlled fertilization techniques and the use of new technologies can reduce the EP-related risks (Sandin et al., 2019).

Global warming potential

Global warming potential (GWP) is a composite indicator that expresses the impact of different greenhouse gases released throughout the total production process on the climate in terms of carbon dioxide equivalents (kg CO_2-eq) (Rosenbaum et al., 2018). For textile fibers, cradle-to-gate GWP values arise from factors such as fertilizer use, pesticide application and irrigation in agricultural processes, energy consumption, and, particularly for animal fibers, methane emissions (van der Werf, 2004; Wiedemann et al., 2020). In the graph, GWP ranges for fibers are presented for the stages from the field or farm up to the production facility. By incorporating the subsequent production, use, and end-of-life stages, it becomes clear that even natural fibers can display quite high impacts. (Nemecek et al., 2024).

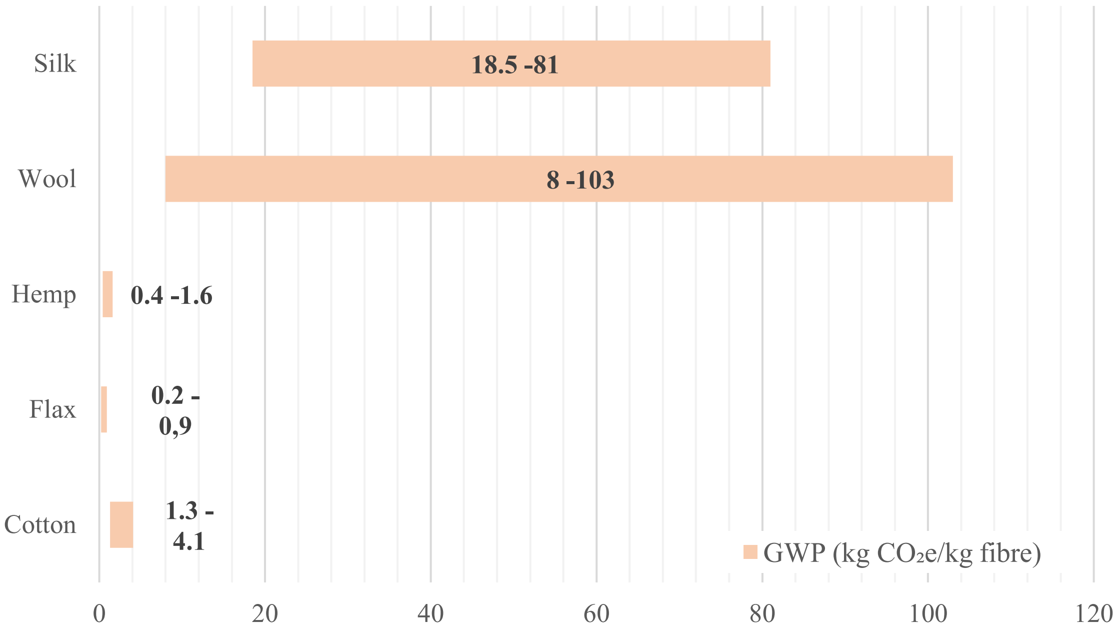

Figure 5. Cradle-to-gate GWP ranges for natural fibers

In cotton fiber production, N_2O emissions from nitrogen fertilizers and pesticides, together with the energy used for irrigation, create a moderate level of GWP (Sphera, 2021; Sphera, 2025). LCA studies have reported that in the global warming potential (GWP) profile of cotton production, approximately 80% of the total greenhouse gas emissions arise directly or indirectly from irrigation and fertilizer use. (Sphera, 2025; IFEU, 2022). For conventional cotton, global averages are around 3 kg CO_2-eq per kilogram of fiber, while regional differences fall within the range indicated in the graph (Kalliala & Nousiainen, 1999; Vitale et al., 2025). For organic cotton, values of approximately 1 kg CO_2-eq per kilogram of fiber have been reported; however, due to lower yields and limited production volumes, this does not significantly change the overall global picture (Textile Exchange, 2014; Textile Exchange, 2020).

Flax has the lowest GWP values among natural fibers (Gonzalez et al., 2023). In European countries where flax cultivation is practiced, several studies have reported values of about 0.65 kg CO_2-eq per kilogram of flax fiber (Alliance for European Flax-Linen & Hemp, 2022). Similarly, hemp follows flax and exhibits low GWP values (De Beus, Carus & Barth, 2019). For both bast fibers, their inherently rapid growth, reliance on rainfall-based irrigation and low fertilizer requirements are expected to result in low GWP levels (Jaczynska et al., 2025; Scrucca et al., 2020). It is also known that flax and hemp fibers can store carbon in their structure through photosynthesis (Shelly et al., 2025; Le Duigou et al., 2011). Therefore, some studies describe their agricultural phases as carbon-neutral or even carbon-negative (Gomez-Campos et al., 2021). Nevertheless, by taking energy consumption and other factors into account, they still generate low but positive GWP values (González-Garcia et al., 2010).

As with other impact categories, animal fibers constitute the high-risk group in terms of GWP among natural fibers. For wool production, enteric methane emissions occurring at the farm stage are the primary reason for high values and can account for up to about 80% of total GWP (Brock et al., 2013). The wide range observed for wool arises from the simultaneous production of other outputs such as meat and milk, as well as from regional differences in farm-management practices (Peri et al., 2020; Bianco et al., 2022). In studies from countries such as Australia and New Zealand, where relatively better management practices are reported, values of approximately 25–40 kg CO_2-eq per kilogram of wool fiber have been found (Alcock et al., 2015; Wiedemann et al., 2015). Another important factor for wool is the impact of scouring processes (Cardoso, 2013). For silk, which is also of animal origin, high GWP values and wide ranges have likewise been reported (Gonzalez et al., 2023; Astudillo et al., 2014). For silk fiber, the main contributors to high GWP are the energy-intensive thermal processes used for sericin removal and reeling (Astudillo et al., 2014). Energy consumption related to fertilization and irrigation in mulberry cultivation is another GWP-increasing factor (Barcelos et al., 2020). Data from systems with high energy efficiency represent the lower end of the GWP range (Liu et al., 2023).

In conclusion, natural fibers exhibit different GWP profiles due to their diverse production techniques. Beyond the intrinsic structure of each fiber, variations in agricultural or livestock-rearing practices and differences in energy requirements are the main drivers of their GWP values (De Rosa et al., 2019). Among natural fibers, bast fibers—particularly flax—are noteworthy for their efective position in terms of environmental burden (De Beus et al., 2019). Their carbon-sequestering characteristics and low field-input requirements can provide an important starting point for sustainable fashion design (Liu et al., 2023). Cotton, which tends to be perceived negatively in environmental discussions, actually lies in a medium GWP range among natural fibers (Gonzalez et al., 2023). However, as in other impact categories, its widespread use in global textile production increases the overall level of risk (Chen et al., 2021). Although animal fibers display high GWP values and high environmental burdens, their relatively low consumption volumes and long service lifetimes may mean that the actual risk is not as high as the GWP figures alone suggest (van Delden, 2019). For each fiber type, there is always room for improvement through the adoption of modern agricultural and manufacturing techniques and the integration of renewable energy sources into production processes (ISO, 2006-2018).

Conclusions

In the field of fashion, the concept of sustainability should be considered not as a slogan but as a set of principles that need to be applied at every stage. One of the main factors that has brought the sector to this point is the fast fashion approach, which is known to create environmental and social burdens on a wide scale, from the use of water and energy to the monitoring of supply chains and the provision of social rights. For sustainable fashion, a relevant direction is a transformation process in which all parameters such as raw material acquisition, production processes, the use phase, consumer habits and recycling opportunities are addressed as a whole.

The environmental impacts of natural fibers reveal how intricate a set of processes the concept of sustainability actually is. Because of its high consumption rate, cotton is the most dominant fiber in terms of environmental load, but this load can be reduced through good agricultural practices and innovative irrigation applications. For plant-based fibers, flax and hemp offer remarkable opportunities with low agricultural inputs and rainfall-based irrigation, but they also carry negative effects due to the practices used in fiber-extraction processes. In the group of animal fibers, wool and silk occupy an environmentally risky position because of high greenhouse gas emissions and extensive land use in the production stage; however, their low consumption volumes and high quality and long service life mean that the impact they create is at a lower level. For this reason, since the environmental loads of fibers involve different parameters, it is impossible to speak of the superiority of a single fiber.

Sustainable fashion is possible not only through raw material selection but also through traceability at every stage of the production chain, fair working conditions and energy efficiency. The use of renewable energy, the strengthening of repair and recycling infrastructure, and the encouragement of conscious consumer behavior are key elements of this process. As a result, sustainable fashion is more likely to generate lasting outcomes by being approached as a system that maintains integrity from design through to consumption.

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CHAPTER IV

ADVANCED UPCYCLING APPROACHES IN CONTEMPORARY FASHION DESIGN: INNOVATIVE GARMENT CONSTRUCTIONS

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Abstract

This chapter aims to reveal the contributions of upcycling to sustainability, innovation, and cultural continuity within contemporary fashion design. The modern fashion industry, driven by accelerated production and consumption cycles, generates significant environmental challenges, compelling designers, manufacturers, and consumers to explore alternative solutions. Within this framework, upcycling emerges as a prominent method that not only reduces resource consumption but also introduces new functional and aesthetic value to waste or unused garments, thereby enabling the creation of original design outcomes. The study underscores that upcycling functions not merely as an environmentally responsible production practice but also as a design strategy that stimulates creative thinking. By reworking existing materials, fashion designers produce unique, singular, and artistically enriched garments, thereby promoting individuality and innovation in fashion. Furthermore, upcycling practices enhance social awareness, encourage consumers to make more conscious purchasing decisions, and support the integration of circular economy principles within the fashion sector. In conclusion, upcycling represents a creative paradigm in contemporary fashion design in which sustainability and aesthetics converge. This approach signifies a transformative shift in future fashion, placing environmental sensitivity and artistic innovation at its core.

Keywords: Fashion Design, Upcycling, Sustainable Fashion, Wearable Art, Innovative Clothing Design

Introductıon

The rapidly expanding global fashion industry is not only regarded as a field of aesthetic production but also as a multidimensional system shaped by its environmental, economic, and cultural impacts. Mass production, fast-consumption habits, and imbalances in resource use have positioned fashion at the center of contemporary sustainability discussions. In this context, the concept of sustainable fashion—which seeks to reduce the negative environmental effects of the industry and to promote more responsible approaches within production and consumption cycles—has gained increasing significance. Particularly in recent years, designers have begun to repurpose waste materials and creatively transform surplus resources, generating designs that possess both aesthetic and ecological value. This shift has brought the concept of upcycling to the forefront of fashion design.

Upcycling represents an innovative approach that involves not only the reuse of materials but also the development of a new design language and a creative mode of thinking. Upcycling practices in fashion design transform discarded products into objects of artistic and functional value while simultaneously offering a critical perspective on consumer culture. Through this process, fashion extends beyond its conventional role as a dressing practice and evolves into a domain of cultural expression. The upcycling process embodies deep interaction involving both the material itself and broader discussions on sustainability, creative expression, destruction, and reconstruction; it renders existing systems visible while contributing to the urgency and resonance of the issues at hand (Stucker & Bozuwa, 2012, p. 47).

Historically, upcycling has long been practiced. During World War II, textiles and fabrics became essential for the production of uniforms and military equipment, thereby increasing the need for mending and repair. Commercial companies developed patterns encouraging British and American women to reuse fabrics and garments; for example, the project "Make Do and Mend for Victor" demonstrated how a man's suit could be transformed into a women's skirt and matching jacket (Aspinall, 2023, p. 92).

In contemporary contexts, advanced upcycling practices are understood as responses to the unethical practices produced by capitalist structures and economic systems of the 20th century. Recent research on upcycling frequently employs the term "remanufacturing," depending on context and scale (Bigolin et al., 2022, p. 3). This study argues that definitions of upcycling should be expanded by more closely integrating material-based understandings within the design process. The current conceptualization of "remanufacturing," which focuses exclusively on production principles and prioritizes economic outcomes, may obscure the deeper meanings of upcycling and its artistic nuances within the process.

This study fills a gap in the academic literature by emphasizing the significance of material in the upcycling process and foregrounding the relationship between objects, culture, and time. In general, the literature defines upcycling as the transformation of undervalued items—such as discarded textiles or post-consumer garments—into creatively designed, fashionable products. This process typically involves reimagining flat fabrics or end-of-life materials and designing aesthetically appealing garments through the use of new pattern pieces (Chao, 2019, p. 1; Han, Tyler, & Apeagyei, 2015, p. 2 ; Janigo, Wu, & DeLong, 2017, p. 255; Vadicherla et al., 2017, p. 4).

By adopting a material-culture framework (Crane & Bovone, 2006; Gell, 1998; Ingold, 2012; Miller, 1994), simplified definitions of upcycling can be expanded, the value of interacting with devalued materials can be redefined, and the focus can be shifted away from commercial concerns. Through this lens, upcycling can be reconceptualized as an artistic process—one that enables a sustainable material experience and promotes meaningful relationships with materials. As Norman (2007, p. 46) states, “what matters is the history of interactions—the relationships people form with objects and the memories they evoke.” This perspective advances the evolution of sustainable fashion.

This study aims to explore how upcycling approaches in contemporary fashion design shape innovative garment constructions. The first section, "Sustainability in the Fashion Industry and the Rise of Upcycling," discusses environmental awareness and transformative production practices within the fashion sector. The second section, "Cultural Heritage, Traditional Textiles, and Innovative Approaches," examines how local cultures and artisanal traditions are reinterpreted through contemporary fashion in relation to upcycling. Finally, the section titled "Wearable Art and the Dimension of Artistic Expression" investigates the intersection of upcycling and art, addressing the aesthetic and ecological dimensions of fashion through a holistic perspective.

1. The Rise of Sustainability and Upcycling in the Fashion Industry

Sustainability is an approach aimed at protecting human and environmental health, enhancing existing ecological values, and ensuring the transmission of these values to future generations. Joy defines sustainability as the ability to meet the needs of the present generation without jeopardizing the capacity of future generations to meet their own needs, while simultaneously maintaining ecological balance and safeguarding human well-being (Joy et al., 2012, p. 274). Similar to other sustainability frameworks, the concept of sustainable fashion encompasses a broad and multidimensional scope. It includes not only environmental and human health concerns but also ethical principles. Respecting workers' rights throughout production processes, avoiding harm to nature and animals, and upholding human rights form the ethical foundation of this understanding. Additionally, producing long-lasting garments that do not wear out easily, enabling their reuse at the end of their lifecycle, and prioritizing recyclable materials contribute significantly to the protection of ecosystems within sustainable fashion practices (Ayanoğlu & Ağaç, 2017, p. 255–256).

The increasing need to combat climate change on a global scale is driving industrial sectors to develop strategies to reduce carbon emissions. In this context, the fashion industry is one of the sectors attracting attention due to its significant greenhouse gas emissions. According to data published by McKinsey, the sector produced approximately 2.1 billion tons of greenhouse gas emissions in 2018, accounting for approximately 4% of global emissions. This figure represents a volume comparable to the annual greenhouse gas emissions of France, Germany, and the United Kingdom (Berg et al., p. 3). Although initiatives to reduce emissions are ongoing, the sector's current progress lags behind the 1.5°C compatible emissions reduction pathway identified by the Intergovernmental Panel on Climate Change (IPCC) and committed to internationally by the 2015 Paris Agreement. To meet this target, the fashion industry must reduce its emissions to 1.1 billion tons of CO_2 equivalent by 2030. However, projections based on the potential impacts of the COVID-19 pandemic indicate that unless additional measures are taken, the industry will reach 2.1 billion tons of CO_2 equivalent in 2030, generating emissions nearly twice the target (Berg et al., p. 29). In this regard, upcycling emerges as an innovative and highly effective solution for mitigating the environmental impacts of the fashion industry.

Upcycling refers to the process of repurposing discarded garments, objects, or materials while preserving their existing form and generating new products of higher quality or value than the original. In this respect, upcycling differs fundamentally from conventional recycling practices, which rely on breaking down fibers through chemical or mechanical processes to be reused in new fabric production. Reusing materials in their current state significantly extends the lifespan of a garment and prevents additional environmental impacts that may arise from new production processes. These advantages position upcycling as one of the most sustainable production approaches within contemporary fashion. Consequently, upcycling practices are increasingly embraced in modern fashion design and have become an essential component of creative sustainability.

The term “upcycling” was first introduced in 1994 by German engineer Reiner Pilz. In a statement published in the British monthly magazine Salvo, Pilz criticized traditional recycling practices as “down-cycling” and argued that “what we need is upcycling, where old products are given a higher, not lower, value.” However, the roots of upcycling in fashion date back to the 1940s during World War II in the United Kingdom. Due to wartime conditions, the British government restricted civilian clothing production and consumption to reduce the use of raw materials and redirect labor and factory resources to military production. This circumstance made skills such as mending, redesigning, and creating new garments from existing textiles critically important. As the war progressed, material shortages became so severe that many women repurposed household textiles—such as curtains and tablecloths—to produce clothing for their families.

Upcycling regained prominence in later years, particularly during the late 1980s and early 1990s, when the United Kingdom experienced significant economic recession. Influenced by punk culture, young people seeking original, creative, and low-cost fashion began redesigning old garments, thereby revitalizing the upcycling movement. However, the phenomenon of fast fashion had already begun to take shape by this time. Emerging in the early 1970s, this production model was formally adopted by the global fashion industry throughout the 1990s. Fast fashion arose from the development of new production and logistics systems that enabled cheaper, rapid manufacturing and distribution.

The term “fast fashion” was first used on December 31, 1989, in The New York Times in reference to Zara, a brand founded in 1975 and now considered one of the pioneers of this movement. However, Zara and many similar fast-fashion brands have become part of a system that violates human rights and contributes significantly to environmental pollution through production practices that reinforce a disposable consumption culture. According to a report by the Ellen MacArthur Foundation, the disposable production structure of the fast-fashion system further deepens this environmental crisis. Excessive production and accelerated product turnover lead to approximately 85% of all textiles produced each year becoming waste long before reaching the end of their intended lifecycle. A large portion of these discarded items either end up in landfills or are destroyed through incineration. These data clearly reveal the destructive environmental impact of the current fast-fashion model and demonstrate the critical importance of adopting circular and sustainable production strategies—such as upcycling—to reduce the ecological burden of the fashion sector.

Once perceived merely as a niche or craft-based practice, upcycling has been redefined today as an innovative, creative, and trend-setting design approach. In a world dominated by mass production, particularly after the year 2020 (influenced by the pandemic), a strong movement emerged within the fashion industry to restore ecological balance and mitigate the damage inflicted by fast fashion on both nature and labor. During this period, the concept of upcycling gained increasing importance and moved to the center of sustainable fashion discourse. As the era of fast fashion approaches its end, consumers are becoming more aware of the environmental and ethical issues associated with the fashion industry. This growing awareness motivates individuals to prioritize quality over quantity, leading upcycling practices to reemerge as a rising trend among fashion enthusiasts.

While upcycling was viewed as a necessity in past centuries, it is now regarded as a sustainability practice consciously embraced by modern consumers. This renewed approach—motivated by an awareness of the environmental and social consequences of consumption—has positioned upcycling as a catalyst for more responsible, ethical, and ecological transformation in fashion.

In the field of fashion, upcycling refers to the process of reworking existing garments or materials into new pieces of high aesthetic and functional value. This approach has become an important sustainability strategy within the fashion industry as a result of decreasing natural resources and shifting social dynamics. Today, upcycling is valued not only for its environmental sensitivity but also for its creative and artistic potential, making it a widely respected and frequently adopted method among designers and artists.

One of the leading figures in upcycling within the luxury fashion industry is Gabriela Hearst, who created approximately 60% of her Spring/Summer 2021 (SS21) collection using upcycled materials. In an interview regarding this approach, Hearst remarked: "When we first used deadstock in 2017, even saying the word was almost taboo in the language of luxury fashion." This statement indicates that upcycling initially carried a negative connotation in luxury fashion but has gradually undergone a transformation in perception. Luxury fashion brand Gucci promotes the concept of circular luxury through its initiative titled "Equilibrium." Because luxury inherently encompasses principles such as longevity, quality, and rediscoverability, it naturally aligns with circularity. Gucci supports the preservation and reevaluation of its products over time by maintaining their quality and durability. As a result of this commitment, Gucci received the “Climate Change Award” at the 2022 CNMI Sustainable Fashion Awards held during Milan Fashion Week SS2023. Moreover, the inclusion of upcycled pieces in the collections of iconic fashion houses such as Balenciaga, Miu Miu, Louis Vuitton, and Marine Serre demonstrates the growing adoption of upcycling among influential industry leaders (Ellen MacArthur Foundation). Additionally, transforming consumer behavior and promoting a resale culture contribute significantly to reducing carbon emissions within the fashion industry. These developments indicate that upcycling has evolved into a holistic transformation tool that not only reduces environmental impacts but also supports sustainable consumption practices (BRAVO, 2025).

Moreover, outdoor equipment and apparel brands such as Patagonia, Jack Wolfskin, and Marmot have shifted their focus toward sustainable and environmentally responsible production practices. These companies offer upcycling options to customers when their garments show signs of heavy wear. Depending on the condition and level of deterioration, products are either recycled, resold, or donated to charitable organizations. In addition, Vaude and Houdini have emerged as pioneers in the rental services of outdoor clothing. Both brands offer garment rental programs in their stores, with Houdini having launched this service in 2013. The Swedish company aims to present customers with alternative consumption models instead of purchasing new items and emphasizes that rental services provide a sustainable substitute for repeat buying. Houdini also collects customers' discarded polyester garments through recycling bins placed in its retail stores. Customers can freely use these bins, and the company guarantees that the collected items will be professionally recycled.

Today, many outdoor brands develop creative strategies to prevent their products from ending up in landfills. These strategies include transforming waste materials into new products through upcycling, or collecting used items for repair and subsequent resale. Such practices allow the fashion sector to meet its ongoing need for novelty and personal expression while simultaneously reducing the environmental burden associated with producing new clothing. By adopting upcycling on a wider scale, the fashion industry has the potential to take a significant step toward a more sustainable and zero-waste future (ISPO, 2025).

According to Vogue Business's 2024 Innovators list, upcycling encompasses the transformation of used garments into new, high-fashion pieces, offering a unique and environmentally friendly alternative to mass production. For example, Patrick Grant, through Community Clothing, and Hannah Silvani, through New Craft House, are making surplus designer fabrics accessible for home sewing enthusiasts. Other designers, such as Mara Hoffman, focus on sustainable supply chains and consumer education.

The global upcycled fashion market was valued at USD 8,253.97 million in 2024. It is projected to grow from USD 8,979.49 million in 2025 to USD 16,701.28 million by 2032, with a compound annual growth rate (CAGR) of 9.21% during the forecast period. In 2024, the Asia-Pacific region led the upcycled fashion market with a 34.80% share. The market for revalued and repurposed garments has demonstrated a strong upward trend in recent years. This growth is driven by the fashion industry's commitment to reducing its environmental impact, increased consumer awareness of the environmental consequences of their choices, and the growing demand for unique and sustainable clothing.

On the other hand, although luxury brands have begun to embrace this trend, it is the new generation of designers who are propelling the upcycling movement forward. Designers featured on the Alterist platform, for instance, draw attention with their distinctive styles and creative approaches. Upcycling not only contributes to environmental sustainability but also enables each piece to be handcrafted, unique, and artistically original. In this respect, upcycling emerges as a powerful production philosophy that unites aesthetic and ethical values in contemporary fashion (Alterist, 2022).

As awareness regarding the environmental and social impacts of the fashion industry increases, demand for sustainable production and consumption alternatives continues to grow. Today, individuals seek environmentally conscious and practical solutions in the realm of fashion. Fashion is not merely a field of consumption but also a component of cultural identity and social transformation; therefore, it directly influences processes of cultural change. In this context, the upcycling approach stands out as an innovative and sustainable model capable of leading the transformation long needed within the fashion industry.

2. Cultural Heritage, Traditional Textiles, and Innovative Approaches

Cultural heritage represents one of the most significant values reflecting a society's historical accumulation, identity, and aesthetic understanding. In the context of fashion design, the contemporary reinterpretation of cultural heritage establishes a bridge between the past and the present, adding cultural depth to sustainable design practices. Traditional crafts, weaving techniques, motifs, and local modes of production are regarded not only as aesthetic resources but also as instruments of cultural sustainability (Er Bıyıklı et al., 2021, p. 144).

In today's world, objects that help individuals define their identities—such as garments—draw nourishment from rich cultural heritages inherited from the past. Cultural heritage and fashion design, as two closely related categories, often intersect;

valuable elements originating from ancient civilizations are incorporated into design practices to ensure their continuity. Throughout history, artists and fashion designers have drawn inspiration from cultural heritage. For example, during the Renaissance period, the revived reflections of antiquity serve as striking illustrations of how societies integrated the aesthetic influence of ancient artifacts into their designs. In some of the world's richest ancient regions, garments designed for special occasions were considered luxury items that reflected the social status of their owners (Toffoletti, 2014, p. 71). Although transforming an individual's ideas into a product or garment can be enjoyable, design today holds significant power. Designs can distinguish the identity of a particular group or community and become the voice of cultural, social, ideological, and historical transitions—from a product to a space (Barbarasoğlu, 2015, p. 27; Sohn, 2013, p. 75-103; Toffoletti, 2014, p. 87). In this context, upcycling practices bring a new environmental and cultural dimension to fashion design by reinterpreting existing cultural and historical values in sustainable and creative ways.

A deeper examination of the concept of culture reveals the essential role it plays in the lives of individuals and societies. Elements of cultural heritage—such as art, crafts, garments, traditions, and customs—constitute an integral part of daily life and reflect the identity of communities. However, it is noteworthy that these elements—considered among a nation's "most valuable products"—can easily be overlooked within the fast pace of modern life. Cultural products symbolize a community's distinct values, history, ideologies, and traditions. Today, individuals often turn to consumption as a reflex for maintaining their livelihoods within a fast-paced, convenience-oriented lifestyle, resulting in the perception of cultural values as objects merely to be presented to visitors. On the other hand, products inspired by cultural elements have the capacity to carry and represent the essence of a culture on a global scale. This potential can only be realized by developing products that draw inspiration from cultural elements, embody their core values, and meet international standards.

The fashion and clothing industry plays a central role in preserving and reinterpreting cultural heritage through designs inspired by selected cultural elements. Projects focused on promoting textile and garment products bring together cultural elements with concepts of textile, art, and fashion, demonstrating how regional cultures can be reinterpreted into contemporary fashion products. Such works serve to communicate and introduce cultural heritage to consumers. Products designed by reinterpreting textiles directly associated with a region's cultural identity are envisioned to reflect the trend of sporty elegance, offering convenience and sophistication for working women in daily life. Within this framework, upcycling practices enable the reassessment of existing cultural and historical values and support the development of sustainable fashion practices. This approach contributes not only to environmental sustainability but also to the creative and contemporary preservation of cultural heritage.

In response to the homogenized fashion sensibility brought about by globalization, approaches that highlight local identities and craftsmanship have gained increasing importance. Designers preserve cultural heritage while creating original designs by integrating traditional weaving techniques with modern materials and contemporary forms. Weaving, one of the sub-disciplines of fashion, is a fabric production method based on the systematic interaction of warp and weft yarns (Thorpe & Larsen, 1967, p. 1–2). The construction of woven fabric depends on the arrangement of the interlacing points of the yarns, and patterns are typically represented on squared paper (Gürcüm, 2005, p. 210). The technical properties of fabric vary according to factors such as yarn type, density, weave frequency, and pattern structure, offering designers the freedom to control and modify fabric composition (Keleş & Yılmaz, 2022, p. 1). Woven fabric design is a process that requires both aesthetic and technical knowledge, beginning with concept development and continuing through decisions on material selection, weave structure, and production techniques (Metlioğlu, 2012, p. 177; Metlioğlu, 2015, p. 42). Creativity in design may emerge through the use of new materials and techniques or through reinterpreting classical patterns using innovative structures and technologies. Aesthetic value is directly influenced by the selection of yarn type, weave structure, and the harmony among yarn colors (Çoruh et al., 2019, p. 1608; Özdemir & Kahyeoğlu, 2020, p. 910).

Today, the upcycling approach enhances both sustainability and creative expression by enabling the reuse of old or waste textile materials within woven design. The fusion of traditional weaving techniques with upcycling reduces material waste while enabling the creation of aesthetically and functionally innovative textiles. This approach is not merely an aesthetic preference but also an expression of cultural awareness and ethical positioning. Integrating cultural heritage with contemporary design provides designers with a historical point of reference, while offering viewers and users an opportunity to reconnect with their cultural roots. Indeed, innovative approaches in fashion hold the potential to reproduce traditional elements using new materials, forms, and technological possibilities without excluding their original contexts (Koca & Koç, 2023, p. 90).

To understand how cultural heritage and upcycling are transformed into tangible outcomes in contemporary fashion design, it is useful to examine leading designer examples. These cases reveal not only aesthetic approaches but also sustainable and culturally oriented design philosophies. Bora Aksu, for instance, brings cultural heritage into contemporary fashion by harmonizing traditional Turkish motifs with modern silhouettes. Handmade details within Aksu's collections are reinterpreted through inspirations drawn from Anatolian textiles, and upcycled materials are incorporated into production processes (Er Bıyıklı et al., 2021, p. 145; Odabaşı, 2016, p. 42). This approach supports both cultural continuity and environmental sustainability. Similarly, Dilek Hanif exemplifies upcycling by incorporating old garment pieces and waste textiles into her collections. The designer combines traditional fabric textures with modern cuts, offering historical references while enhancing the value of discarded materials. This approach optimizes resource use in fashion design while contributing to the preservation of cultural heritage (Yıldız & Mermerci, 2024, p. 150).

Internationally, Stella McCartney stands out as one of the leading figures prioritizing sustainable fashion and upcycling as core design principles. Her collections bring together natural dyes, recycled textiles, and ethical production methods, emphasizing environmental and ethical values (Şevkay & Bayburtlu, 2020, p. 165). Furthermore, her integration of traditional stitching techniques into certain collections exemplifies how cultural heritage can be reinterpreted in a universal design language (Öngen, 2016, p. 1253).

These examples demonstrate that upcycling and cultural heritage together create an innovative expressive field in fashion. By blending traditional techniques with modern materials and technologies, designers transform sustainability into an aesthetic value while simultaneously cultivating cultural consciousness among viewers and wearers. Thus, contemporary fashion evolves from being merely a domain that meets clothing needs into a multilayered expressive field encompassing cultural, ethical, and ecological dimensions.

In the age of fast fashion, upcycling and garment-repair practices foster a deeper connection between consumers and their clothing. As more consumers embrace upcycling and repair culture, the fashion industry continues to transform. This movement encourages individuals to extend the lifespan of their garments, reduce waste, and support creativity and individuality. Accordingly, upcycling is also regarded as an essential tool in sustaining cultural heritage. The reinterpretation of traditional fabric remnants, old garments, or handwoven textiles supports environmental sustainability while enabling the renewal of cultural memory through modern designs. Thus, contemporary fashion becomes a dynamic expressive domain where cultural identity is preserved and aesthetic innovation is realized.

A review of upcycling-oriented studies in garment design reveals that research generally centers on sustainability, material reuse, and innovative design approaches. Various scholars have identified methods such as deconstruction, patchwork, appliqué, embroidery, draping, dyeing, fabric manipulation, crochet, pattern deformation, reconstruction, and recombination as frequently used techniques in upcycled design practices.

Studies in this field generally converge around the following themes:

- Sustainability and functionality: Ainamo (2014) and Eum and Oh (2023) highlight that upcycling offers innovative environmental and aesthetic contributions to the fashion sector, emphasizing the prominence of techniques such as deconstruction and collage.

- Use of waste materials: Research by Aus et al. (2021), Bigolin et al. (2022), and Erol (2022) underscores that textile and leather waste generated during production processes can be repurposed through patchwork, knitting, or reconstruction techniques, thereby reducing environmental impact.
- Design and educational practices: Studies conducted by Burns (2024) and Bigolin et al. (2022) reveal that incorporating upcycling into educational processes enhances students' experimental and sustainable thinking skills.
- Aesthetic and conceptual approaches: Cassar (2024) relates upcycling processes to the concepts of "care" and "value," while Na et al. (2024) and Moon et al. (2024) analyze the symbolic meanings embedded in deconstruction practices.
- Brand applications and collective production: Er Bıyıklı et al. (2024) and Eum and Oh (2023) discuss the importance of producer-designer collaboration through upcycling collections of brands such as Yargıcı and Marine Serre.
- Denim and material-specific studies: Research by Gürsoy and Sünter Eroğlu (2024), Şenol (2021), and Santiago et

al. (2024) provides examples of redesigning denim products using techniques such as cutting, unpicking, stitching, and appliqué.

- Participatory and political design approaches: Studies by Von Busch (2008) and Franzo and Salome (2025) conceptualize upcycling not only as an aesthetic mode of production but also as a practice that involves users in the process and interrogates the social dimensions of fashion.
- In conclusion, the literature demonstrates that various techniques and approaches to upcycled garment design have been developed. These studies contribute significantly to the field by promoting the reuse of materials, encouraging experimental and mindful production processes within design, and strengthening a sustainable fashion culture.

3. Wearable Art and the Dimension of Artistic Expression

Wearable art is a contemporary design approach that blurs the boundaries between fashion and art, transforming the body into a surface of expression. This approach moves beyond the traditional understanding of clothing as merely a functional element, allowing the artwork to be redefined in a wearable form. In this context, clothing becomes not simply an object of use but an artistic medium that carries individual and collective meanings (Sarı, 2017, p. 74-76). Wearable art generally refers to unique or limited-edition works produced in the form of garments or accessories that embody aesthetic and conceptual intentions.

By distancing ordinary clothing from the logic of quantitative production—emphasizing originality, artifact status, and exhibition potential—wearable art positions garments closer to the realm of art. Thus, clothing becomes both an aesthetic object and a wearable installation on the body. This definition emphasizes the movement's deep connections with craftsmanship, experimental materials, and performance practices (URL-1; Hemmings, 2003, p. 13).

The origins of wearable art can be traced to early 20th-century intersections of art and dressmaking, the Arts and Crafts tradition, and the textile/fiber arts movement. From the 1960s onward, wearable art evolved alongside performance art, body art, and experimental fashion. During this era, artists used the body as a canvas, demonstrating that art could be integrated into everyday life. By the 1970s, the term art-to-wear gained clearer definition, encompassing the reinterpretation of craft traditions, feminist handwork, and local techniques within contemporary art contexts (Leventon, 2006, p. 146). Throughout the 1990s and 2000s, the boundaries between haute couture and contemporary art became increasingly porous; designer-artists such as Alexander McQueen and experimental ateliers transformed garments into interdisciplinary projects merging sculpture, performance, and media. This historical trajectory illustrates that wearable art is an interdisciplinary field encompassing fashion, craft, performance, and technology (Stabb, 2004, s. 229; Yang, 2020). Today, the approach has acquired new meaning through its alignment with upcycling and sustainability. Wearable art pieces created from waste materials, repurposed fabrics, or biodegradable substances embody both environmental and aesthetic awareness. Such works position fashion as a conceptual and artistic process rather than merely an industrial mode of production. Through upcycling, designers attribute new functions and meanings to materials while adopting a critical stance toward consumer culture. In this respect, wearable art represents not only aesthetic creativity but also an ethical and ecological design philosophy.

A defining characteristic of wearable art is its innovation in materials and techniques. While traditional fiber techniques—knitting, stitching, embroidery, felting—remain significant, modern practices incorporate materials such as plastic, resin, metal, 3D-printed structures, biomaterials, and electronic textiles. This diversity transforms the garment in two ways: on one hand, its physical form—volume, surface, silhouette—is elevated to a sculptural and conceptual level; on the other, through sensors, LEDs, or living materials, it becomes a dynamic interactive installation shaped by movement and relationality. For instance, Iris van Herpen's 3D-printed, experimentally structured works transform clothing into "living sculpture," while contemporary sensor-enhanced performative costumes explore the cognitive–kinematic relationship between the body and its environment (Stinson, 2015; Birringer & Danjoux, 2009, p. 22).

The artistic expressive power of wearable art can be examined on three fundamental levels (Leventon, 2006, p. 20; Günay, 2011, p. 52):

- Conceptual/iconographic: myths, social critique, or aesthetic narratives embedded in the design;
- Visual/formal: meanings conveyed through material, color, and texture;
- Performative/relational: the work's activation on the body and its interaction with the viewer.

These layers feed into one another: a wearable art piece is not merely a "visual object" but also a narrative activated within the conditions of display—runway, gallery, or stage performance. Consequently, wearable art often addresses themes such as body politics, identity, subjectivity, and ecological narratives, with the body acting simultaneously as a carrier and a producer of meaning (Birringer & Danjoux, 2009, p. 4; Hemmings, 2003, p. 14).

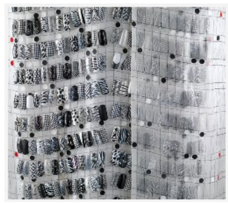
The contemporary evolution of wearable art has expanded its narrative possibilities through digital technologies and interaction design. Garments equipped with sensors, actuators, lighting systems, and software-controlled mechanisms produce dynamic narratives that respond to bodily movement, environmental data, or audience interaction. In academic literature, such garments are defined as interfacial or performative garments, emphasizing their function not only as aesthetic forms but also as tools of information and communication. Thus, wearable art engages spectators both conceptually and experientially, drawing them actively into the work (Birringer & Danjoux, 2009, p. 7).

Wearable art is one of the critical alternatives that challenges the mass-production and mass-consumption logic of the traditional fashion industry. The artistic reworking of waste materials (upcycling), the transformation of second-hand textiles, and the use of biomaterials constitute not only environmentally conscious choices but also aesthetic and ethical statements: material selection becomes a medium through which the designer communicates political positions, social critiques, or ecological narratives. In this sense, wearable art serves as both the methodological and conceptual precursor of contemporary upcycling approaches (Yu, 2025, p. 8; Adamson, 2025).

Wearable art stands as one of the aesthetic and conceptual motors driving upcycling approaches in contemporary fashion design. Innovative interventions in material and technique, alongside body-centered performative narratives, offer new readings of sustainability, identity, and technology. Academic research on wearable art should not remain limited to object-based analyses; rather, it must be approached through interdisciplinary methodologies that encompass production, exhibition, and audience experience. In this way, wearable art becomes both a rich theoretical resource for researchers and a practical laboratory for designers (URL-1; Smelik, 2020, p. 12).

The position of wearable art within contemporary fashion also lays the foundation for reinterpreting the relationship between body, identity, and expression. Each design becomes a narrative on the body, reflecting individual identity. Wearable art pieces produced through upcycling support not only sustainable material use but also the integration of artistic expression into everyday life. Thus, creativity, ethical values, and ecological responsibility emerge as complementary foundations of design in contemporary fashion.

Upcycling practices within wearable art are regarded as an innovative trajectory that unites sustainable fashion with an artistic dimension. In this approach, designers do not merely reuse waste or surplus materials; they transform them into conceptual and aesthetic languages, turning garments into artworks. Each design thus becomes an expression of both environmental awareness and individual creativity. In this context, Hussein Chalayan stands out as one of the pioneers of wearable art, drawing attention with designs that question the relationship between body, technology, and identity. Chalayan's collections, which incorporate recycled materials and transformable garment forms (Figure 1, A-B), demonstrate that fashion is not merely a superficial aesthetic but also an intellectual field (Birringer & Danjoux, 2009, p. 4). In his work, the garment becomes a performative object; transformation occurs both at the material and conceptual levels.

A.   B. 

Source: A. https://www.metmuseum.org/art/collection/search/704351

B. https://www.metmuseum.org/art/collection/search/626150

Figure 1. A. Hussein Chalayan, Wearable Art Example, silk, plastic (acrylic), Autumn/Winter 2014–15; B. Hussein Chalayan, Transformable Garment, 1999.

Similarly, Iris van Herpen creates a sustainable design language by bringing together advanced technology and meticulous craftsmanship. Using techniques such as 3D printing, laser cutting, and reshaped plastic materials, she produces organic forms inspired by nature. Van Herpen's designs emphasize the transformative potential of material, situating fashion as an innovative platform at the intersection of art and science (Bolton, 2016, p. 204). This approach demonstrates that upcycling is not merely an act of reuse but a practice that reshapes the meaning and perception of material.

Reet Aus is also one of the strongest advocates of the upcycling movement within sustainable fashion. Aus transforms industrial waste and unused textile remnants into original wearable art pieces (Figure 2), adopting zero-waste design methods in the process. Her work proves that post-industrial waste can be elevated to aesthetic value and that ethical modes of production can be integrated into the fashion industry (Gwilt, 2014, p. 87).

Source: (Aus, R., et al., 2021, p. 11,12,14)

Figure 2. Upcycled dresses (Design: Reet Aus).

These examples show that wearable art is not only a field of formal innovation but also a space for intellectual inquiry. Through upcycling, designers introduce a critical perspective on consumer culture, transforming the fashion object into an ecological, cultural, and artistic narrative medium. Thus, contemporary fashion design is redefined through the principles of sustainability; the garment, beyond being an expression of identity, gains presence as a wearable form of contemporary art.

4. Examples of Innovative Garment Designs Through Upcycling Methods

The increasing visibility of the environmental impacts of fast fashion and the growing global awareness of climate change have prompted fashion consumers to demand transformation within the sector. This situation has led sustainability to become a fundamental strategic priority for fashion brands and has intensified regulatory pressure. One of the practices gaining momentum within the framework of the circular economy approach is upcycling. Upcycling is defined as the transformation of used garments, surplus fabrics, or waste materials into new products through redesign. This method contributes both to reducing waste and to extending the lifespan of products.

Giyi is one of the examples of this approach in Türkiye. The handwoven belt (Image 3, A), produced through the weaving of the brand’s surplus cupro fabrics on handlooms in collaboration with women’s cooperatives, and the reversible denim vest (Image 3, B), designed from surplus denim fabrics, demonstrate how upcycling practices can be integrated with social cooperation and craftsmanship.

A.  B. 

Source: A. https://giyiworld.com/upcycled-giyi-kemer B. https://giyiworld.com/waste-not-yelek

Figure 3. A. Upcycled Handwoven Belt; B. Upcycled Vest by Giyi

Similarly, international brands are also turning toward upcycling-focused collections. The denim skirt featured in Urban Outfitters' *Vintage & ReMADE* collection (Figure 4, A) reflects a craftsmanship-based production approach aimed at reducing waste through the redesign and updating of used garments. The jacket woven from upcycled fabric remnants by KARDO Amardeep (Figure 4, B), along with the dress composed of upcycled denim pieces and produced entirely by hand and made-to-order by the brand E.L.V. Denim (Figure 4, C), represent distinctive examples in which sustainability, circularity, and traditional craftsmanship converge.

A. 

B.  C. 

Source: A. https://www.urbanoutfitters.com/shop/remade-by-uo-gummy-denim-shirt-trim-mini-skirt?color=091&searchparams=q%3Dupcycled%26sayt%3Dtrue

B. https://www.urbanoutfitters.com/shop/kardo-amardeep-upcycled-jacket?color=001&searchparams=q%3Dupcycled%26sayt%3Dtrue

C. https://elvdenim.com/collections/art-of-upcycling/products/dark-blue-denim-dress

Figure 4. A. Upcycled Denim Skirt Designed for Urban Outfitters' Vintage & ReMADE Collection; B. Upcycled Jacket by KARDO Amardeep; C. Made-to-Order Upcycled Denim Dress by E.L.V. Denim.

Another example in which upcycling integrates with cultural heritage is the solo exhibition titled "From Tradition to the Future: The Journey of Upcycling" (Figure 5). Comprising fifteen original garments, the exhibition is grounded in a design approach that brings together the principles of sustainable fashion with traditional weaving culture. The refunctionalization of handwoven Uzbek atlas fabrics and Türkiye's traditional kutnu textiles through their combination with denim—a material widely used in contemporary apparel production— is noteworthy for its emphasis on preserving cultural continuity, sustaining artisanal traditions, and highlighting the transformative potential of modern design.

In this process, drawing on the patterns of the chapan, a traditional outer garment of Uzbekistan, and the kaftan, a historical outerwear form in Türkiye, strengthened the designs' connection to their cultural origins while enabling the reinterpretation of traditional silhouettes through a contemporary sustainability lens. Each garment featured in the exhibition is positioned not merely as a fashion object but as a cultural narrative and an indicator of environmental awareness. In this respect, the exhibition offers a meaningful context at the intersection of sustainability, traditional identity, and contemporary design.

Source: https://gsf.comu.edu.tr/arsiv/haberler/gelenekten-gelecege-ileri-donusum-yolculugu-kisise-r1611.html

Figure 5. Minara Guliyeva, upcycling-themed garments from the solo exhibition *"From Tradition to the Future: The Journey of Upcycling"* (22–29 October 2025), Urgench / Uzbekistan.

When these visuals are evaluated collectively, it becomes evident that upcycling has developed in alignment with both local production practices and the sustainability strategies of global fashion brands. This approach reflects an innovative design understanding that supports waste reduction in the fashion industry, foregrounds craftsmanship, and aims to minimize environmental impacts.

Conclusion

In the field of fashion, sustainability refers to an approach in which items that have lost their value are reintegrated into the life cycle rather than being discarded into the environment throughout their entire lifespan—from production to use and end-of-life. In recent years, interest in sustainable practices within the fashion industry has increased significantly; methods such as upcycling, repair, and redesign offer important economic and environmental advantages. These approaches enhance quality in fashion, contribute creatively to production processes, and encourage more efficient use of resources. In doing so, they enable the industry to move away from a fast-consumption culture and evolve into a more conscious and sustainable structure.

Sustainable fashion not only prioritizes environmental and human health in production processes but also aims to protect workers' rights, animal welfare, and ethical values. Moreover, designing long-lasting products, enabling reuse and recycling, and reducing environmental impact throughout the production–consumption cycle generate positive outcomes for the ecosystem

(Fletcher, 2014, p. 21). In recent years, fashion designers have increasingly produced collections that carry both aesthetic and ecological value by repurposing waste materials and creatively transforming old products. The concept of upcycling that emerges through this approach not only optimizes material use but also aims to develop innovative design solutions and foster a critical perspective on consumption habits (Gwilt, 2014, p. 45).

Upcycling involves reinterpreting old garments, surplus fabrics, or recyclable materials through creative design processes. This process enables both aesthetic and ethical transformation in fashion design. It also has the potential to increase consumer awareness regarding the value and cultural significance of sustainable products. Ultimately, sustainability and upcycling approaches in the fashion industry form the foundation of a holistic design understanding that brings together environmental responsibility, ethical design, and aesthetic innovation (Niinimäki & Karell, 2019, p. 12).

While globalization has led to the spread of similar aesthetic understandings and the weakening of cultural authenticity in fashion, designs rooted in local cultures emerge as a form of resistance against this uniformity. Designers contribute to the reconstruction of local identity by integrating regional motifs, traditional sewing techniques, or symbolic elements with contemporary formal approaches. Thus, fashion becomes a functional tool for preserving cultural memory and strengthening intercultural dialogue. Traditional weaving techniques represent not only an aesthetic form of expression but also an important component of sustainable production. Textiles produced with natural yarns, plant-based dyes, and handcrafting embody values that are both environmentally and culturally sustainable. Contemporary designers draw inspiration from these weaving traditions, combining the technical knowledge of the past with modern production technologies to create innovative designs (Er Bıyıklı et al., 2021, p. 146).

From an upcycling perspective, the reinterpretation of old handwoven textiles, traditional garment pieces, or unused fabric products not only reduces waste but also enables the cultural heritage embedded in these materials to be reproduced in contemporary forms. This approach reintroduces not only the material itself but also the cultural meanings it carries back into circulation.

Today, digital technologies offer powerful tools for preserving and reinterpreting cultural heritage in contemporary fashion design. Through 3D modeling, digital printing, augmented reality (AR), and virtual fashion applications, traditional patterns, fabric textures, and motifs can be digitally reproduced, providing significant advantages for both documentation and integration into the design process (Güngör, 2019, p. 68). Digital reproduction allows cultural heritage to transcend physical boundaries and reach a wider audience. Consequently, traditional crafts are represented not only in museums or local production sites but also on global digital platforms. This supports cultural continuity while enabling the new generation of designers to merge local motifs with digital aesthetics.

Therefore, the convergence of cultural heritage and traditional weaving practices with contemporary fashion design strengthens the principle of sustainability not only from an environmental perspective but also through cultural and ethical dimensions. In this context, upcycling practices form the basis of a holistic design approach that preserves cultural identity, employs technology creatively, and supports aesthetic innovation.

Wearable art represents a creative approach that transforms fashion from a purely functional field of clothing into a form of artistic expression. This concept allows designers to convey their aesthetic, cultural, and conceptual vision through garments, offering the viewer not only a product but also an experience (Bozbıyık & Gülgürler, 2023, p. 70). By blurring the boundaries between art and fashion, wearable art enables creative ideas and social messages to be articulated directly through the body. Today, designers employ wearable art approaches to push aesthetic boundaries, turning fashion items into works of art. For example, the three-dimensional printing and innovative material experiments used in Iris van Herpen's collections exemplify how fashion's visual language can be integrated with art. While Van Herpen uses technology as a tool for artistic expression, her designs also support upcycling and sustainable material use (Smelik, 2020, p. 6). Similarly, Japanese designer Issey Miyake redefined the boundaries between clothing and art through garments inspired by origami and folding techniques. Miyake's designs go beyond functional clothing to offer an aesthetic experience through movement and form (Kawamura, 2018, p. 102).

When wearable art practices combine with upcycling techniques, a design approach emerges that is sustainable both environmentally and aesthetically. Reimagining used textile products, waste materials, or traditional woven pieces as artistic objects not only reduces material waste but also adds cultural and conceptual depth to the design. In this regard, wearable art serves not only as an individual aesthetic experience but also as a means of conveying social and environmental messages. By integrating cultural, artistic, and sustainable values, designers transform fashion into a multilayered expressive domain and introduce new perspectives into contemporary design thinking.

In conclusion, upcycling in contemporary fashion design represents a holistic understanding that transcends the boundaries between sustainability, cultural heritage preservation, technological innovation, and artistic expression. Fashion is no longer merely an aesthetic production field but a form of expression redefined through social awareness, environmental responsibility, and cultural continuity. The innovative garment designs developed through the combined use of upcycling, digital technologies, and local crafts present a future-oriented vision of fashion that is both environmentally conscious and culturally grounded. In this regard, upcycling-based design approaches grounded in sustainable and ethical values play a pioneering role in the transformation of the fashion industry and redefine creative design practice through an ecological and human-centered vision.

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CHAPTER V

INTERNATIONAL SUSTAINABILITY STANDARDS AND PRACTICES IN THE TEXTILE SECTOR

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Introduction

The textile industry, one of the world's largest sectors, has become the focal point of the sustainability agenda due to its substantial environmental and social impacts. The high volume of resource consumption has led to textile manufacturers and brands being observed more closely by both consumers and regulators. As a result of this pressure, integrating sustainability principles into business strategies has shifted from being an optional development to an essential operational step for textile producers and brands.

Research in this area emphasizes the importance of adopting sustainable practices throughout the textile supply chain. Today, the textile and apparel sector must move away from the traditional linear production model to a circular economy. This circular approach focuses on resource efficiency through the 3Rs of sustainability: reusing, recycling, and minimizing waste (Chan et al., 2024). This shift also allows companies to meet the growing consumer demand for eco-friendly products (Hossen et al., 2024). Furthermore, the implementation of advanced technologies, such as smart dyehouses supported by artificial intelligence, has become crucial for significantly reducing resource consumption and environmental impact (Kır et al., 2024).

At this exact point, certification and transparency stand out as two of the most critical components of sustainability in the textile field. Certifications, in particular, play a critical role in verifying the sustainability claims made by companies and promoting accountability. Muñoz-Torres et al. (2022) stated that social life cycle analysis can enhance the verification of corporate claims about sustainability (Muñoz-Torres et al., 2022). Furthermore, these certifications are important for building consumer trust and ensuring that companies adhere to ethical and environmentally responsible practices. Companies that are transparent about their sustainability practices and have reliable certifications tend to attract more environmentally conscious consumers. Similarly, Hossen et al. (2024) noted that the rise in consumer awareness about eco-friendly products has pushed brands to integrate sustainability more diligently into their marketing and operational strategies (Hossen et al., 2024). Shan et al. emphasize that major apparel companies, such as Patagonia, have successfully incorporated sustainability into their supply chains through sustainability certifications (Shen et al., 2017).

Despite these positive developments, the complexity of textile supply chains presents one of the biggest challenges in this area. Haywood et al. (2021) observed that obtaining accurate information on sustainability practices from various stakeholders across the supply chain remains a significant handicap (Haywood et al., 2021). This complexity often leads to "greenwashing," where companies falsely market their products as sustainable without actual actions to support those claims (Nahid-Ull-Islam et al., 2025). Therefore, effective policy development and enforcement are essential to ensure that all sustainability claims are both credible and transparent.

International Sustainability Standards in the Textile Sector

This book chapter examines sustainability standards in the textile and apparel sector under three main categories: Environmentally Focused, Raw Material and Recycling Focused, and Social Responsibility and Ethics Focused standards.

Primary Environmentally Focused Certifications and Standards

Environmental sustainability is defined as the ability to maintain the qualities or attributes valued in the natural and biological environment (Muthu, 2016). Textile processing is a resource-intensive activity involving high consumption of water, chemicals, and energy. Environmentally focused standards aim to reduce the environmental footprint of textile production by minimizing water, energy, and chemical use. The certifications and standards examined within this study are presented in Figure 1.

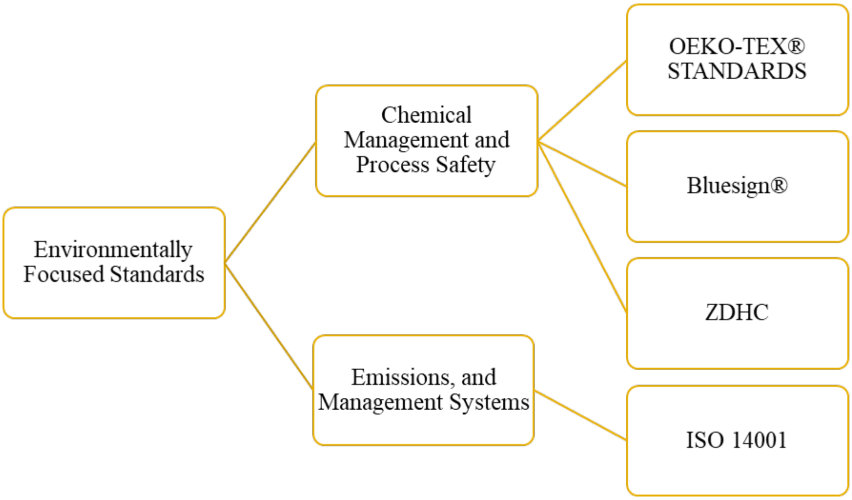

Figure 1. Environmentally focused sustainability certifications and standards examined in this study

OEKO-TEX® Standards

The OEKO-TEX® was established in 1992 to ensure that textile products are harmless to human health through laboratory testing (OEKO-TEX, 2025). It is a modular group of certifications that provides tools for managing and communicating safety, sustainability, and transparency across textile and leather supply chains (Popescu, 2024; OEKO-TEX, 2025). It serves as a global label for raw, intermediate, and finished textile products tested for harmful substances, covering legally restricted and health-hazardous chemicals. Some of the main certification schemes deal with product safety (STANDARD 100), chemical inputs (ECO PASSPORT) and transparent final products (MADE IN GREEN).

- STANDARD 100 is the most recognized label of the OEKO-TEX® Association and primarily focuses on product safety. It certifies that the final product is harmless to human health (Popescu, 2024). The standard includes testing for more than 1,000 harmful substances, including those regulated or prohibited by REACH and CPSIA (Zimon et al., 2020; Vadicherla and Saravanan, 2014; Amutha, 2016). To obtain STANDARD 100 certification, all components of a textile product such as outer fabric, sewing threads, linings, prints, and even non-textile accessories like buttons or zippers must meet the established criteria (Popescu, 2024).
- ECO PASSPORT, introduced in 2016, focuses on the safety of chemicals used in textile and leather production. It aims to verify that chemical products used in manufacturing are not harmful to human health and are environmentally friendly (OEKO-TEX, 2025). It defines technical requirements for the certification of textile chemicals, auxiliaries, and colorants, ensuring that toxic substances are controlled at the input stage (Pant and Kanchi, 2024).
- MADE IN GREEN is a combined label that maximizes consumer transparency and traceability. Products carrying this label must meet both the STANDARD 100 criteria (tested for harmful substances) and be produced in facilities certified under STeP (OEKO-TEX, 2025). Each

MADE IN GREEN product includes a unique ID or QR code that allows consumers to trace the supply chain (Pant and Kanchi, 2024).

Bluesign® System

The Bluesign® System is a globally recognized voluntary eco-label and management system designed for sustainable textile production (Popescu, 2024). It is managed by Bluesign Technologies AG, based in Switzerland (Lee, 2016). Using the Input Stream Management approach, it prevents hazardous chemicals from entering the production process at the outset, thereby reducing environmental impact at the source (Plakantonaki et al., 2023; Pant and Kanchi, 2024). This approach contrasts with the traditional "end-of-pipe" testing model by requiring the use of safer chemicals, materials, and processes throughout production.

ZDHC - Zero Discharge of Hazardous Chemicals Program

The ZDHC Program elevates industry standards by enforcing the zero discharge of hazardous chemicals during textile processing (Pant and Kanchi, 2024). It compels the footwear and apparel industries, along with their suppliers and subcontracted facilities, to eliminate the release of toxic substances into global water systems (Vadicherla and Saravanan, 2014). ZDHC was established as a direct response to campaigns by non-governmental organizations, particularly the Greenpeace Detox Campaign, which highlighted the issue of toxic chemical use and discharge in textile manufacturing

(Pant and Kanchi, 2024). Launched in 2011, the initiative is best known for its "Roadmap to Zero Programme", aiming for a fundamental transformation in chemical management across the industry (ZDHC, 2025).

ISO 14001 - Environmental Management System

ISO 14001, developed by the International Organization for Standardization (ISO), is a Environmental Management System (EMS) standard. The standard offers an organizational structure that allows companies to enhance their environmental performance, meet all legal and mandatory requirements, and successfully reach their stated ecological goals (ISO, 2025). By managing resources, energy, and waste more efficiently, ISO 14001 helps reduce costs and optimize production processes. It can lead to reductions in packaging, raw material, energy, and water consumption, while also strengthening corporate image and attracting customers and business partners (Amutha, 2016).

Raw Material and Recycling Focused Certifications

In the global textile sector, raw material selection, organic farming practices, and the reintegration of waste materials into the production cycle (recycling) play a critical role in achieving sustainability. These standards allow the verification of organic or recycled material content in products, thereby ensuring transparency and traceability throughout the textile supply chain. Figure 2 presents the certifications and standards examined within this study.

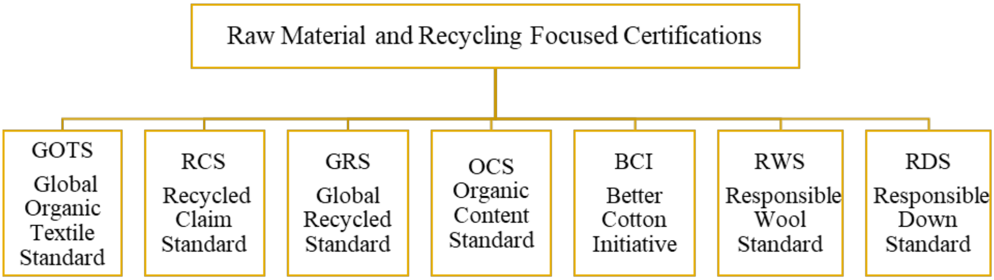

Figure 2. Raw Material and Recycling Focused Certifications Examined in This Study

GOTS -Global Organic Textile Standard

The Global Organic Textile Standard (GOTS) is a globally recognized standard for organic fibers that integrate both ecological and social criteria (Popescu, 2024). Its main focus is to ensure environmental and social responsibility throughout the supply chain, from raw material harvesting to the final product (GOTS, 2025; Intertek, 2025). It guarantees the organic status of textiles through environmentally friendly waste management, fair labor practices, and the prohibition of toxic dyes (Popescu, 2024). GOTS requires products to contain at least 70% organic fibers and prohibits the use of toxic chemicals (Pant and Kanchi, 2024). It also enforces strict social criteria based on International Labour Organization (ILO) conventions, including fair wages, safe working conditions, and the prohibition of child labor.

RCS - Recycled Claim Standard

The Recycled Claim Standard (RCS) is a chain-of-custody standard used to track recycled raw materials throughout the supply chain (Amutha, 2016). It is based on the principle of traceability and verifies the presence and amount of recycled material in a product (Textile Exchange, 2025a). RCS certified products must contain at least 5% recycled content. The standard focuses solely on material content; it does not address environmental aspects of processing (such as energy, water, or chemical use), product quality, social issues, or legal compliance (Amutha, 2016).

GRS - Global Recycled Standard

The Global Recycled Standard (GRS) was originally developed by Control Union and transferred to Textile Exchange in 2011 (Borsacchi, 2025). GRS is a more comprehensive and stringent standard than RCS. In addition to verifying recycled material content, it evaluates the environmental and social responsibility of production processes (Textile Exchange, 2025a). It includes requirements such as chemical restrictions, wastewater management, and social criteria aligned with ILO conventions. GRS applies to products containing at least 20% recycled content, but to carry the GRS label, products must have a minimum of 50% recycled content (Pant and Kanchi, 2024).

OCS - Organic Content Standard

The Organic Content Standard (OCS) was developed by Organic Exchange and is now managed by Textile Exchange

(Amutha, 2016). Its primary aim is to verify the presence and amount of organic material in a final product (Textile Exchange, 2025b). The OCS provides a transparent, consistent, and independent third-party certification process to confirm organic material claims (Control Union, 2025). It applies to non-food products containing 5% to 100% organic material (Almeida, 2014). Unlike GOTS, OCS does not assess environmental or social criteria during production, it solely verifies the organic origin of the material.

BCI - Better Cotton Initiative

The Better Cotton Initiative (BCI) is a global program designed to promote more responsible cotton farming practices (Saygılı et al., 2019). It aims to reduce the environmental and social impacts of cotton production through farm-level improvement programs (Better Cotton, 2025). BCI provides training and capacity-building for farmers on sustainable cotton cultivation and footprint reduction (Birkocak et al., 2023). The initiative seeks to establish an environmentally friendly and socially responsible agricultural model for sustainable cotton production. BCI is based on seven core principles:

1. Crop Protection Practices
2. Water Stewardship
3. Soil Health
4. Biodiversity and Responsible Land Use
5. Fiber Quality
6. Decent Work

7. Management Systems (Better Cotton, 2025)

RWS - Responsible Wool Standard

The Responsible Wool Standard (RWS) is developed by Textile Exchange through an open, multi-stakeholder process (Amutha, 2016). It aims to ensure the welfare of sheep and the sustainable management of grazing lands throughout the wool supply chain. The standard requires that sheep are treated according to the Five Freedoms of animal welfare and strictly prohibits mulesing practices. It also promotes land management practices that protect soil health and biodiversity (Textile Exchange, 2025c). Chain of Custody certification is required from the farm to the final product, allowing consumers to verify that the wool used is truly RWS certified (Amutha, 2016). The use of wool fibers certified under RWS and the Sustainable Wool Standard (SCWS) increased between 2022 and 2023 (Gupta, 2025).

RDS - Responsible Down Standard

The Responsible Down Standard (RDS) is owned and managed by Textile Exchange. It ensures that ducks and geese from which down and feathers are sourced are treated humanely (Amutha, 2016). Live-plucking and force-feeding are strictly prohibited. Similar to RWS, the standard requires compliance with the Five Freedoms of animal welfare and maintains full Chain of Custody traceability from farm to final product (Textile Exchange, 2025d).

Social Responsibility and Ethically Focused Standards

This book chapter also examines the main global certifications and standards that monitor and report on labor rights, fair working conditions, and ethical practices in the textile supply chain (Figure 3).

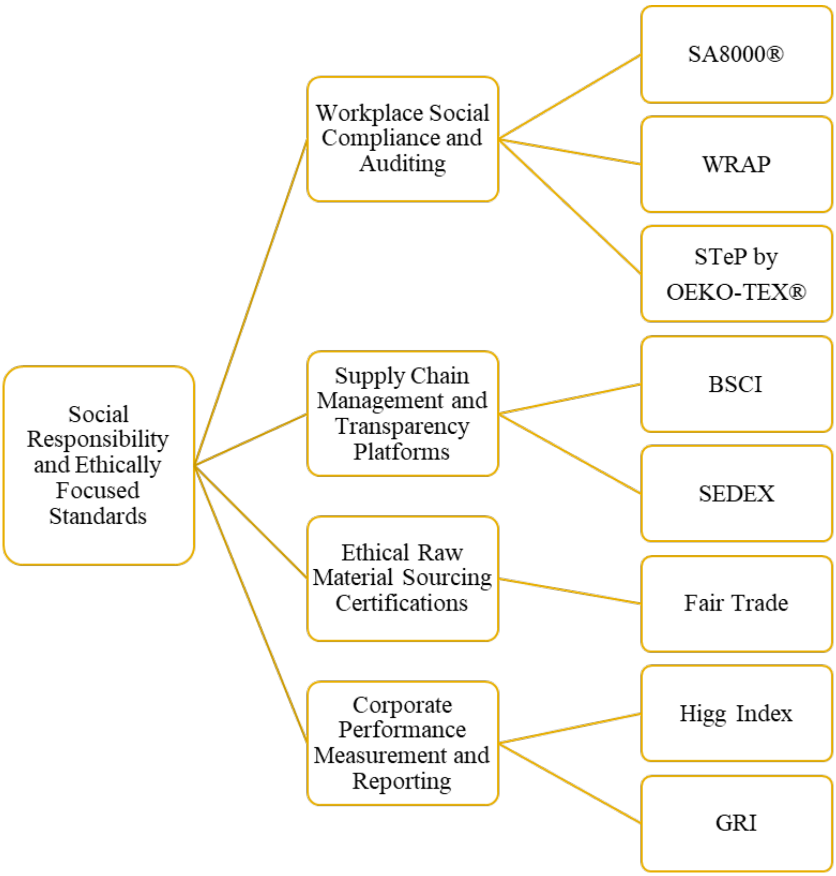

Figure 3. Social Responsibility and Ethically Focused Standards Examined in This Study

SA8000® -Social Accountability 8000

The SA8000® standard is based on the principles of universal human rights and the conventions of the International Labour Organization (ILO) (Borsacchi, 2025). It is an auditable management system standard that certifies suppliers such as factories, farms, and other workplaces. The certification does not apply directly to brands or retailers (SAI, 2025; Project Cece, 2025). SA8000 addresses nine key labor areas: child labor, forced labor, health and safety, freedom of association and collective bargaining, discrimination, disciplinary practices, working hours, remuneration, and management systems (Textile Standards, 2025). Certification of management systems according to international standards such as SA8000 has become almost essential for operating in global markets (de Abreu, 2014).

WRAP - Worldwide Responsible Accredited Production

WRAP is a factory-based certification program focused on ethical and legal production in facilities that manufacture apparel, footwear, and sewn products. In other words, it is a social compliance accreditation specifically designed for garment manufacturers (Walter and Pethile, 2025). It has become the largest factory-based certification program in the world, recognized by hundreds of global brands and retailers (WRAP, 2025). WRAP certification is required for textile companies exporting to the U.S. market, and its acceptance within the EU is also increasing (Walter and Pethile, 2025). The program is structured around 12 core principles, including:

compliance with laws and regulations, prohibition of forced and child labor, prevention of harassment and abuse, health and safety, freedom of association, non-discrimination, working hours, compensation and benefits, customs compliance, and security (WRAP, 2025).

STeP - Sustainable Textile Production by OEKO-TEX®

STeP by OEKO-TEX® is a modular certification system for textile and leather production facilities that evaluates their sustainability performance rather than the final product itself. Certification is awarded at three levels depending on the degree of sustainable production and working conditions: Level 1 – entry level; Level 2 – good implementation with potential for further optimization; Level 3 – exemplary implementation (Amutha, 2016). STeP serves as a tool for brands, retailers, and manufacturers to communicate their sustainability achievements to the public in a transparent and credible way (Vadicherla and Saravanan, 2014).

BSCI -Business Social Compliance Initiative

The Amfori BSCI is part of a group of ethical sourcing and production standards. It is a system designed to help companies progressively improve working conditions within their supply chains (Warasthe et al., 2020). BSCI focuses on social responsibility themes such as fair trade practices, safe working conditions, gender equality, elimination of child labor, and corporate responsibility (Pant and Kanchi, 2024).

SEDEX -Supplier Ethical Data Exchange

Sedex is a global platform established to promote transparency, ethical practices, and sustainability within supply chains. It helps organizations strengthen their commitment to social and ethical responsibility (Sedex, 2025). Sedex supports companies in managing and monitoring environmental and social sustainability information across the supply chain (Chkanikova and Kogg, 2018). The SMETA (Sedex Members Ethical Trade Audit) methodology was developed for Sedex members as a tool to assess performance related to ethical and social responsibility within supply chain operations (Sedex, 2025).

Fair Trade Certification

Fair Trade Certification represents an ethical alternative to conventional trade systems. It aims to ensure better trading conditions for producers, promote sustainability, and guarantee fair wages. Fairtrade commits to reducing poverty and improving the living conditions of farmers and workers in developing countries (Vadicherla and Saravanan, 2014; Walter and Pethile, 2025). By prioritizing social and economic justice, it seeks to empower producers in developing economies (Fair Trade, 2025). A Fairtrade Minimum Price is established to cover the sustainable cost of production and enable social development within producer organizations (Vadicherla and Saravanan, 2014).

Higg Index -Social/Labor Module

The Higg Index is a comprehensive assessment tool developed to measure the environmental and social impacts of apparel production. It was first introduced as Higg Index 1.0 on June 26, 2012, and later updated to Higg Index 2.0 (HowtoHigg, 2025). The Social/Labor Module is a component of both the Brand and Facility tools of the Higg Index. It evaluates various social and labor practices within a manufacturing facility, including compensation, working hours, worker participation and communication, treatment and development, and health and safety (Radhakrishnan, 2014). This module enables companies to accurately measure and benchmark sustainability performance, supporting meaningful improvements that protect workers, communities, and the environment (Pant and Kanchi, 2024).

GRI (Global Reporting Initiative) Standards

The Global Reporting Initiative (GRI) Standards are globally recognized frameworks for sustainability reporting (WBA–GRI, 2024). They help organizations identify and manage their economic, environmental, and social impacts, thereby enhancing transparency and accountability toward stakeholders (de Abreu, 2014). The World Benchmarking Alliance (WBA) collaborates with GRI to advance corporate accountability and analyze the relationship between reporting and social performance (WBA–GRI, 2024).

Challenges and Criticisms of Certification

Sustainability certifications in the textile industry play a crucial role in raising environmental and social standards. However, the complexity of these certification systems and the operational changes they require also bring significant challenges. The textile supply chain is highly fragmented and layered spanning raw material producers, spinners, weavers, dye houses, and garment manufacturers, which makes it difficult to trace certified materials accurately. Additionally, the transfer of certified material quantities from one stage of the supply chain to another carries the risk of errors and manipulation.

These certification systems also create cost and implementation barriers for small and medium-sized enterprises (SMEs). Although SMEs make up a large portion of the global textile supply chain, they often face the risk of exclusion due to the heavy financial and administrative burdens of certification (Shenglufashion, 2025). The most significant obstacle for SMEs is the high financial cost of certification. In addition to the initial certification fees, annual audits, licensing costs, and mandatory technological upgrades impose further expenses.

Another major issue is the proliferation of eco-labels that appear similar but have unclear or inconsistent meanings. Because these labels rely on different methodologies and standards, consumers find it difficult to interpret and compare them effectively. This leads to information overload, confusion, and uncertainty (Popescu, 2024).

A prominent criticism in this context is greenwashing; the deceptive use of green marketing to create the false impression that a company's products, goals, or policies are environmentally friendly (Roy Choudhury, 2014). Companies may use limited certifications, such as those verifying only chemical safety, to market products as fully sustainable. When such practices are exposed, consumers tend to lose trust not only in those specific brands but also in sustainability claims in general (Kallevig and McQuillan, 2025).

Conclusions

This book chapter has examined the main international standards and certification systems that have emerged alongside the growing importance of sustainability in the textile and apparel sector. The most widely used certifications were introduced, and the fundamental challenges and criticisms associated with certification processes were discussed.

The textile industry faces a delicate balance between its economic significance and its severe environmental and social impacts. To overcome these challenges, there is an urgent need to transition toward circular economy based sustainable practices. Within this transition, reliable certification systems serve as essential guiding instruments. However, the absence of a globally unified sustainability framework has led to inconsistent regulations and standards across jurisdictions. These inconsistencies hinder harmonization and allow companies operating in regions with weaker regulations to gain unfair competitive advantages. To address this issue, international organizations and governments must collaborate to establish uniform global standards that ensure accountability and equitable sustainability practices across the textile supply chain.

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CHAPTER VI

TRANSMISSION TRADITIONAL HANDICRAFTS TO THE YOUNGER GENERATIONS IN THE 21st CENTURY

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Abstract

Traditional handicrafts in Turkey have developed throughout history across a broad spectrum from palace culture to folk traditions, however this heritage has come under threat due to globalization and the rise of consumer culture. This study analyzes the challenges encountered in transmission intangible cultural heritage to younger generations and offers solution-oriented approaches through digital technologies, educational institutions, social activities, and international perspectives. The interactive use of digital tools and social media platforms, project-based and game-based approaches in education, the contributions of civil society, and family-centered transmission processes are discussed in terms of the sustainability of cultural heritage. In addition, by comparatively examining practices in countries such as Japan, India, Italy, and Mexico, models specific to Turkey are proposed. Consequently, it is emphasized that holistic, innovative, and culturally sensitive methods should be adopted in transmission traditional handicrafts to younger generations.

Keywords: Traditional Arts, Digitalization, Sustainability, Education, Younger Generations

Introduction

The lands of Anatolia have hosted countless civilizations throughout history, and the rich handicraft heritage blended with this accumulation has reached the present day, acquiring a unique identity of its own. Handicrafts are products based on knowledge and skill, created manually or with simple tools especially using natural raw materials and reflecting the emotions, thoughts, and abilities of individuals who embody the culture, traditions, and customs of their society (Onuk and Akpınarlı, 2005, p. 27). Generally produced with local materials and techniques, handicrafts should not be regarded merely as aesthetic objects; they should also be considered heritage elements that convey a community's cultural identity, values, and ways of life. Indeed, handicrafts in Turkey do not merely bear traces of the past but also offer an aesthetic and cultural connection to contemporary society. As one of our cultural riches, handicrafts represent the totality of values created by society (Özdemir, 2009, p. 73). Within this framework, handicrafts are viewed as a significant means of ensuring cultural sustainability and transmission heritage to new generations. The value of traditional handicrafts, particularly in terms of safeguarding intangible cultural heritage, is also emphasized by the "Convention for the Safeguarding of the Intangible Cultural Heritage" adopted by UNESCO (Arıoğlu and Atasoy, 2023, p. 28; Fedakar and Kuzay Demir, 2018, p. 95; Akyıldız, 2023, p. 95; Bayraktar, 2014, p. 22).

Traditional Turkish handicrafts bring to mind not only visual arts such as *tezhip* (illumination), *ebru* (marbling), *hat* (calligraphy), and *miniature painting*, but also applied arts including carpet weaving, kilim embroidery, ceramics, and tile making. Originating from traditional production methods, these crafts have at times evolved into the refined and distinctive workmanship of the palaces, while at other times diversified into functional products that served the daily lives of the public. Each of these arts has been transmitted from generation to generation through the master apprentice tradition, reaching the level of richness it enjoys today. Over centuries, changing living conditions have transformed some handicrafts, while others have disappeared over time. Despite this, in our lands enriched by diverse cultural heritage, these traditions continue to be passed down from generation to generation through innovative and modern interpretations that extend beyond their traditional fields of use. The handicraft heritage of Turkey also stands out for its efforts to preserve local characteristics and maintain its uniqueness in the face of globalization. Today, the transformations brought by modern life and the concept of a consumer culture surrounding society have created an environment where every material is used for a short time and quickly replaced by new products resulting in a context in which everything is consumed rapidly. In this environment, people tend to show reluctance toward consuming objects that carry spiritual or emotional meaning, yet they simultaneously fall into an insatiable cycle of consumption driven by the desire to constantly acquire new things. Because this situation threatens the future of traditional handicrafts, issues such as their promotion, education, and integration into daily life have gained importance. Moreover, the fact that handicrafts have often been evaluated by fields such as sociology, literature, politics, art history, history, and folklore but without sufficient emphasis on their connections to culture, economy, and industry has led to an incomplete understanding of their broader significance. This shortcoming also reveals the orientation of conventional and "traditionalized" cultural evaluations. Furthermore, producing new works inspired by traditional crafts and ensuring their functional use can contribute to regional development and employment opportunities. Handicrafts, as values that originate from our roots and nourish us spiritually, become preferred when presented in a functional manner. As long as handicrafts are not merely regarded as a means of addressing unemployment among low-income individuals but are instead presented from a national perspective to the global sphere, their permanence will be ensured. When handicrafts are restructured and properly planned, they will remain among the sustainable arts (Oğuz, 2002, p. 10).

This study not only identifies the challenges encountered in transmission traditional handicrafts to younger generations but also aims to develop solution proposals by drawing on examples from different countries. It also examines how cultural heritage is reinterpreted in the digital age and how it establishes a connection with young individuals. Developing strategies specific to Turkey by taking successful cultural heritage transmission practices from other countries as examples is significant both for ensuring the sustainability of traditional handicrafts and for promoting these values on a global scale.

Challenges in the Transmission of Traditional Handicrafts Across Generations

In the transmission of traditional handicrafts to younger generations, it is of great importance not only to develop effective methods but also to understand the various structural and socio-cultural challenges that hinder this process. The fact that individuals born after the year 2000 have grown up surrounded by digital technologies has led this generation to use the internet and technological tools extensively; this situation has continuously increased the potential for utilizing digital technologies (Barış and Emre Kaya, 2025, p. 1150). However, while today's youth grow up in a rapidly digitalizing and constantly changing world, they may view traditional forms of production as uninteresting or "old." In particular, the short attention spans of Generation Z individuals, their tendency to access information superficially, and their habits of rapid consumption make it difficult to transmit cultural values such as handicrafts, which require patience and labor.

Another significant challenge is the considerable weakening of the traditional master–apprentice relationship within modern lifestyles. Once the cornerstone of handicrafts, this model of learning has now been largely replaced by formal education systems; however, during this transition, the accumulation of practical knowledge and the process of cultural transmission have substantially diminished. The declining social status of the concept of mastery is among the factors that reduce young people's motivation to pursue these fields. In response to this issue, individuals who have achieved mastery in traditional crafts such as ceramics, felt making, and weaving are officially recognized and made visible in Turkey through the "National Inventory of Living Human Treasures" initiative (UNESCO, 2023). Yet even this mechanism cannot solve all problems related to transmission and remains insufficiently functional, especially due to the indifference of younger generations and the influences of modern lifestyles.

Furthermore, the economic sustainability of traditional handicrafts constitutes another major issue in the transmission process. Considering the production time, cost, and market value of artistic works, working in this field is not perceived as an attractive career path for young people. Particularly in rural areas, as young individuals interested in these arts migrate to urban centers, masters of handicrafts are unable to pass on their knowledge to new generations. Indeed, it has been reported that in Eastern Turkey, traditional handicrafts have been steadily declining due to a decrease in the number of masters, lack of interest among young people, and unfavorable working conditions (Gumus Ciftci and Walker, 2017, p. 13).

The breakdown of intergenerational cultural transmission within families—specifically, the inability of grandparents to convey their experiences to younger generations—also represents a major problem. Traditional handicrafts embody not only technical knowledge but also a way of life, an ethical stance, and a cultural context. The withdrawal of this context from everyday life renders the transmission process superficial. According to the "Designers Meet Artisans" guide, developing sustainable business models between artisans and designers can open new pathways for the transmission of cultural heritage. Such collaborations enable both the reinterpretation of products through innovative approaches and the strengthening of the social status of artisans (UNESCO, 2005).

Finally, the limited amount of time allocated to cultural heritage and handicrafts within today's education system, the predominantly theoretical nature of the courses, and the insufficient qualifications of teachers further exacerbate these challenges. When all these factors are considered together, it becomes evident that ensuring the sustainability of traditional handicrafts requires not only promotion and education but also the transformation of social perceptions and the development of structural policies.

Method and Target Audience

This study discusses the methods proposed for transmitting the elements of the Intangible Cultural Heritage (ICH) to younger generations and for increasing awareness in this field. The main focus of the study is to develop innovative and sustainable approaches in the process of preserving and disseminating cultural heritage.

The target audience consists of younger individuals studying at preschool, primary, secondary, and higher education institutions. Various methods are proposed by taking into account the readiness and knowledge levels of young people at these different educational stages. At the core of the proposed methods lies the use of tools suited to the interests and habits of young people raised in the digital age. In this context, digital tools and social media platforms—which occupy an important place not only in the lives of young people but also in the everyday life of society as a whole—are considered strategic instruments in the process of cultural transmission. The opportunities provided by digital environments allow traditional handicrafts to be presented in a visual, interactive, and participatory manner; this, in turn, enhances young individuals' interest in cultural values and makes the learning process more dynamic.

Transmission Strategies for Younger Generations

Various methods are proposed for the transmission of Intangible Cultural Heritage (ICH) to future generations. These methods are evaluated under four main categories: digital applications, educational institutions, social activities, and best practices derived from international approaches.

Digital Applications

Communication and technological advancements directly and indirectly influence cultural values, which are in constant change and transformation depending on living conditions (Rzayeva, 2018, p. 53). In the process of transmitting Intangible Cultural Heritage (ICH) to younger generations, digital tools, simulations, and social media platforms play an active role. The integration of digital technologies into young people's daily lives makes it possible to strategically use these tools for the transmission of cultural values. Digital content prepared according to the educational levels of young people can increase participation in traditional arts, while visually rich and interactive materials can support the learning process and raise awareness. Presenting ICH elements through digital games and augmented reality (AR) applications attracts the interest of younger audiences. The easy accessibility of mobile applications compatible with Android and iPhone Operating Systems (iOS) can enhance young people's awareness and foster the establishment of both individual and collective cultural connections. Through a mobile application that introduces Anatolian motifs used on textile surfaces, as illustrated in Figure 1, users can access information such as the history, definition, and meaning of the motifs, as well as the opportunity to design them digitally (OpenAI ChatGPT, 2025).

Figure 1. Anatolian Motif Generated by Artificial Intelligence (OpenAI ChatGPT, 2025)

In this context, projects such as the "Digital Archive of Intangible Cultural Heritage," implemented by the Ministry of Culture and Tourism, serve as significant examples of transferring traditional handicrafts into digital environments. Through this archive, young users can access handicrafts categorized by region in digital format; these presentations, supported by visual and auditory content, facilitate learning. Similarly, in the field of fashion design today, augmented reality (AR) technologies are utilized to digitalize and reinterpret cultural motifs. This virtual universe, which aims to provide a three-dimensional digital world, is regarded as a new form of interaction in which the physical and digital worlds merge (Abanazoğlu and Değerli, 2022, p. 469). For example, with AR applications such as Tilt Brush, students can carry out their designs on virtual mannequins, thereby enhancing their creative expression skills (Figure 2). Such technologies contribute to integrating cultural heritage into the modern fashion world while also becoming inspiring tools for young designers (Ağca and Kozbekçi Ayranpınar, 2021, p. 5).

Figure 2. Tilt Brush Fashion (VRScout, 2016)

At the same time, the works of contemporary fashion designer Dilek Hanif (Figure 3) present remarkable examples of how traditional handicrafts are reinterpreted in the digital age. In her couture collections, Hanif blends traditional techniques such as needle lace, *tel kırma* (metal thread embroidery), and *suzani* with a modern aesthetic understanding, thus connecting cultural heritage with younger generations through contemporary fashion. Through tools such as digital presentation techniques, social media promotions, and AR-supported fashion shows, traditional arts are made visible once again via fashion. Such practices play a role not only in enhancing artistic value but also in strengthening cultural memory. The integration of traditional textures into design processes serves as a source of inspiration for young designers and demonstrates how effectively the opportunities of the digital age can be utilized for the sustainability of cultural values.

Figure 3. Dilek Hanif Collection (www.dilekhanif.com, 2025)

Dilek Hanif's design shown in Figure 4 demonstrates not only the art of embroidery but also how traditional silhouettes can be harmonized with a contemporary understanding of fashion.

Figure 4. Dilek Hanif Bindallı Design
(www.dilekhanif.com, 2025)

On social media platforms that are widely used by younger generations (such as Instagram, TikTok, YouTube, Twitter, and Facebook), short videos, viral content, posts, stories, and hashtags increase the visibility of Intangible Cultural Heritage (ICH), raise awareness levels, and help make it popular among youth. Another effective technique for attracting the attention of younger audiences is to make use of current trends. Traditional copper craftsmanship, for instance, can be adapted to modern fashion by incorporating it into contemporary jewelry designs (Figure 5) or interior decoration, allowing the aesthetic and functional features of traditional handicrafts to be reinterpreted in line with today's styles.

Figure 5. Modern Copper Jewelry Set
(www.zeynepbuyukbay.com, 2025)

Presenting cultural heritage through digital technologies with appropriate strategies not only increases young people's level of awareness but also contributes to the development of their sensitivity toward these values. Therefore, digital platforms hold strong potential for ensuring the sustainability of traditional handicrafts. Interaction through modern tools offered on digital platforms strengthens the consciousness of preserving this cultural heritage among young people. In 2016, Pera Museum collaborated with BlippAR to implement a project that presented augmented reality (AR) applications on selected works from its Orientalist collection (Figure 6). Through this experience, visitors were able to scan artworks using an application installed on their mobile devices, access digital content, and interact with art in an engaging, interactive manner. This example demonstrates how augmented reality technology can serve as an effective tool for conveying cultural heritage to diverse audiences (Uluğ, 2020, p. 90).

Figure 6. A scene from the Pera Museum AR experience (https://bit.ly/3wBKZeg, 2025)

Educational Institutions

Educational institutions hold a central role in preserving the heritage of traditional handicrafts and transmitting this heritage to future generations. They are also the primary entities that create and offer the most effective platforms for sustaining and passing down cultural heritage. The innovative methods employed in today's education systems serve as essential tools in this regard. Courses and departments themed around traditional arts, integrated into the curriculum, not only enable younger generations to become more familiar with Intangible Cultural

Heritage (ICH) but also help students develop respect for diverse cultural elements and broaden their perspectives. In addition, through the inclusion of game-based learning practices in curricula, students can learn while having fun and engage in project-based activities that allow them to reinterpret traditional handicrafts creatively and participate actively in the process. In this context, the participation of young people in activities aligned with sustainable development goals highlights their crucial role in this field (Altunsabak, 2016, p. 21).

It is emphasized that the transmission of cultural experiences and knowledge from elderly individuals to younger generations makes cultural roots more comprehensible and reinforces the sense of identity (Shih and Tseng, 2025, p. 78). The contributions of educational institutions in this regard are not limited to individual achievements; they also serve to strengthen cultural awareness and shared values across society. Indeed, educational institutions act as a bridge for the future development of traditional arts, encouraging young people to understand the evolution of these arts and adapt them to contemporary conditions, thereby aiming to sustain cultural heritage in the modern world. Therefore, diversifying the methods used in education and expanding their scope is of critical importance for ensuring the sustainable transmission of traditional handicrafts into the future. Structuring educational content in accordance with age groups and educational levels stands out as a key factor in increasing students' interest and participation. At the primary education level, integrating fun, game-based applications supported by visual elements can facilitate the adoption of cultural heritage elements by young individuals. Storytelling, puppet shows, drama activities, and interactive games can make the learning process more engaging, particularly for preschool and primary school students. These methods not only support children's imagination but also accelerate their recognition and internalization of cultural values while encouraging active participation in cultural narratives and themes. As a result, the information learned is retained in memory for a longer time.

In secondary education, more analytical approaches and project-based studies are encouraged to allow students to explore these arts in their own creative ways. Reward systems and enjoyable competitions increase young people's active participation in the learning process while creating a dynamic environment that promotes learning. Another effective approach is the inclusion of hands-on workshops inspired by local traditions. Experiencing traditional handicraft activities within the classroom enables students to engage with these values in both tactile and visual ways.

The traditional handicraft workshops organized within the scope of the "Children Adding Value to Their Culture" project held in Bolu clearly demonstrate the impact of such practices on children (Bolu Provincial Directorate of National Education, 2025). Accordingly, hands-on workshop activities such as glass craftsmanship—based on traditional production techniques—

serve as effective tools that allow students to directly engage with cultural values (Figure 7). Such activities, especially for individuals with a strong visual-spatial learning tendency, serve as an important bridge in the internalization of cultural heritage.

Figure 7. "Children Adding Value to Their Culture" project (bolu.meb.gov.tr, 2025)

At the university level, projects conducted in this field make significant contributions both academically and socially to the preservation, documentation, and digitalization of Intangible Cultural Heritage (ICH). In this way, students are encouraged to design their own projects, thereby enhancing their creative thinking and problem-solving skills. In particular, the research and detailed archiving of traditional handicraft elements play a critical role in transmitting cultural values to future generations. To achieve this, students should be encouraged, course materials should be enriched, and teachers should be provided with the necessary training and resources.

Including cultural actors such as masters of traditional handicrafts in these projects enables students to learn about cultural heritage not only theoretically but also through direct experience. Organizing cultural events can further enhance this process by improving students' organizational skills and encouraging public participation. Another alternative to make project activities more effective is to organize field studies that allow students to gain hands-on experience. Through cultural workshops, students can interact directly with local communities and learn by observing the practical applications of traditional crafts that have survived from past to present (Figure 8).

Such an approach not only increases students' cultural awareness but also fosters a collective consciousness regarding the preservation of these values. In this way, handicrafts cease to exist merely as traditional "authentic" products and are transformed into "functional/practical" objects. The sustainability and revitalization of traditional handicrafts stand as examples showing that tradition and modernity should not be considered opposites but rather complementary concepts (Gürçayır Teke, 2017, p. 72).

Figure 8. Traditional Handicrafts Workshop Event at Iğdır University. (www.igdir.edu.tr, 2024).

Finally, bringing together students from different countries through international collaborations can enable cultural heritage projects to be addressed from a broader perspective. In this way, while young people introduce their own cultural heritage, they also have the opportunity to encounter other cultures and deepen their understanding of tolerance and cultural diversity. These findings reveal that educational institutions play a significant role in the transmission of Intangible Cultural Heritage (ICH) through active learning methods. It becomes clear that active participation serves as a powerful tool in increasing young people's interest in traditional handicrafts and fostering awareness of the need to preserve this heritage.

Social Activities

Families, non-governmental organizations, and local administrations play a major role in transmitting traditional handicrafts to future generations. Fairs, festivals, symposiums, talks, conferences, panels, promotional meetings, workshops, and artistic events should be encouraged as effective means of bringing together different segments of society to ensure the preservation and transmission of traditional handicraft heritage. Organizing such events and ensuring the participation of local communities can help reach broader audiences, increase the visibility of cultural heritage, and contribute to the preservation of regional identities. These activities serve as effective tools for raising cultural awareness and fostering young people's interest in these values. In particular, workshops that ensure the active participation of youth provide a hands-on learning environment for the transmission of cultural heritage (Figure 9). Workshops create awareness both at the individual and societal levels and should be considered as vital instruments for the sustainability of cultural heritage. Moreover, exhibitions organized during these events introduce different dimensions of cultural heritage and create important opportunities for social interaction and unity within the community.

Figure 9. "Hâlkâr" Workshop at Muş Alparslan University (www.alparslan.edu.tr, 2024).

Cultural activities organized by non-governmental organizations and the Ministry of National Education (MoNE) enable an increase in social awareness. Therefore, events that encourage the participation of young volunteers can be effective in promoting the dissemination of cultural heritage. The courses and training programs organized by MoNE on traditional arts contribute to the development of both the knowledge and skills of participants (Figure 10).

Figure 10. MoNE Public Education Course

In addition, families play a successful role in naturally transmitting cultural values to their children in daily life. Encouraging children to practice the handicrafts they observe from their elders can be one of the most effective methods for sustaining this heritage. All these collaborations present a holistic approach to preserving traditional handicrafts and transmitting them to future generations.

The Transmission of Traditional Handicrafts: International Approaches

In many countries around the world, exemplary practices aimed at preserving and transmitting Intangible Cultural Heritage (ICH) to younger generations can serve as valuable sources of inspiration for Turkey. In these countries, cultural heritage is regarded not merely as a relic of the past however as an integral part of contemporary identity, supported through creative and innovative methods.

Japan is one of the leading countries in preserving traditional arts. Masters known as "Cultural Treasures" are supported both economically and socially through state-sponsored programs (Figure 11). In schools, art forms such as origami, ikebana, and kintsugi are taught as part of the curriculum. Additionally, in Japan, cultural objects are being digitized through AR technology. As an example of this system, Japan's "Living National Treasure" protocol provides official recognition and financial support to master artisans, thereby encouraging them to sustain their artistic production and transmit their knowledge to younger generations (UNESCO, 2023; Agency for Cultural Affairs, 2021).

Figure 11. "Cultural Treasure" Project (Shih ve Tseng, 2025).

In India, traditional textile arts such as block printing and ikat weaving are actively taught both in handicraft markets and within design departments at universities. Design schools encourage young people to engage in this field by integrating traditional techniques with modern fashion concepts (Figure 12).

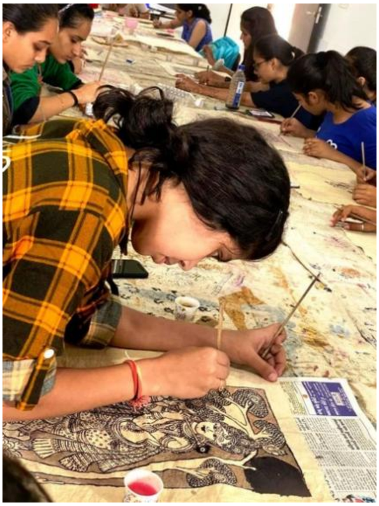

Figure 12. Block Printing Technique (Pinterest, 2025).

In Italy, local festivals and workshop events are organized to keep the art of glassmaking alive, supporting both tourism and cultural awareness. Young artists ensure the continuity of these crafts by creating contemporary products using traditional techniques (Figure 13). In addition, in Italy, UNESCO-supported “Living Heritage” programs have revitalized the master–apprentice models.

Figure 13. “The Italian Glass Weeks” Festival (Live Venice, 2024)

Mexico organizes cultural camps in the Oaxaca region that bring together local residents, students, and tourists to sustain traditional ceramic and weaving arts (Figure 14). In these camps, participants receive hands-on training directly from local artisans, allowing them to interact closely with cultural heritage.

Figure 14. Ceramic Workshop in Oaxaca (Get Your Guide, 2025)

These examples demonstrate that cultural heritage should not only be preserved but also continuously reinterpreted and reproduced. Similarly, in Turkey, integrating handicrafts into the education system and connecting them with other fields such as tourism, economy, and digitalization can help younger generations establish a stronger connection with these values.

Conclusion

This study aims to present innovative solutions for transmitting the heritage of traditional handicrafts to younger generations and raising awareness of this heritage. It offers recommendations for developing methods that will attract the interest of the younger generation and increase their participation to ensure the sustainability of traditional handicrafts.

- ❖ Since digital tools and social media platforms are an integral part of young people's daily lives, they serve as effective instruments for instilling appreciation for the value of traditional handicrafts. Presenting content designed according to the educational levels of young people in digital environments can yield successful results in capturing their attention and fostering awareness. Additionally, presenting elements of traditional handicrafts through modern tools such as mobile applications, augmented reality, and digital games can enhance sensitivity toward these values. Designing short videos, trend campaigns, and viral content that appeal to young audiences can also be a powerful approach.

- Programs and plans integrated into school curricula, which play a strategic role in the intergenerational transmission of traditional handicrafts, should be utilized to increase the younger generation's interest in cultural heritage. Especially in active learning, game-based applications, project-based activities, and the active participation of students are significant factors in achieving positive outcomes. At the university level, supporting student projects can be considered an effective method for documenting and disseminating cultural heritage. For instance, projects such as *"Design-Make-Sustain,"* supported by the Ministry of National Education, serve as exemplary models that enable students to recognize and experience local values through practical engagement. In these projects, students participate in hands-on workshops related to handicrafts, gaining both theoretical knowledge and direct experience in production processes. Particularly at the secondary education level, such programs allow cultural heritage to be internalized through experiential learning rather than remaining solely at the level of theoretical knowledge. Similarly, offering elective courses on traditional art disciplines in certain vocational and technical Anatolian high schools encourages students to engage with these fields and develop a sense of professional identity.

- Families, non-governmental organizations, and local administrations should play an active role in the transmission of Intangible Cultural Heritage (ICH). Festivals, fairs, promotional events, and workshops should be encouraged to foster community participation.

- Cultural activities supported by the UNESCO National Commission of Turkey represent another effective mechanism for transmitting ICH to younger generations through local actors. Particularly within the *Cultural Heritage and Creativity Sector,* festivals, celebrations, and workshops enable young people to engage directly with traditional arts. For example, during events organized under the *"Living Heritage Workshops"* initiative, young participants learn handicrafts such as *ebru* (marbling), *çini* (tile art), and weaving from expert artisans, take part in hands-on production processes, and explore the meanings of traditional motifs through experiential learning. The continuity of such activities in collaboration with local administrations contributes to the preservation of cultural values while fostering a sense of belonging to these values among the younger generation.

In conclusion, employing creative and innovative methods supported by digital technologies plays a crucial role in transmitting traditional handicrafts to future generations. It is recommended to adopt interactive models suitable for the readiness and knowledge levels of learners at all educational stages, from preschool to higher education. These innovative solutions not only ensure the transmission of traditional handicrafts as cultural heritage but also have the potential to strengthen social solidarity by enhancing intercultural dialogue and understanding. Moreover, developing strategies specific to Turkey, inspired by successfully implemented cultural heritage transmission models in other countries, is of great importance for ensuring the sustainability of traditional handicrafts and promoting these values on a global scale.

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CHAPTER VII

A SUSTAINABLE HAT DESIGN WITH A MODULAR APPROACH

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1. Introduction

Is fashion a sustainable phenomenon? To adequately assess this, one must have a thorough understanding of both sustainability and fashion concepts. It is difficult to provide a clear definition of fashion, a phenomenon that influences what we wear when leaving the house, what we consume that day, which movie we watch, and which music we listen to. At the same time, fashion, which can encompass both the desire to be different from others and the desire to belong to a social collective, undoubtedly has both a social and an individual aspect (Kang, 2020). However, it is also an undeniable fact that it is one of the important means of communication through which a person can express themselves as they are (Eco, 2020). The ability to express one's culture, affiliations, and preferences by choosing what to wear, how to look, and what to say is an important indicator of this. To understand this complex and multi-layered structure, it is necessary to first understand its origins. When we trace the origins of the English word “fashion,” the Turkish equivalent of the Turkish word “moda,” we see that it was anglicized from the Old French word “façon” or “fazon,” which comes from the Latin words ‘facere’ and “factio” (meaning to make or do). Over time, this word has carried meanings such as form, structure (in the 1300s), common custom (in the 1400s), and style of dress, reaching the present day (Kang, 2020).

The concept of sustainability, which has taken center stage in interdisciplinary research in recent years, carries a meaning that can be summarized as “meeting the needs of the present without compromising the ability of future generations to meet their own needs,” as stated in the final report of the Brundtlandt Commission (Cengiz, 2021; Keeble, 1988). Robert Gilman defines the same concept as “the ability of a society, ecosystem, or any ongoing system to continue functioning indefinitely into the future without depleting its primary resources” (Yücel & Tiber, 2018a). So, how does sustainability, with such a definition, position itself in the face of fashion, which is in a constant state of change? To answer this question, we must first clearly understand the role of fashion within society. Lipotevsky describes modern society as a “hyper-consumerist society” dominated by brands. For such a society, fashion will not only represent clothing but, as Baudrillard puts it, will become the embodiment of a consumption ideology and a tool for reproducing social inequality (Ovsiankina & Kuprii, 2021). Therefore, a person's social status will depend on how “fashionable” they are, and maintaining this status can only be achieved through “buy and buy more.”

The phenomenon of consumption, although it constitutes the existence of a market and economic system, has taken on a structure that aims to satisfy the desires and wishes of the individual rather than meeting basic needs (Halaçeli Metlioğlu &

Yılmaz Gözene, 2024; Tan, 2019). This situation is associated with the individual's search to fill the void in their soul, to regain a sense of stability, or to achieve emotional satisfaction (Ovsiankina & Kuprii, 2021; Tan, 2019). This constantly and rapidly changing culture of consumption leads to the use of resources as if they were unlimited and creates a structural conflict over resources, ultimately harming both the consumer and the ecological system (Can & Ayvaz, 2017; Yücel & Tiber, 2018). In particular, the desire for change inherent in the nature of fashion and business models such as "fast fashion" support continuous production and the pursuit of novelty, leading to a shortened product life cycle (Bianchi & Birtwistle, 2012; Fletcher & Tham, 2019).

Contrary to the traditional market approach, fast fashion, which operates across multiple seasons, significantly shortens the lifespan of garments by rapidly offering the latest trend examples in the form of low-cost, cheap, and disposable products, leading to a major textile waste problem (Bianchi & Birtwistle, 2012; Brewer, 2019; Eker İşçioğlu & Yurdakul, 2018; Vehmas et al., 2018). This model feeds an industrial economy that operates as a linear system consuming natural resources in a take-make-dispose manner (Stahel, 2016). The textile industry has become one of the world's most polluting sectors due to its high use of chemicals and dyes in the production process and its contribution to 20% of global industrial water pollution. Producing just 1 kilogram of cotton requires approximately 20,000 liters of water (Brenot et al., 2019; Fletcher & Tham, 2019; Samanta et al., 2019; Senthil Kumar & Grace Pavithra, 2019).

This desire for constant change and transience inherent in fashion creates a structural conflict with the principle of sustainability, which advocates for the protection and preservation of the planet, leading to the perception of sustainable fashion discourse as an oxymoron (Blumer, 2017; Henninger et al., 2016a; Ovsiankina & Kuprii, 2021).

Developed as an alternative to fast fashion and rapidly gaining traction in Europe, where it has attracted numerous sustainability-conscious consumers and organizations, the concept of sustainable fashion inherently rejects the appeal, loyalty, and consumption continuity characteristics of fast fashion (Choi et al., 2014; Gürcüm & Yüksel, 2011). This concept is part of slow fashion, which emerged as the complete opposite of fast fashion, but it is often incorrectly defined as the opposite of fast fashion (Henninger et al., 2016). Sustainable fashion examines sustainable design under three different headings: material-focused design, pattern-focused design, and modular design (Ayanoğlu & Ağaç, 2017). In material-focused design, the suitability of the material for its purpose, its recyclability, etc., come to the fore, while in pattern-focused design, the goal is to produce in the right patterns and therefore the right sizes, leading to long-term use and less waste.

Modular design is an innovative approach used in various fields within the design discipline. The concept of modularity emerged in the computer industry sector in the 1960s. This concept brings competitive advantages and benefits to the sector (Cileroglu & Nadasbas, 2017a). A modular product can be defined as a product consisting of various parts that can be easily assembled and disassembled by the user. Modularity provides advantages in terms of flexibility, customizability, and renewability of the product. Such modular products are created by bringing together components designed according to specific standards based on user needs and preferences. The simplest example that can be given in the context of modular design is Lego. By putting together appropriate modules, toys of various shapes can be obtained. In clothing design, matching modules can provide flexibility, variety, and the ability to create style.

Modular design has also been making a name for itself in clothing design in recent years. Modular garments create functional and visual diversity with pieces that have attachable and detachable connections or models that can be worn in multiple ways. In clothing, modular design refers to the complete separation of garments into different parts and the ability to combine these parts as separate modules to be reassembled with other parts (Li et al., 2018). With modular clothing design, products can be designed that are socially appropriate in various regions and can be worn in different weather conditions and time periods. This also allows for the long-term use of a single product in different styles.

Designers are also interested in modular design, which is an important way to ensure that fashion is truly sustainable. The 'Modular Cycle' collection designed by Wei Hung Chen is one such success story. Chen has combined clothing modules by adding snap buttons to the garments he designed (Figure 1). Modules with different shapes have been combined with other pieces in the collection to provide variety. The multifunctional nature of modular design also contributes to sustainability in the production process. Designers can tailor designs to consumer preferences and needs. This results in less raw material usage and less waste. Consumers owning products that can be worn in multiple forms will not contribute to continuous production and consumption. The dress designed by Sebastian Errazuriz in 2003 (Figure 1) was influenced by the constant changes in each season and consumer demand. The zipper dress was produced with 120 specially made zippers. The idea behind the dress design was to create a single dress that could be easily reconfigured to suit hundreds of variations. With this zipper dress, Sebastian Errazuriz creates garments in different forms, such as a full-length evening gown, skirt, T-shirt, necklace, and even a belt. Thus, a multifunctional dress has been designed that can be worn in different forms and sizes. The designer has given the user the opportunity to adapt it to their every need (Şevkay, 2021a).

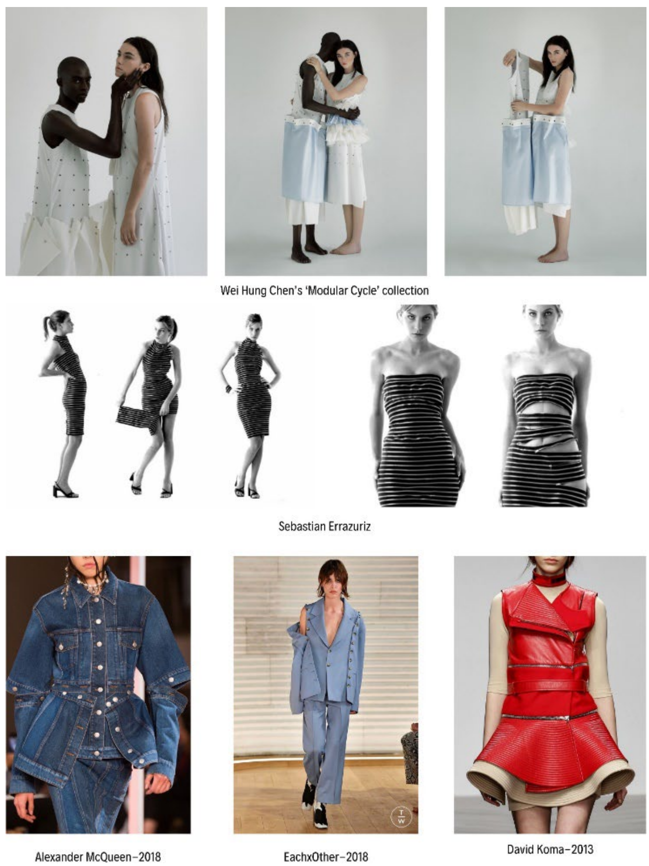

Figure 1. Examples of Modular Design (URL-1,2,3,4)

The potential of the modular design approach to achieve sustainable fashion goals by extending the lifespan of garments, enabling personalization, and providing aesthetic diversity is supported by theoretical and applied studies in the existing academic literature (Cileroglu & Nadasbas, 2017; Şevkay, 2021). However, applied design research examining the concrete contributions modularity can make to environmental and economic sustainability transformation is limited, particularly in the context of style-focused accessories, such as seasonal products like hats, which are prominent as a means of expressing the individual's symbolic identity and the principle of transience in fashion. This study aims to fill this gap and examine how modular design in an accessory can express sustainable usage practices through a concrete example proposal. Thus, a product with a modular structure that emphasizes sustainable fashion and incorporates different aesthetic and usage features has been produced.

2. Method

This study focuses on the production of a modular hat within the scope of sustainable fashion. The method steps followed in this study, which was conducted using the Design and Development research method, are shown in Figure 2. This research method is used to develop, test, and evaluate the feasibility of new products, tools, models, and processes (Büyüköztürk et al., 2021). In the first stage, within the scope of the literature review, academic studies on the concepts of sustainability, modular design, and fast fashion were examined and analyzed. In the visual research phase, visual sources such as fashion shows and collections, which are outside of academic sources but would be useful in the product design phase and would give us an idea about modular design, were utilized.

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Figure 2. Process Flow

Based on the information obtained, an attempt was made to create a sustainable modular hat design. This method aimed to achieve diversity, flexibility, and sustainability in the product. Adobe Photoshop CS6 was used in the design process. The design was adapted from a basic hat template. Modular parts were created using fabrics and accessories that would not compromise the structure of the hat. These parts, which can be attached to the hat with snaps, were analyzed for their removability, and the design was finalized after reevaluating the conditions for suitability. The design was left open for further development.

3. Design Process

The hat is an important accessory as old as humanity itself and has been used in different cultures for a very long time. While hats were initially designed to serve a physical purpose, such as protection from cold and heat, over time they have become a means of reflecting the wearer's culture and beliefs. This accessory, used throughout history, has shown great differences according to time, conditions, and needs. By looking at the type of hat, conclusions can be drawn about the person's religious beliefs, profession, political views, and culture (Topçu, 2022). For example, jeweled and beaded headdresses have been used throughout history as symbols of power, wealth, and prestige, often worn on special occasions such as weddings (Blum, 1993). The hat, in fashion, has become an integral part of the garment's overall unity, designed not so much for the function of covering the head as for coordinating with the rest of the outfit. In the early 20th century, Paul Poiret revived the turban style, which was named the “timeless hat” by the Paris Hatmaking Congress in 1938 (Blum, 1993). With the Hat Revolution in the Republic of Turkey, hats were added as a complement to clothing for different occupational groups and became part of everyday life (Topçu, 2022). During World War II, the turban was used by French women as a symbol of passive resistance to express patriotism (Blum, 1993). However, by the 21st century, hats had ceased to be a status symbol both globally and in Turkey, and their frequency of use had significantly decreased. Today, while retaining its primary purpose, the hat continues to be used in various styles to complement everyday outfits, as caps, or as headwear to protect against the cold.

3.1 Expected functions of the product

According to Fletcher, modular design has a more desirable potential compared to other design approaches. Modular design has three environmental values: diversity, flexibility, and sustainability (Li et al., 2018).

Modular design involves the user in the product's component selection and assembly process. It enhances the product's appeal and interactivity. It actively involves the user in the design and pays attention to their feelings (Li et al., 2018). Different module styles mounted on the designed basic hat mold allow the hat to be changed according to the user's clothing style, thus meeting different needs. Modules that can be used in different seasons can extend the life cycle of the hat as much as possible. Modules used on the hat and mounted with snaps can be changed in line with the style changes of the young female population who will use the hat, providing variety.

All clothing products go through five processes, including design, production, sale, use, and disposal. Compared to a conventional hat, a modular hat design offers flexibility as an advantage in every process. One of the benefits of modularity for designers is that it provides them with greater flexibility to accommodate changing processes (Gershenson et al., 1999). Designers can design modules according to user demand, and users can have the module they need (Li et al., 2018). For example, the designed hat module has the flexibility to be used in all four seasons. The user can change the outer appearance according to the season and the inner module according to the temperature.

A unique feature of modular design that conventional clothing lacks is continuity. A modular hat can be used with a range of products, just as it can be used with a single garment. The modular hat used this season can be combined with various modules from the next season. Continuity can be enhanced by purchasing different modules to suit changing seasons, ages, and styles (Li et al., 2018).

3.2. Purpose of the Product

As seen in today's trends, keeping up with and purchasing hats that match the ever-changing fashion within a year is a difficult situation for consumers. The damage caused by rapidly changing and hard-to-follow fashion trends is clearly visible. With modular hat design, the goal is to ensure seasonal continuity by using second-hand parts, waste fabric, and accessories. Furthermore, this hat design, which can be separated into modules and combined with different modules to provide variety, aims to reduce production costs. Modular parts that can be changed according to the target audience's preferences allow for product personalization. The user's involvement in the assembly process after production is intended to make the product more appealing. The target audience is young women who are constantly consuming and influenced by popular culture.

4. Results

During the design phase, a basic hat module was first created to ensure the hat could adapt to seasonal changes and be reconfigured with different accessories. Technical and artistic drawings of the hat were prepared during the design process, and these drawings were then transformed into the product. Cotton fabric was chosen so that the product could be used in all four seasons, and various materials in seasonal textures and colors were selected for the modules to be added. Accessories such as earflaps, pom-poms, visors, and wide brims were chosen to offer the user different styles of hat models.

Figure 3. Artistic Drawing of the Hat

Figure 3 shows a dome-shaped hat design. It has been chosen for its suitability for modular design. This hat forms the core part of the design. The dome shape ensures that future modules can be placed evenly on the hat. Symmetrically placed snap fasteners position the modules evenly without distorting the shape of the hat. The strip at the bottom is the piece that covers the snap section where seasonal accessories and fabrics are placed. It has been added to prevent overlapping modules from spoiling the appearance. When this piece is attached, the hat can be used in its basic form.

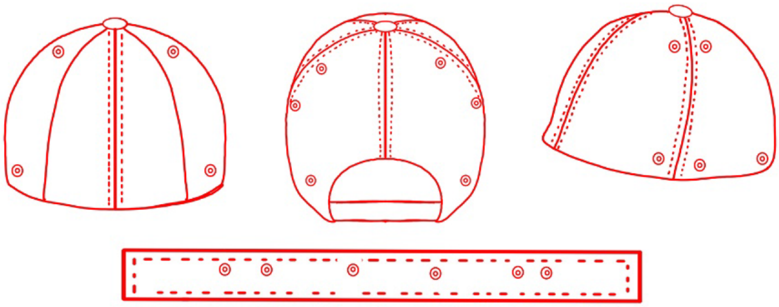

Figure 4. Technical drawing of the hat

Figure 4 shows the technical drawings of the modularly designed cap and the removable strap. The basic cap design is shown from three different views: front, back, and side.

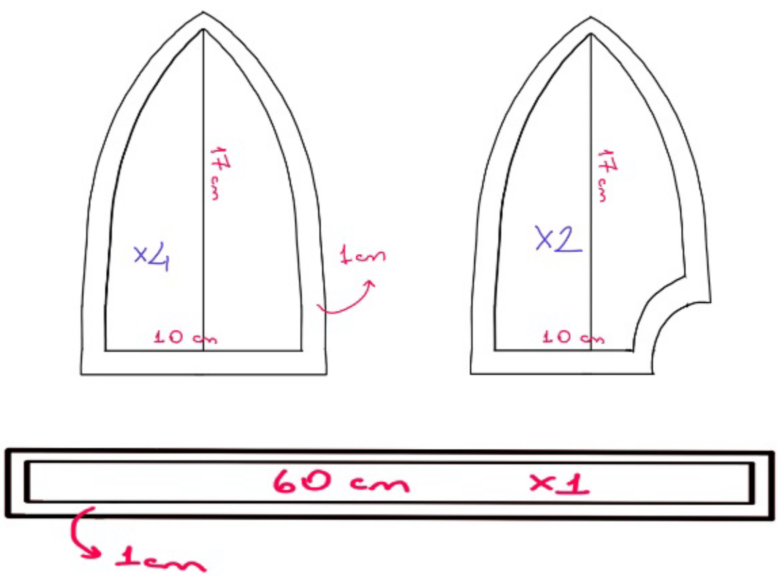

Figure 5. Pattern of the main cap and band

Figure 5 shows the basic mold for the dome-shaped hat, consisting of six pieces. Prepared according to standard hat measurements, each piece of this mold is 17 cm high and 10 cm wide, with a 1 cm seam allowance along all edges. Optionally, the back of the hat may be left without a window. The opening window can be secured with elastic or Velcro. To produce a hat with a window, four pieces should be cut from part 1 and two pieces from part 2. This basic hat pattern allows for the equal placement of the modules. The band encircling the hat is a single piece 60 cm long and again includes a 1 cm seam allowance along all edges. This piece completes the hat form. To ensure maximum sustainability, patterns can be cut from end-of-life clothing and fabric scraps, or a second-hand hat can be used as a base model.

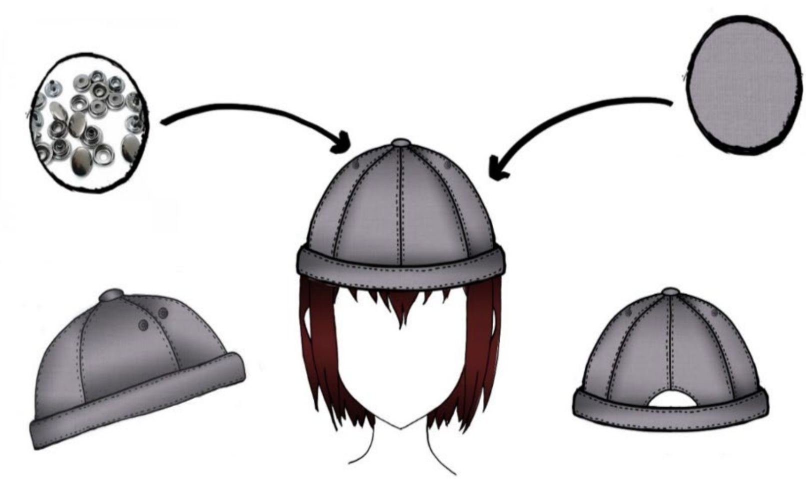

Figure 6. Artistic drawing of the hat and materials planned for use

The front, back, and side views of the basic hat, along with the accessories and fabric types used, are shown in the visual (Figure 6). This hat, whose parts can be changed seasonally, is made of cotton fabric so it can be used in all four seasons. The main model hat can be created using waste fabric and accessories and can be used throughout the year. Thus, seasonal concept transitions are achieved through the interchangeable modules.

The basic hat features a removable snap mechanism on the top and sides. This system allows the wearer to easily change the style, model, and seasonal characteristics of the hat in just a few minutes. The ability to attach modules of different shapes and sizes, such as ear flaps, pom-poms, and visors, demonstrates the modular flexibility of the design. The snap system, which allows the modules to be securely attached to the hat, was chosen for its low cost and ease of use. In addition, the color of the cotton fabric used in the artistic design was chosen to match the color of the snaps; thus, the points where the modules are attached have been integrated into the design in a way that does not disrupt the aesthetic integrity.

Figure 7. Models of the modular hat design

Figure 7 shows drawings of different hat models created by adding modular pieces to the basic hat form. The dome hat model shown in Model 1 represents the basic and simple hat model. It can be used in all four seasons with various fabrics. The symmetrically placed snaps in Model 1 provide variety by changing the style and model of the hat with the addition of different accessories.

Model 2 shows a baseball cap created by adding a front visor module to the basic cap (Figure 7). This cap has been designed for the summer season according to current trends. The piece on the front (visor), used for protection from the sun, can be prepared by adding interlining or a stiff material inside to maintain its shape. The main body and visor can be made from summer fabrics such as cotton and linen. This piece, prepared for the summer season, can be customized using different fabrics and patches as desired.

The Model 3 features both aesthetic and functional modules added to the basic hat form (Figure 7). This model emphasizes the personalization and seasonal adaptability aspects of the modular system. The addition of a colored band module and decorative accessories in the shape of ears creates a more fun and personalized design, offering both summer and winter functions. To adapt to the winter season, the striped fabric used in this part is polar fleece. Since it is a removable module, snaps can be added to the inner sides to cover the hat appropriately for winter days. Instead of polar fleece suitable for winter, various winter wool fabrics can also be used. When used for the summer season, accessories in fun and various shapes, such as cat ears, can be attached to the top of the hat to instantly add flexibility. Brightly colored, summer-style strips attached to the bottom edge of the hat ensure compatibility with the summer season.

In Model 4, the basic hat form has been transformed into the currently popular bucket hat style by adding a brim module around the hat (Figure 7). This hat is designed for spring and fall. This model is enriched with patchwork and features a shawlpatterned fabric popular in bucket hats. This patterned fabric is cotton and durable, making it suitable for use throughout two seasons.

These models are created by attaching and detaching different modules onto the same basic hat, thus offering a modular design concept that allows for seasonal, functional, and style-oriented transformations.

Figure 8. Front, back, and top view of the hat

Figure 8 shows the main part of the hat. This photo presents the appearance of Model 1, the main body of our modular hat design, made from dark blue denim fabric. The hat consists of a six-piece crown and brim. Cotton denim waste fabric has been used to ensure sustainability in product manufacturing. The snaps placed symmetrically on the top and around the hat serve as connection points for the visor, fleece, and other design modules to be added to the hat. The modular band on the side aligns and fits perfectly onto the hat body thanks to the snaps on it.

Figure 9. Appearance of Model 1 (Docker cap) on a young model

The photos in Figure 9 show how the basic cap looks on a young user. The dome-shaped basic cap, made of denim fabric, appears ideal for everyday use. It can be easily paired with both sportswear and everyday clothing.

Figure 10. Appearance of Model 2 (Baseball cap) on a young model

In Figure 10, model 2 (Baseball Cap) was created by adding a light pink visor, an embroidered patch, and a decorative button to the main cap. Modular parts were attached to the cap using snaps. Thanks to the modules added to the cap, the cap with the main form has been transformed into a baseball cap. The visor added to the cap protects the user from sunlight and provides a sporty look. Accessories such as visors, patches, and decorative buttons with different shapes can be added to the cap to provide modular variety.

Figure 11. Appearance of Model 3 (Design cap) on a young model

In Figure 11, Model 3 (Design cap) was created by adding cat ears and a band module to the main cap using snaps. This model demonstrates the personalization and entertainment potential of the modular system. The red-and-white checkered band and ears in the image add a more fun and personalized look to the cap. This design is not only aesthetically pleasing but also offers the user unlimited transformation possibilities according to the season and style thanks to its modularity. Instead of the summer fabrics used in this design, winter fleece or wool fabrics can be preferred with the change of season.

Figure 12. Appearance of Model 4 (Bucket cap) on a young model

In Figure 12, the bucket hat style is achieved by attaching the brim module to the main hat using snaps. This model is designed especially for spring and fall months and protects the wearer from the sun. The brim can be removed and attached using the snap mechanism on the main body. Various patterned fabrics, such as the checkered pattern shown in the image, add visual richness to the model. The selected fabric structure ensures suitability for use throughout two seasons.

4.Conclusion

Sustainable modular design has been shown to create environmentally friendly designs by reducing the environmental damage caused by continuous production and consumption. It is believed that the spread of the concept of sustainable fashion and the production of products that meet consumer objectives have made producers more conscious of sustainability. Thus, producers who utilize fabric scraps generated during production will contribute to the economy. Under the banner of sustainability, the protection of natural resources will also contribute to the image of institutions and brands. Thus, companies that utilize waste will establish themselves in branding and different markets (Kılıç, 2013).

Fıçıcıoğlu designed an accessory collection that consists of clothing pieces with various forms that can be attached to and removed from a basic garment form. This collection has functions such as collars, belts, and vests. The accessories, which are attached to the basic garment form and used with different clothes, create an aesthetic appearance. These accessories, made up of garment pieces, do not require additional accessories, thus providing convenience in terms of economy and practicality and aiming to minimize environmental damage (Fıçıcıoğlu, 2022).

This study examines seasonal sustainability through modular hat design. A modular hat system that can be separated into parts has been developed, enabling the creation of various hat designs composed of different components. A design was created that could be used on different garments to suit the individual's style. The modular product reduced production costs through minimal fabric and material usage, making the product sustainable and fashion-forward. It was observed that various style studies could be conducted using the fabrics and accessories employed. For example, the accessories and fabric used in the winter hat model created a soft and charming effect. The same mold can be used to create a gothic effect with black plush, chains, and punk badges. This allows the design to adapt to rapidly changing fashion trends and be suitable for different weather conditions, ensuring long-term use. The modular design contributes to the consumer's style creation with its flexibility and variety.

The ability to easily attach and detach modules and use them in different seasons offers the opportunity to combine past and future fashion trends. The basic hat form, which allows for the mounting of multiple modules, enables style changes and scalability. This encourages consumers to make individual and creative choices. It is evident that modular hat design allows for the creation of products that are sustainable, requiring minimal materials and raw materials while offering long-term usability, and aligning with the concept of timeless fashion (Fıçıcıoğlu, 2022). The study concluded that, within the framework of sustainable design, modular design holds greater potential and is more preferable compared to other design approaches.

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Image Resources

URL-1: https://www.notjustalabel.com/wei-hung-chen

Erişim Tarihi: 30.07.2024

URL-2: https://sebastian.studio/multiples-zipper-dress

Erişim Tarihi: 30.07.2024

CHAPTER VIII

WEARABLE TECHNOLOGIES AND SMART TEXTILES

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1. Introduction

Wearable technologies and smart textiles represent the coming together of diverse disciplines to create a common language. These disciplines include electronics engineering, materials science and engineering, textile technology, and fashion design. In this vein, radical transformations have begun in both academic literature and industrial applications in recent years. The global growth of the wearable technology market is linked to momentum in mobile communication technologies, advances in sensor architecture, the proliferation of the IoT ecosystem, and increased consumer expectations for real-time data tracking; rapidly expanding usage patterns in health, sports, security, and industrial monitoring are evaluated from an economic perspective (Kılıç, 2017). It is thought that smart textiles are becoming a more attractive platform with fashion-oriented applications such as nanotechnological coatings, conductive fibers, integrated sensors, LED and optical fiber-laid modules classified as passive-active-ultra-smart (Degerli, 2019; Baydemir, 2019). From a technical textiles' perspective, advanced features such as conductive polymers, carbon nanotubes, graphene-based structures, nanocoatings, textile-based antennas, and circuit components are flexible elements of wearable electronics.

Furthermore, usage-dependent features such as washability, drapability, sensor density, and energy efficiency are highlighted as critical thresholds for reducing industrial processes (Kan and Lam, 2021; Hassabo et al., 2023). When we look at the functional depth of e-textiles, the integration of mechanical sensors (piezoresistive, piezoelectric, triboelectric), electrophysiological sensors (ECG, EMG, EEG), chemical and ionic sensors (pH, electrolyte, sweat analytics) and textile-based display technologies (OLED, micro-LED, electroluminescence) represents the transformation of smart e-textile structures into complex systems capable of bidirectional data exchange (Cho et al., 2022). By classifying smart textiles into passive, active, and ultra-smart categories, it is stated that these structures have evolved from being merely warning-detecting systems to autonomous interaction surfaces with decision-making capabilities, and that thanks to IoT integration, multi-sensor, energy-generating, and data-processing garments will approach the nature of "walking computers" in the future. The interaction mechanisms of piezoelectric, triboelectric, optical, and electrochemical sensors with textile fabrics, flexible energy storage technologies, wireless communication, and antenna structures are evaluated within an interdisciplinary framework, revealing the technical, ergonomic, and production limitations of smart e-textile systems (Younes, 2023).

When combined with the sustainability paradigm, this technical transformation integrates with enzyme-based processes, low chemical consumption coatings, recycled polymer fibers, waterless dyeing techniques, and smart fiber production processes that aim to reduce the environmental costs of the textile industry. However, limiting factors such as energy efficiency, durability, recycling chain management, and the lack of standardization in e-textile products continue to pose critical obstacles to sustainable production. When all the literature is evaluated together, it is clear that today's wearable technology ecosystem is not limited to clothing integrated with electronic hardware; but has evolved into a multi-layered innovation field that simultaneously incorporates user-focused data processing, real-time biophysical monitoring, environmental sensitivity, energy production–storage cycles, materials engineering, aesthetic design, and sustainability principles (Hossain et al., 2024).

Therefore, the future of smart textiles will be shaped by the deepening of interdisciplinary R&D processes, the transformation of material-based innovations into marketable prototypes, and the proliferation of IoT-based integrated wearable platforms. The literature indicates that this transformation signals a sustainable paradigm shift in both technical and socio-economic dimensions.

Figure 1. Wearable technologies and smart textiles (https://freepik.com)

2. lassification of Smart Textiles

2.1. Passive Smart Textiles

Passive smart textiles constitute the simplest yet functional building block of smart textile technologies, defined in current literature as the "first generation" or "basic sensing layer". By positioning passive smart textiles as sensor-centric systems that can only detect environmental, mechanical, or biophysical stimuli but cannot process or convert these signals and produce any response, these structures are associated with the concept of "one-way intelligence" (Sajovic et al., 2023). Passive smart textiles are considered the initial stage of smart textile evolution, and these systems consist of materials that only monitor variables but lack the capacity to change behavior or adapt (Allish et al., 2024). From a fashion and textile design perspective, passive smart textiles are mostly used in the form of thermochromic, photochromic, or moisture-sensitive dyes, UV-responsive coatings, simple sensor surfaces made with conductive yarns, and fabrics that visually respond to environmental conditions but do not produce electronic feedback and that these structures play an important role in prototypes aimed at perceptual awareness, aesthetic diversity, and providing the user with situational information in the field of fashion (Meriç & Üreyen, 2024).

Passive smart textiles are defined as the simplest form of sensor integration, emphasizing that these structures only collect data and do not perform functions such as energy conversion, electronic control, adaptive behavior, or feedback generation. thus, the flow of information is unidirectional from the environment to the textile (Dejene, 2025).

These are referred to as “sensing-focused textile interfaces,” where user interaction is minimal, inputs such as touch, pressure, position, tension, temperature, or humidity are detected, but the user does not receive feedback regarding this input. It is noted that these systems are evaluated based on fundamental parameters such as accuracy, comfort, flexibility, and ease of use in terms of user experience (Guennes et al., 2025).

When all these studies are considered together, it is seen that passive smart textiles form the most fundamental layer of the smart textile ecosystem, provide the necessary infrastructure for the development of active and ultra-smart systems, take on the primary sensor function between the environment and textiles, and play an entry-level but indispensable role in both technical and design-oriented applications.

Figure 2. Passive smart textiles (https://leinuotechnology.com)

2.2. Active Smart Textiles

Active smart textiles represent the second generation of smart material architecture, which constitutes an advanced stage in the evolution of smart textile technologies beyond passive systems and is defined in the literature by the "sense–respond" principle. Active smart textiles are classified as structures that go beyond sensing environmental stimuli and can produce a physical, thermal, optical, or electrical response. It states that materials such as electroactive polymers, piezoelectric fibers, electrochromic surfaces, shape memory polymers/alloys (SMP/SMA), optical fiber components, and heating conductive filaments fall into this category (Sajovic et al., 2023). It is emphasized that active systems can convert sensor data into actuators that produce feedback in the form of light, heat, color, mechanical deformation, or vibration, positioning these structures in a wide range of applications from sports performance analysis to rehabilitation processes, from military clothing to thermal comfort management (Allish et al., 2024). In the context of fashion and textile design, it is stated that active smart textiles can create visual, volumetric, and functional changes through LED-integrated surfaces, shape memory alloys, electroactive polymers, and fiber optic modules, enabling designers to produce dynamic surfaces that interact with the user (Meriç & Üreyen, 2024).

Active smart textiles are considered a critical stage where sensor-actuator interaction is combined with energy production systems. It is emphasized that active textiles transform into "self-powered active textiles" that can generate their own energy, particularly in structures integrated with triboelectric (TENG), piezoelectric (PENG), thermoelectric generators, and magnetoelastic transducers, thus reducing dependence on external power sources and enabling the textile to function like a machine (Dejene, 2025). Examining the interaction dimension of active smart textiles, it is stated that the sensor-actuator combination in these systems creates a two-way feedback loop with the user, meaning that tactile, mechanical, optical, or thermal inputs are converted into instantaneous responses based on user behavior. It is stated that flexible electronics, microcontrollers, and conductive circuit networks are the fundamental components of this technology (Guennes et al., 2025). When all these studies are evaluated together, active smart textiles emerge not merely as surfaces that sense environmental variables, but as functional textile platforms that interact with the user, produce physical responses, exhibit adaptive behavior, and can generate their own energy under certain conditions; thus, they form a critical intermediate step in the transition from passive systems to ultra-smart structures in the smart textile ecosystem.

Figure 3. Active smart textiles (https://amazon.com)

2.3. Ultra Smart Textiles

Ultra-smart textiles are defined as autonomous wearable platforms that integrate data processing, decision-making, learning, and contextual adaptation processes, forming the third and most advanced generation in the evolutionary hierarchy of smart textile technologies, surpassing the sensing capacity of passive systems and the response generation capability of active systems. Ultra-smart textiles are positioned as "learning systems" that go beyond sensor-actuator-energy units and are equipped with microprocessors, communication modules, artificial intelligence algorithms, and machine learning components, enabling them to analyze environmental data and select the most appropriate response themselves. Health garments that perform physiological risk analysis, textiles that optimize athlete behavior by processing performance data, and exosuit structures that provide robotic support are examples of this class (Sajovic et al., 2023). It is emphasized that the addition of IoT-based communication modules, biometric data analysis software, wireless control systems, and self-powered TENG/PENG/TEG structures to this category enables ultra-smart textiles to offer an advanced wearable computing infrastructure that provides user-specific, autonomous, and continuously adaptable services (Allish et al., 2024). From a fashion design perspective, it is stated that ultra-smart textiles develop "learning and self-decision-making" aesthetic-functional hybrid systems in the field of fashion through garments that interpret biometric data, provide corrective feedback by detecting posture disorders, create interactive stage costumes with emotional state analysis, and self-regulate with context awareness (Meriç & Üreyen, 2024). It is stated that the "wearable nervous system" created by ultra-smart textiles with artificial intelligence, flexible electronics, multi-sensor-actuator networks, and embedded processors enables complex functions such as processing environmental inputs to support muscle movements, analyzing abnormalities and sending alerts, or performing autonomous thermal management according to body temperature. When combined with self-powered structures, this gives rise to fully independent, autonomous textile architectures (Dejene, 2025). Examining the interactive dimension, it is stated that thanks to control units, edge computing structures, and learnable algorithms in ultra-smart textiles, textiles are transformed into multi-layered adaptive interfaces that not only perceive the user but also predict user behavior, optimize themselves according to stimuli, and simultaneously influence both pragmatic and hedonic user experiences (Guennes et al., 2025). The common assessment of all these studies is that ultra-smart textiles form the top tier of the smart textile ecosystem, fully implementing the “perceive → analyze → decide → adapt” cycle, redefining human-machine interaction, and serving as advanced wearable computing platforms that provide the fundamental infrastructure for future autonomous healthcare systems, robotic wearables, defense applications, augmented reality garments, and personalized fashion design.

Figure 4. Ultra smart textiles (https://shieldex.de.com)

3. Wearable Technologies in Fashion and Textiles

3.1. Fashion and Aesthetics

The introduction of wearable technologies into the fashion industry is primarily aesthetic and performance-oriented. LED-integrated dresses, fiber optic garments, surfaces that emit light using electroluminescent cables, and costumes that change color using electrochromic materials are prime examples of where fashion and technology intersect in the context of performance art. Particularly in performing arts and fashion shows, interactive costumes that change light patterns with the dancer's movements and respond to musical rhythms transform the artist's body into a “digital surface that transforms with movement”. In this context, clothing ceases to be merely a covering or an aesthetic object and becomes a dynamic interface that communicates with the audience, supports the choreography, and enhances the dramatic narrative of the performance. It emphasizes that in such uses, clothing is positioned as a “performance tool”; the primary purpose of technology integration is not functional tracking but visual impact, surprise, and the creation of a new fashion language. Thus, fashion and performance arts constitute one of the most visible areas of use for wearable technologies, both symbolically and experientially (Ziccardi, 2020).

Figure 5. Fashion and aesthetics (https://venuez.com)

3.2. Daily Wear, Comfort, and Lifestyle-Oriented Uses

Wearable technologies are shifting from stage and performance settings to everyday life, giving rise to the concept of "wearable lifestyle products". Smart jackets designed for everyday use, heated panel jackets, moisture and sweat-managing sports tops, touch-controlled gloves, and smart bags supporting wireless communication combine aesthetics with functionality. It emphasizes that such e-textile-based garments provide the user with "second skin" comfort; thanks to their flexibility, lightness, and wearability, electronic functions can become a natural part of daily life (Meena et al., 2023). It states that smart fabric systems in everyday clothing, which provide thermal comfort, perspiration control, moisture management, and adaptation to environmental conditions, enable individuals to manage their personal climate control through their clothing. Thus, wearable technology is transforming into a "life infrastructure" that enhances comfort, performance, and well-being not only in specific sports or medical scenarios but also within daily routines (Xu et al., 2025).

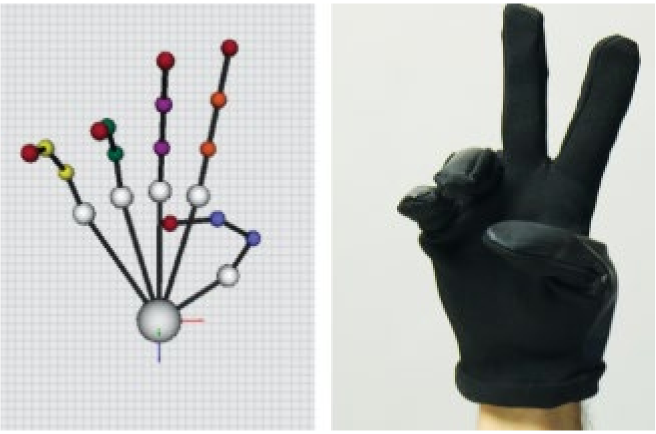

Figure 6. Daily wear, comfort, and lifestyle-oriented uses (https://textilegence.com)

3.3. Sports, Fitness, and Performance Management

The sports and fitness sector stands out as one of the areas where smart textiles are used most intensively and systematically (Ziccardi, 2020; Meena et al., 2023; Xu et al., 2025). Sensor-integrated sportswear can monitor key metrics of sports physiology in real time, such as heart rate, breathing rhythm, muscle activity (EMG), body temperature, perspiration rate, stride length, joint range of motion, posture, and fatigue indicators (Xu et al., 2025). These data are critically important for both amateur and professional athletes in terms of training optimization, performance analysis, and load management. Light-emitting sportswear and designs that enhance visibility are said to strengthen sports safety while also creating an aesthetic sports fashion language. It highlights that e-textile-based sportswear eliminates the need to carry devices, unlike traditional fitness equipment, allowing data collection directly through the garment without restricting movement (Meena et al., 2023). It also notes that athletic performance is closely related not only to training but also to the quality of rest during sleep and recovery periods; smart pajamas and bed textiles that track sleep provide detailed data on rest quality for athletes, contributing to the holistic management of the training cycle (Xu et al., 2025). Thus, smart textiles have become an integral component of performance management, injury prevention, and recovery processes in the field of sports and fitness.

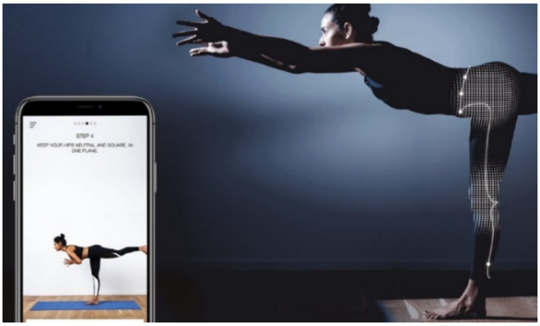

Figure 7. Sports, fitness, and performance management (https://m.blog.naver.com)

3.4. Health, Medicine, Digital Health, and Rehabilitation

It addresses the use of e-textiles and smart textiles in the health and medical field within the context of "digital health infrastructure." Smart garments with integrated sensors can monitor biosignals such as electrocardiography (ECG), respiration, pulse, body movement, muscle activity, skin temperature, hydration, posture, and even stress indicators in real time (Meena et al., 2023; Xu et al., 2025). This enables out-of-hospital, home-based, and long-term health monitoring for individuals with chronic diseases, the elderly, or patients with limited mobility. It is emphasized that such garments can play a critical role in monitoring chronic heart failure, respiratory disorders, epilepsy, and neurological diseases by providing 24-hour data (Xu et al., 2025). Furthermore, e-textile-based therapeutic applications can be used in rehabilitation processes such as electrotherapy, circulation improvement, wound healing, local heating/cooling, and muscle stimulation; thus, the garment becomes not only a monitoring tool but also a therapeutic one (Meena et al., 2023). It can be said that smart textiles add a data-driven and adaptive dimension to treatment processes by monitoring muscle functions, joint movements, and nerve signals in physical therapy and neurological rehabilitation (stroke, Parkinson's, muscle weakness, etc.). In this context, health and rehabilitation are among the areas of application with the highest potential for social impact for wearable technologies (Xu et al., 2025).

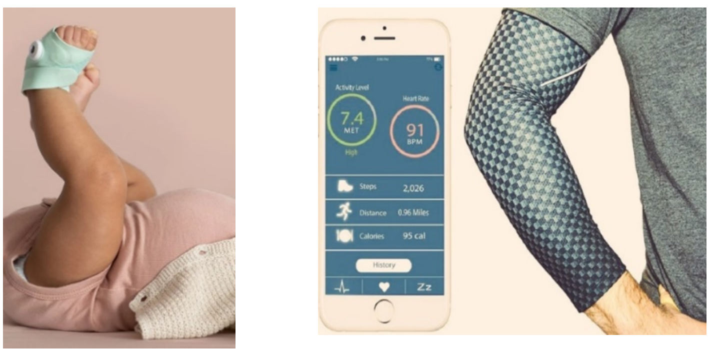

Figure 8. Health, medicine, digital health, and rehabilitation (https://m.blog.naver.com)

3.5. Safety, Occupational Health, Protective Fashion, and Risk Management

It addresses the use of wearable technologies in the context of safety and occupational health, considering both professional work environments and everyday risks. Smart protective clothing integrated with sensors that detect risk factors such as gas, temperature, humidity, chemical exposure, and impact in occupational safety garments are critical for preventing workplace accidents and establishing early warning mechanisms (Ziccardi, 2020). Similarly, location tracking modules integrated into children's clothing, lighted jackets that increase visibility for bicycle and motorcycle users, smart jackets that send automatic signals in emergencies, and motorcycle vests with airbag mechanisms are examples of safety-focused smart fashion. Smart garments with functions such as fall detection, irregular heart or breathing rhythm detection, and monitoring periods of immobility play an important role in both safety and health risk management, especially for elderly individuals. In this context, safety and protective fashion is emerging as an increasingly broad application area that intersects the occupational health, personal safety, and risk management functions of wearable technologies (Xu et al., 2025).

Figure 9. Safety, occupational health, protective fashion, and risk management (https://m.blog.naver.com)

3.6. Elderly Care, Long-Term Monitoring, and Independent Living

Aging populations, limited mobility, and the need for long-term care emphasize the importance of smart textiles in addressing this need. Smart clothing enables tracking in various healthcare systems (e.g., heart rate, respiration, body characteristics, activity level, sleep episodes, and fall tracking), enabling remote monitoring for both caregivers and healthcare professionals (Meena et al., 2023; Xu et al., 2025). Smart packages that detect falls, compression garments that support muscle weakness, and textiles that monitor the characteristics of Alzheimer's patients are supporting individuals' independent living. These alliances, rather than simply being devices that collect biomedical data, also contribute to the absence of concepts such as "independent aging" and "active aging" as essential elements (Xu et al., 2025).

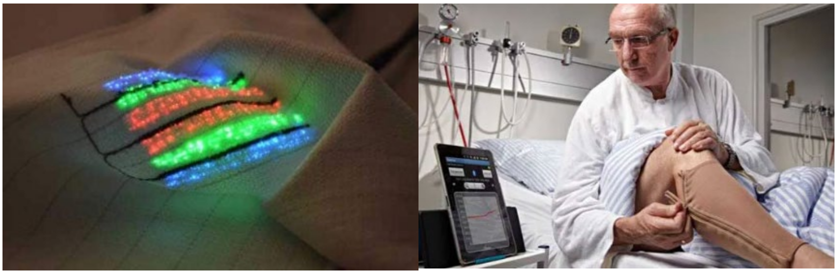

Figure 10. Elderly care, long-term monitoring, and independent living (https://eu.mouser.com)

3.7. Digital Fashion Ecosystem, Personalization, Interactive Fashion, and Data-Driven Applications

Wearable technologies are seen to create not only physical functions but also a data-driven and interaction-based digital fashion ecosystem. It has been observed that fashion is increasingly transforming into a "digital data platform" due to smart garments collecting movement, location, health, and behavioral data (Ziccardi, 2020). It is emphasized that personalization and emotional aesthetic experiences come to the fore through dresses that change color according to the user's mood, digital accessories synchronized with social media, and fabric surfaces that create animations when touched; fashion has become a means of expressing digital identity. It is stated that smart textiles, integrated with IoT, cloud computing, artificial intelligence, and data analytics, transform clothing into a "personal health and performance assistant"; these systems can analyze user data to produce risk predictions, behavior improvement suggestions, and personalized health/performance programs. Thus, wearable technologies not only transform the physical properties of fabric but also pioneer the evolution of fashion, health, and sports ecosystems into data-driven, personalized, and interactive structures (Meena et al., 2023; Xu et al., 2025).

Figure 11. Digital fashion ecosystem, personalization, interactive fashion, and data-driven applications (https://thenationalherald.com)

4. Materials and Technologies Used

Smart textiles are hybrid structures that integrate electronic systems with textile structures, performing multifunctional roles such as sensory perception, data transmission, energy production, and providing feedback to the user. This technology is not limited to wearable electronics; it encompasses a wide range of applications, from biomedical monitoring and/or tracking bands to thermoregulatory sportswear, military camouflage systems, and energy-generating fabrics. Reviews show that smart textiles offer a multi-layered hierarchy, covering different integration areas from the material level to the system level (Stoppa & Chiolerio, 2014; Shi et al., 2019). In the literature, smart textiles are generally evaluated along three material axes:

1. Conductive materials,
2. Smart polymers that respond to stimuli,
3. Nano-structured components for energy generation and storage (Stoppa & Chiolerio, 2014).

4.1. Conductive Fibers, Coatings, and Flexible Circuit Systems

Conductive fibers (metal-coated polymers, silver/copper-coated yarns), reduced prints (reduced graphene oxide-rGO), carbon nanotube (CNT), and graphene-based coatings are the most common materials used to impart electrical properties to textiles for conducting electricity. These materials perform the functions of sensors, heating elements, flexible transmission lines, or antennas. Stoppa and Chiolerio's comprehensive review summarize the production methods of conductive yarns, coating techniques, and their effects on textile mechanical properties (Stoppa & Chiolerio, 2014). Studies detailing material hierarchies and microelectronic integration strategies for more advanced systems include various design examples ranging from the fiber level to microchips and wiring (Shi et al., 2019).

4.1.1. Silver-coated and metallic threads

Silver-coated fibers are frequently used in medical monitoring applications due to their low resistance and good biocompatibility. However, issues such as cost, oxidation, and washability limit their widespread use (Stoppa & Chiolerio, 2014). Hexoskin, OMsignal, and Adidas MiCoach shirts can record heart rate, oxygen saturation, and breathing rate in real time using these types of conductive fibers.

Figure 12. Hexoskin (https://hexoskin.com)

4.1.2. Graphene, rGO, and carbon-based composites

Graphene and rGO (reduced graphene oxide) based coatings offer a good balance between flexibility and conductivity; however, coating homogeneity, adhesion, and wash resistance are areas that need to be addressed in production engineering. Graphene-functionalized textile electrodes are being investigated as a common starting point for flexible storage units (supercapacitors) (Newby et al., 2023).

Carbon nanotubes (CNT) are an important alternative material in smart clothing, providing high conductivity retention even under elastic deformation. Foroughi et al. (2016) developed sensor-equipped fabric panels that maintain their conductivity during stretching using CNT composite fibers (Foroughi et al., 2016). This material has found commercial applications in heating fabrics, EEG/ECG (electroencephalogram/electrocardiography) electrode textiles, and wearable rehabilitation bands.

Graphene-based flexible circuit fabrics are also a rapidly emerging research area in the literature. Textiles developed under the Graphene Flagship (EU Project, 2015-2023) possess important properties for wearable systems, with a 99% conductivity retention capacity under bending. The Vollebak Graphene Jacket, with its graphene-integrated heat regulation garment design, has become one of the first examples of this field in the commercial sector.

Figure 13. Vollebak graphene jacket (https://vollebak.com)

4.2. Smart Polymers Sensitive to Thermal, Mechanical, and Chemical Stimuli

Smart polymer-based textiles possess functions such as shape change in response to external stimuli, pore control, and color change. Shape-memory polymers (SMP) are used in adaptive textiles, smart garments for thermal protection, and protective clothing with active morphology change due to their ability to return to their original geometry when exposed to thermal stimuli (Hu et al., 2012; Meng & Hu, 2009; Ratna & Karger-Kocsis, 2008). Polyurethane-based SMPs, in particular, offer flexible, lightweight, and user-friendly material behavior in wearable systems due to their low trigger temperatures and repeatable shape recovery performance, making them an important alternative for functional smart textile designs (Meng & Li, 2013).

Thermochromic and photochromic polymers that change color are opening up new creative design areas in the field of fashion and aesthetics. Thermochromic pigment textiles developed by the London College of Fashion using inkjet printing have been used in performance art, providing color flow based on body movement (Chen, 2023). Similar prototypes have also been featured in the Intimacy Dress project by the Netherlands-based Studio Roosegaarde, where a fabric technology that becomes transparent when the heart rate increases has been developed.

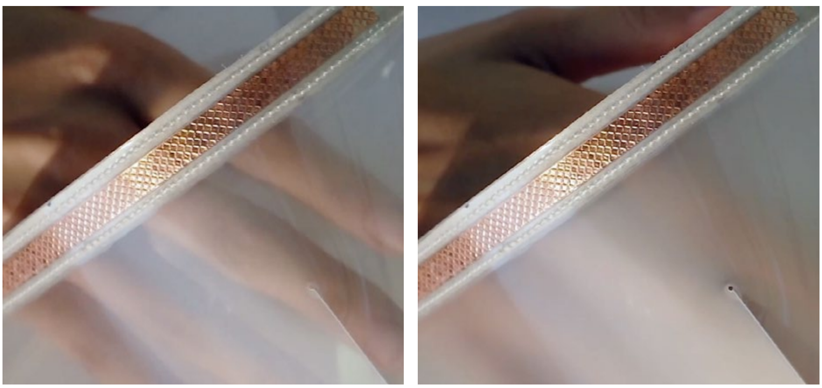

Figure 14. Technological fabric that becomes transparent as the heart rate increases (https://www.studioroosegaarde.net/project/intimacy)

4.3. Energy-Generating and Energy-Storing Textiles

Since the power source is the most fundamental limiting factor in most wearable systems, energy-harvesting textiles have emerged as a critical area of research. Piezoelectric polyvinylidene fluoride (PVDF) nanofibers are among the leading materials for converting kinetic energy into electricity.

In solar-textile applications, the North Face Solar Backpack and Tommy Hilfiger Solar Jacket are the most well-known examples of energy-generating textiles available on the commercial market. In addition, graphene-polyaniline hybrid nanofiber supercapacitor fabrics have gained significant recognition in the literature as washable energy storage elements.

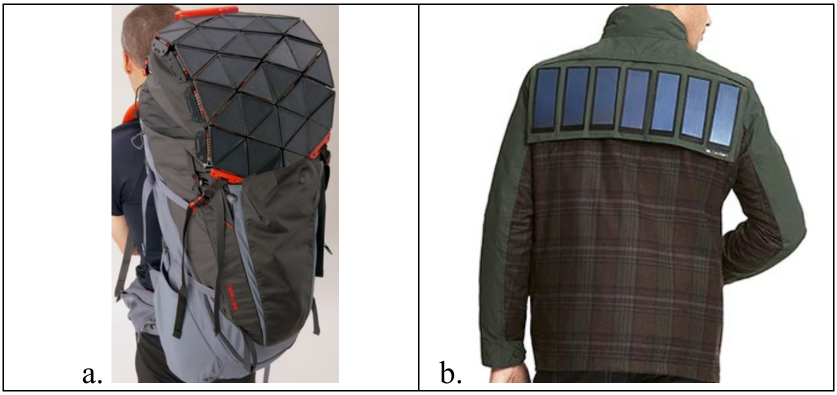

Figure 15. a. the North Face Solar Backpack (https://www.bradbristerdesign.com/the-north-face-sunup), b. Tommy Hilfiger Solar Jacket (https://wearables.com/products/solar-panel-jacket-mens)

Energy independence is critical for the widespread adoption of smart textiles. In this context, there are two main lines of research: mechanical energy harvesting (piezoelectric, triboelectric) and textile-compatible energy storage (flexible supercapacitors, fiber-battery applications).

- *Piezoelectric solutions:* PVDF (polyvinylidene fluoride) and PVDF-composite nanofibers are used as flexible piezoelectric generators to convert walking or motion energy into electrical energy; ZnO nanorod-coated PVDF fibers offer a practical approach for breathable and wearable piezo-generators (Kim et al., 2018).

- *Triboelectric nanogenerator (TENG):* TENG technologies utilizing the triboelectric effect have been found particularly suitable for textile-based energy harvesting; t-TENGs (textile-TENGs) can collect kinetic energy with high efficiency and support integration with active sensors (Huang et al., 2021; Wang, 2013).

- *Energy storage (textile supercapacitors):* Flexible and fabric-compatible supercapacitors are being developed using graphene, carbon nanotube (CNT), and metal oxide-based electrodes; recently published reviews summarize the production methods and challenges encountered with textile-based supercapacitors (Newby et al., 2023; Flores-Larrea et al., 2021).

5. Technical, Structural, and Sustainability-Based Issues in Smart Textiles

While smart textile technologies have high potential for industrial-scale production, a review of the existing literature in this field reveals critical technical challenges that need to be addressed. These problems can be grouped under four main headings:

1. Durability-washability,
2. Energy sustainability,
3. User acceptance,
4. Recycling and sustainability.

5.1. Durability-Washability

One of the biggest differences between laboratory prototypes and actual consumer products is long-term durability and washing performance. Metallic coated fibers, rGO coatings, or flexible circuits may show performance loss under friction, moisture, chemical detergents, and mechanical fatigue (Stoppa & Chiolerio, 2014). For example, studies on the post-washing conductivity retention and mechanical fracture resistance of fiber-integrated sensors indicate that coating optimization and encapsulation strategies are essential (Shi et al., 2019).

It is known that exposure of electronic circuits within textiles to moisture and detergent significantly affects the lifespan of products. In the first phase of the Google-Levi's Project Jacquard, it was reported that the sensor threads experienced a loss of conductivity after 25–30 washes.

Figure 16. Google-Levi's Project Jacquard (http://global.levi.com/jacquard/jacquard-with-buy-link.html)

For this reason, current studies have focused on microencapsulation, polymer stabilization, and PFC-free (perfluorinated compounds) hydrophobic nano-coatings in order to develop environmentally safer surface modifications. Research has reported that fluorine-free water-repellent coatings can maintain their wash resistance for up to approximately 50 wash cycles; however, their effects on breathability and comfort remain a controversial topic (Yu et al., 2021; He et al., 2023).

5.2. Energy Management and Uninterrupted Operation Issue

The most significant technical barrier to the commercialization of smart textiles is the provision of reliable and long-lasting energy. Although piezoelectric and triboelectric solutions have shown significant progress at the prototype level, hybrid energy solutions (harvesting + flexible storage) are required for applications that require continuous data transmission and high power (Huang et al., 2021; Kim et al., 2018; Wang, 2013).

Furthermore, energy management and the integration of energy storage units into the fabric must be balanced within the flexibility-weight-comfort triangle (Shi et al., 2019).

5.3. User Acceptance

User acceptance is directly related to parameters such as visibility, weight, and tactile comfort. Research shows that the visibility of electronic components affects consumer perception and that a balance must be struck between aesthetics and function (Stoppa & Chiolerio, 2014). Furthermore, since smart textiles can collect health data, they also raise issues of data privacy, security, and ethics; these issues must be considered during the design phase (Shi et al., 2019).

5.4. Recycling and Sustainability

Multi-layered electronic-textile composites pose a major obstacle to recycling. Components such as copper, Ag-nano, gold electrodes, and lithium-ion polymer batteries are difficult to separate in conventional textile recycling (Newby et al., 2023). The 2023 EU Textile Strategy has brought the requirement for modular, removable components in smart textiles to the forefront. This approach is being tested in the Samsung E-Textile Patch and DuPont Intexar systems.

Figure 17. DuPont Intexar (https://www.dupont.com)

6. Future Perspectives

The future of smart textiles extends far beyond sensor-integrated products. Functional textiles are expected to evolve into a new biomechatronic platform that combines hardware, software, and materials science.

6.1. IoT-Integrated Smart Textiles

The concept of fully-integrated IoT garments is becoming increasingly common in the literature. In these systems, textiles do not merely collect data; they also incorporate processing, data storage, and wireless transmission components. When smart textiles are combined with IoT architectures, they offer high added value in applications such as real-time health monitoring, driver fatigue detection, sports performance optimization, wireless patient monitoring in hospitals, and location and fall detection in elderly care. Shi and colleagues (2019) emphasized the importance of integrating data processing and local (edge) computing capabilities with fabric when developing the concept of STIMES (smart textile-integrated microelectronic systems) (Shi et al., 2019).

6.2. Artificial Intelligence-Powered Personalized Wearable Products

Machine learning algorithms will enhance the personal adaptability of smart textiles. Machine learning models can design adaptive heating/cooling, compression, or alert systems based on an individual's biometric profile. This personalization offers practitioner-specific solutions in medical rehabilitation, chronic disease management, and performance sports. Artificial intelligence will also be used for anomaly detection and predictive maintenance from sensor data. Yadav & Yadav (2025) have developed a new system for health, fitness, and personalization that can measure and analyze biometric data such as heart rate, hydration, and glucose in real time and non-invasively using electrochemical sensors + textiles + AI algorithms. Artificial intelligence-powered:

1. posture-improving shoulder straps
2. temperature-regulated sportswear
3. stress-based color-reactive garments are no longer just prototypes, but commercial products.

6.3. Biodegradable Electronic Textiles and Environmental Transformation

Sustainable material transformation is one of the most critical parameters for the future. In recent years, researchers have focused on developing biodegradable conductive polymers, water-soluble electronic components, and composites that can be broken down in nature to reduce the burden of e-waste. Biodegradable electronic structures such as cellulose-based conductive fibers, biological carbon-fiber alternatives, and hydrogel sensors derived from seaweed are rapidly increasing in the literature. Progress in this direction will both reduce environmental impact and facilitate compliance with regulatory requirements (Newby et al., 2023).

6.4. Projections and Research Areas

The following topics are expected to be among the priority areas for research and development over the next 5–10 years.

- Production of washable, long-lasting conductive fibers,
- High-efficiency, flexible energy storage units,
- Tribo/piezo/solar-based hybrid energy harvesting,
- Material- and design-focused biodegradable electronics,
- Data privacy and regulatory compliance protocols. These areas are expected to gain priority in both academic literature and industrial R&D investments (Wang, 2013; Huang et al., 2021; Newby et al., 2023).

7. Conclusion

This chapter explores the changing and evolving nature of the textile and fashion industries in terms of smart textiles and material-focused technological innovations. Developments over the past decade have not only enabled new functionalities for clothing but also allowed textiles to transcend traditional boundaries, expanding into a wide range of disciplines, from healthcare technologies and military systems to sports performance tracking and personal security applications. In this context, textiles are no longer merely clothing; they serve as platforms capable of reading biological signals, generating energy, responding to environmental stimuli, and interacting with the wearer.

Industrial applications such as Google Jacquard, Adidas PulseBoost HD, Under Armour health-tracking apparel, Sensoria smart running socks, and Levis-Google sensor-enabled denim textiles demonstrate that smart textile technologies are becoming a viable and scalable reality in the global fashion market. However, fundamental challenges highlighted in the academic literature—such as wash resistance and elasticity loss, the need for energy storage, wearer comfort, sustainability issues, and recycling challenges—remain relevant. This suggests that future research should focus on these areas. Future projections suggest that clothing products will transform from a static structure into a dynamic technological interface within the fashion and textile ecosystem. This transformation demonstrates that the cultural dimension will not be lost; on the contrary, local craftsmanship, motifs, identity, and aesthetics will be recreated through contemporary technology. Numerous literatures, including UNESCO, emphasize that fashion design will reinterpret past references and generate both aesthetic and economic value in a globally competitive environment. Thus, the textile industry will maintain its status as both a technological and cultural resource.

In conclusion, it can be said that wearable technologies and smart textiles offer significant opportunities not only in academic terms but also in terms of commercial production and social benefits. However, the need for sustainable systems is essential. Therefore, future work in this area is expected to focus on cost-effective, user-centric integrated fabric-sensor systems that minimize environmental impact. When all the data is considered together, it can be strongly predicted that smart textiles and wearable technologies are among the key innovation areas shaping the future of the fashion industry and will become much more visible, functional, and accessible in the next decade.

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CHAPTER IX

TEXTILE-BASED WEARABLE TECHNOLOGIES USED IN PATIENT MONITORING

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Introduction

Traditional healthcare systems have faced numerous obstacles (Yip et al., 2019) in addressing widespread health challenges in recent years, such as population aging (Gurwitz and Pearson, 2019) and global pandemics (Osier et al., 2020), resulting in inefficient, delayed and limited medical services (Chen et al., 2021). For example, chronic diseases affecting elderly people require constant monitoring and long-term nursing care (Kvedar et al., 2016). Hospitals in resource-limited areas lack access to comprehensive diagnostic tests for the increasing number of elderly people (Sen et al., 2020). In these cases, diseases often reach a more advanced stage before a diagnosis is made (Davenport et al., 2017). Furthermore, the traditional healthcare system is disease-centric and fails to consider patient variability (Vargas and Harris, 2016). Doctors prescribe single-drug treatments based on population averages rather than personalized treatment (Collins and Varmus, 2015). Therefore, inadequate, delayed, and inaccurate medical services have traditionally harmed numerous patients, leading to rapidly escalating costs and medical burdens.

It is necessary to monitor patients with chronic diseases, including diabetes, cardiovascular diseases, and neurological disorders, in real time and continuously (Iqbal et al., 2021).

According to the World Health Organization (WHO), three-quarters of all deaths worldwide are due to chronic diseases, which impose a high economic burden (Amine et al., 2003). Therefore, different strategies are needed to diagnose and monitor such diseases. Wearable technologies will be an effective strategy in this regard (Someya et al., 2016). Wearable technologies are defined as devices that are attached to clothing or the human body (Xie et al., 2020). Despite the increasing aging population in European countries, the number of caregivers, the need for doctors to monitor patients' conditions for extended periods outside the hospital, the increase in personal care activities at home, and the desire of users to monitor their own health are increasing the need for these technologies (Bonato, 2003; Pentland, 2005).

Traditionally, the textile industry is defined as the production of fibers, yarns, fabrics, and textile products. Technological advancements, increasing market competition, and changes in society have led to the need for new solutions, and industrial textile applications are becoming increasingly widespread. Textiles possess unique properties such as lightness, flexibility, dimensional variability, and the ability to achieve specific properties through varying degrees of structural and surface modification. Because of these characteristics, the keys to textile innovation lie in interdisciplinary research in medicine and engineering (Mečņika et al., 2015).

Collecting real-time data from patients not only provides healthcare professionals with insights but also allows for early diagnosis and personalized treatment plans. Wearable devices enable continuous monitoring of physiological parameters, especially in chronic diseases, by involving patients in proactive health management. As technology advances, wearable devices are poised to reduce healthcare costs, promote preventative strategies, and improve overall health problems (URL 1).

Textile-Based Wearable Technologies

Wearable devices are devices that integrate various electrodes, sensors and data path structures into a textile garment, allowing patients to continue their normal daily activities without discomfort (Azeem et al., 2025). These devices consist of a transducer and a target receptor. The receptor recognizes the target analyte and responds accordingly (Kozitsina et al., 2018). Then the transducer converts the response from the receiver into a useful signal (Bhalla et al., 2016).

Textile-based wearable technologies are designed to measure physiological parameters for chronic diseases, daily activity tracking, and other purposes, and are increasingly gaining ground in everyday life (Akbulut and Akan, 2015). Data collected by a wide variety of sensors, such as heart rate monitoring, lung airway capacity measurement, and accelerometers, are used in many areas to facilitate healthcare, military, and business life. Because it combines multiple disciplines, this field is preferred by researchers in various fields. These systems enable the recording and transmission of physiological data, as well as wireless communication between the user, the patient, and healthcare personnel. Especially when long-term biomonitoring is required, these systems ensure better psychophysiological comfort by ensuring patients remain mobile (Catrysse and Pirotte, 2015; Chan et al., 2007; Alemdar and Ersoy, 2010; Schwarz et al., 2010).

The main features of textiles mobilized by smart applications are flexibility to adapt to the body, tactile comfort, softness and wearability, and internal acceptance and acceptability of textiles by the patient (Van Langenhove, 2007).

Integrating Sensors into Clothing

Sensors that can be integrated into fabric are also called textile-based sensors. These sensors are often used to monitor physiological data or detect exposure to environmental conditions. There are many ways to integrate these sensors into fabrics. Some of these methods include printing, embedding and textile fabrication. Textile production uses techniques such as weaving, knitting or embroidery. Printing uses various methods, including inkjet printing, screen printing, or spray printing. In the embedding process, sensors are embedded into clothing using a polymer matrix (Romano et al., 2018).

Today, various materials are used to produce textile-based wearable devices. These are (URL 2):

1. Conductive Materials: These fabrics typically contain metallic fibers or conductive polymers. This allows for connection to electronic devices.

2. Sensing Materials: These fabrics contain embedded sensors that can detect physical conditions and can measure heart rate, body temperature, and muscle activity. This information is crucial for monitoring a patient's health.

3. Responsive Materials: These fabrics respond to external stimuli. For example, they can change color when exposed to sunlight or adjust their shape according to body movements. This feature is particularly desirable for fashion and sports applications.

In addition to these materials, fiber optics, graphene-based inks and piezoresistive textiles can also be used (Arquilla et al., 2021; Alizadeh Meghrazi et al., 2020; Di Tocco et al., 2018; Islam et al., 2022). Textile-based sensors have advantages over traditional sensors, such as improved wearability, enhanced comfort, and seamless integration into clothing (Arquilla et al., 2021; Eskandarian et al., 2022). These sensors allow for discreet monitoring of both physiological and environmental parameters while maintaining flexibility and customization options. Furthermore, some of these sensors are washable and durable, making them suitable for long-term use in various fields, such as healthcare and sports (Romano et al., 2018; Islam et al., 2022; Rajanna et al., 2020).

Sensors in wearable devices enable patient monitoring by collecting physiological and movement data. Sensors are placed according to the specific clinical application. For example, sensors are used to monitor vital signs, such as heart rate and respiratory rate, when monitoring patients with congestive heart failure or chronic obstructive pulmonary disease undergoing clinical interventions. Sensors used to monitor movement data can be used in applications such as monitoring the effectiveness of rehabilitation interventions in paralyzed patients in the home environment or the use of mobility aids in the elderly (Van Langenhove, 2007).

Sensors respond to physical changes in their environment, such as motion and temperature. Textile electrodes can be used to detect electrical signals from the body, such as electrocardiography from the heart and electromyography from skeletal muscles. Textile-based strain gauges and pressure sensors can detect body movements, such as foot pressure and respiratory movements. Accelerometer sensors detect the speed of movement and can focus on a specific limb or determine the body's overall activity level, depending on placement (Coyle and Diamond, 2013).

Wireless communication is used to transmit data obtained from the patient to a mobile phone or an access point, and from there to a remote center via the Internet. In case of emergency such as a fall, the system detects the situation through data processing and sends an alert message to the emergency center to provide assistance to patients very quickly. Family members and caregivers are alerted when an emergency occurs, but they are also notified in situations such as when the patient needs to take their medications. Clinical staff can monitor the patient's condition remotely and be notified when a medical decision needs to be made (Patel et al., 2012).

Table 1 lists some physiological parameters commonly studied using textile-based sensors (Coyle and Diamond, 2013).

Table 1. Physiological Signals Measurable with Textile-Based Sensors

Physiological measurement	Textile- integrated sensors	Signal source	Typical sensor placement
Breathing patterns	Piezo- resistive stretch sensors, inductive plethysmography, optical fibres	Expansion and ribcage contraction of during breathing	Thoracic- abdominal region
Heart activity	Woven/knitted electrodes	Electrical activity of heart	Thoracic region
Muscle activity	Woven/knitted electrodes	Electrical activity of muscles	Skin surface overlying relevant muscles
Blood oxygen saturation	Optical sensing components, plastic optical fi bres	Light absorption of haemoglobin in blood	Regions with good blood perfusion
Blood pressure	Features of the photoplethysmography (PPG) signal	Arterial pressure pulsations	Finger and wrist earlobe
Body movement, posture	Piezoresistive strain/pressure sensors, accelerometers, gyroscopes, optical fiber sensors	Body kinematics	Dependent on motion to be analysed
Electrodermal activity	Woven electrodes	Skin electrical conductivity	Finger tips
Composition of body fluids	Electrochemical sensors, colorimetric pH fabric	Composition of sweat, saliva, urine	Fluidic sampling system necessary

For textile-based wearable sensors to be used more widely in healthcare, several challenges such as regulation, standardization, data privacy, and security concerns need to be overcome (Adak and Mukhopadhyay, 2023; Ballaji, 2022).

Examples of Products Used for Patient Monitoring

Some wearable devices can be used to monitor a patient's vital signs and send that data to computers or smartphones. For example, smart shirts and belts can measure blood pressure and body temperature during treatment and recovery. These devices can also monitor patient movements and posture. For example, posture sensors can alert the patient or doctor if they're slouching.

Some wearable devices can track a patient's movement, gait and muscle activity. This monitoring could significantly improve the quality of life of patients with balance disorders, individuals with Parkinson's disease or patients with leg prostheses, as it would help them move more independently and safely.

Smart Shirt

Figure 1. Sensatex Smart Shirt

The Smart Shirt shown in Figure 1 was developed using technology from Georgia Tech. Optical and conductive fibers are integrated into this shirt to monitor the patient's vital signs. The shirt is designed for physiological monitoring in a variety of situations, including chronically ill patients, athletes, individuals living alone, elderly and infants (Coyle and Diamond, 2013).

Lifebelt

A lifebelt is a garment that can remotely monitor patients, automatically assess their condition based on collected and analyzed vital signs, and provide access to patient medical data at any time. It is most commonly used during pregnancy. It is a valuable decision-support tool for obstetricians, who can receive alerts when there is a possibility of pregnancy complications, a physical examination of the patient is necessary (Van Langenhove, 2007).

Figure 2. Frontal View of the Lifebelt

Lifebelt allows for regular monitoring even when the mother is in remote areas where access to adequately equipped healthcare facilities is time-consuming, difficult and costly, or where local weather conditions make travel limited or impossible. The front view of the Lifebelt is given in Figure 2.

Lifebelt is an innovative early diagnosis and decision support tool used during pregnancy. For participating healthcare personnel and hospitals/medical centers, Lifebelt allows monitoring various parameters of the mother, such as heart rate, blood pressure, body temperature, weight, oxygen saturation and abdominal growth, as well as parameters of the fetus, such as fetal heart rate. All of this is presented in a convenient report format that can be accessed at any time.

Breathing T-Shirt

Figure 3. Breathing T-shirt

Researchers at Laval University in Canada have developed a smart T-shirt (Figure 3) that monitors the wearer's breathing rate in real time. This T-shirt operates without any wires, electrodes, or sensors attached to the body and features an antenna sewn into the shirt's chest. The antenna is made of a hollow optical fiber coated with a silver layer and a protective polymer coating. It detects and transmits signals generated by breathing movements, which can be sent to a smartphone or computer.

Exmobaby Clothing

Exmobaby clothing is a sleepwear designed to measure vital signs of babies. This system includes an electrocardiogram, internal skin temperature, humidity, and motion sensors. It can wirelessly transmit the baby's vital sign data to a computer up to 30 meters away.

ECG Monitoring Vest

Wearable Medical Device company Nuubo has developed a garment-based ECG Monitoring System. As seen in Figure 4, this is a wearable vest-shaped device with embedded electrodes for measuring vital signs. These electrodes monitor and assist patients in cardiac rehabilitation (URL 3).

Figure 4. ECG Monitoring Vest (URL 4)

Nuubo is used to detect and diagnose irregular heart rhythms. It helps doctors diagnose potential heart rhythm problems while patients are going about their normal daily activities, even when they are not in a clinic or hospital.

Osteoarthritis Glove

Quantic Nanotech has developed the QNanotech glove, which provides vibration and correction functions to relieve joint pain.

Figure 5. Osteoarthritis Glove (URL 5)

Electronic Gloves combine different physical therapies, scientifically proven to effectively relieve hand stiffness and joint pain. It's an innovative system that combines the benefits of outpatient therapy in a single, at-home device with the push of a button. This glove is shown in Figure 5.

BalanceBelt

Figure 6. BalanceBelt (URL 6)

Patients suffering from severe balance disorders, such as Bilateral Vestibular Loss, experience significant imbalance and difficulty walking. Bilateral Vestibular Loss affects approximately 81 out of every 100,000 people, or more than 6 million people worldwide. By detecting the direction the user is leaning and reporting body position through vibrations, the BalanceBelt helps patients with severe balance disorders move freely without the need for assistance, a cane, or a wheelchair.

EEG Caps

EEG caps can facilitate early diagnosis of disorders such as Attention Deficit Hyperactivity Disorder (ADHD) by monitoring the neural activity of children during their daily activities. This non-invasive approach allows early intervention in such disorders (Casson et al., 2018; Liu et al., 2024). This cap is shown in Figure 7.

Figure 7. EEG Caps (URL 7)

Edema Stocking

Edema ApS has developed a sock to measure and manage changes in leg volume, particularly in patients experiencing lower extremity edema (Figure 8). This sock is washable and is not yet available to patients, but clinical trials and validation are underway. In the future, this sock could be used to monitor congestive heart failure or preeclampsia associated with edema, hypertension, and protein in the urine during pregnancy.

Figure 8. Edema Stocking (URL 8)

Intellitex Suit

The Intellitex Suit shown in Figure 9 is an example of a smart biomedical garment made of electroconductive textile materials that allows for the best possible monitoring of infant and pediatric patients. The use of both knitted and woven stainless steel electrodes offers a solution to the disadvantages of traditional electrodes (Van Langenhove, 2007)

Figure 9. The Intellitex Suit

Conclusion

Research demonstrates the high potential for textile materials to be used as sensor elements, interconnects, and transmission links in smart biomedical clothing. The use of electronics in patient care and treatment provides reliable monitoring. The most significant advantages are improved patient comfort and the reusability of sensors.

Remote health monitoring can reduce the burden on the healthcare system and reduce costs to society by reducing frequent hospitalizations. Monitoring patients helps identify symptoms associated with the disease and this is crucial for diagnosis, clinical intervention and rehabilitation treatments for serious medical conditions. In recent years, there has been a significant increase in the use of mobile and wearable devices, leading to the emergence of smart textile solutions that offer continuous monitoring. These alternatives are fueling a technological shift in healthcare that includes continuous monitoring and tracking of individuals.

Wearable devices can facilitate early detection of health problems and promote preventive medicine by providing real-time feedback. They can also help individuals receive timely interventions and personalized treatment plans through remote patient monitoring.

As technology advances, wearable systems become more complex, clothing can become deformed during use, and issues such as limited washability can arise. This is a potential obstacle to widespread adoption of these systems. However, with increasing consumer awareness, wearable monitoring clothing is expected to find wider adoption among individual consumers. These clothing systems could play a significant role in supporting the independence of individuals with disabilities and the elderly, particularly given the aging population.

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CHAPTER X
SOLAR-POWERED FASHION ACCESSORIES: INTEGRATING RENEWABLE ENERGY INTO SUSTAINABLE DESIGN

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Abstract

The present study explores the integration of solar energy technologies into fashion accessories design, focusing on the development of a solar-powered handbag. This project responds to the increasing dependence on mobile devices and the demand for sustainable energy solutions in everyday life. Using a qualitative and exploratory methodology, the study combines principles of wearable technology, sustainable design, and renewable energy. The handbag incorporates a small photovoltaic panel connected to a portable power bank, enabling the charging of electronic devices through solar power. Beyond its functional purpose, the accessory symbolizes the convergence of aesthetics, technology, and environmental awareness, aligning with the UN Sustainable Development Goal 7 — Affordable and Clean Energy. The results suggest that wearable energy solutions can enhance the sustainable design field by merging functionality, aesthetics, and ecological responsibility, promoting more conscious and self-sufficient consumer behavior.

Keywords: wearable technology; sustainable design; solar energy; fashion accessories; renewable energy

Introduction

The contemporary fashion landscape is increasingly influenced by the dynamics of technology, sustainability, and digital mobility. As societies become more urbanized and dependent on portable devices, the demand for energy accessibility has become an everyday necessity. Smartphones, smartwatches, and wireless headphones have transformed personal habits, but they have also created new forms of dependency on continuous electrical supply. This growing need for energy independence is not only a technological concern—it is also a cultural one, as it redefines how humans interact with objects, the environment, and time itself. Within this context, design must move beyond ornamentation, offering solutions that respond simultaneously to functionality, aesthetics, and environmental responsibility.

Fashion has historically reflected technological transitions, from the mechanization of textile production to the rise of digital design and smart textiles. Today, the convergence between design and renewable energy represents a new frontier in this evolution, transforming fashion into a vehicle for ecological awareness. Wearable technologies, once associated mainly with performance or data tracking, are increasingly being explored as mediators between the body and the environment—tools capable of harvesting, conserving, and redistributing energy. Such developments require fashion design as a field of experimentation where innovation aligns with the ethics of sustainability, autonomy, and social engagement.

At the same time, sustainability has become one of the most pressing discourses in the creative industries. The fashion sector, recognized as one of the most polluting in the world, faces the urgent challenge of adopting cleaner production methods and circular design principles. Integrating renewable energy into wearable products offers a tangible path toward these goals, connecting technological innovation with responsible design practices. By incorporating photovoltaic systems into accessories, designers can propose not only functional solutions but also narratives of empowerment and self-sufficiency—qualities increasingly valued by contemporary consumers.

The dialogue between energy, technology, and aesthetics opens new perspectives for the fashion industry, enabling designers to rethink the purpose of everyday objects. A solar-powered handbag, as proposed into this study, for instance, embodies both innovation and symbolism: it provides practical energy autonomy while communicating a commitment to environmental awareness. Through such products, design can play an active role in shaping

behavioral change and promoting sustainable consumption habits. More than a fashion statement, these innovations represent the emergence of an ethical paradigm in which fashion becomes a catalyst for ecological transformation.
The justification for this research lies in the necessity of aligning technological progress with environmental responsibility. While renewable energy solutions have advanced significantly in architecture and transportation, their integration into fashion design remains limited and underexplored. This gap reveals an opportunity for interdisciplinary collaboration between designers, engineers, and sustainability researchers, fostering a new generation of products that merge usability, symbolism, and ecological function. Addressing this challenge contributes to expanding the discourse of fashion beyond surface aesthetics, positioning it as a strategic agent in the broader agenda of sustainable development.

The main contributions of this study are twofold: first, to demonstrate the feasibility of integrating solar energy systems into fashion accessories without compromising their aesthetic integrity; and second, to establish design as a mediator between renewable technology and consumer culture. By developing a solar-powered handbag, this project exemplifies how wearable technology can provide both practical benefits—such as on-the-go energy generation—and cultural value, reinforcing the notion of fashion as a medium of awareness and change. The study thus proposes a design framework that combines material innovation, functionality, and symbolic communication.

Furthermore, the objective of this research is to develop and analyze a functional, sustainable, and aesthetically coherent handbag equipped with a solar charging system capable of recharging small electronic devices. The project seeks to explore the convergence between renewable energy and fashion design, examining its ergonomic, technical, and emotional dimensions. Furthermore, it aims to discuss how wearable solar technologies can promote energy autonomy and support the shift toward more conscious patterns of production and consumption within the fashion system.

This article is organized into six sections. Following this introduction, the second section presents the theoretical framework, discussing the relationship between wearable technologies, sustainable design, and cultural meaning in fashion. The third section outlines the methodological approach, detailing the research stages, data collection, and prototype development. The fourth section describes the design process and technical integration of the solar system. The fifth section discusses the results and implications for sustainable innovation. Finally, the sixth section concludes the study, summarizing its contributions and suggesting directions for future research on renewable energy in fashion design.

Wearable technologies, sustainable design, and cultural meaning in fashion: an integrated perspective

As fashion moves beyond its traditional aesthetic and functional boundaries, it increasingly embodies technological integration, environmental ethics, and social symbolism. Wearable technologies—ranging from sensor-embedded garments to solar-powered accessories—have evolved from being purely functional tools to becoming expressive, value-driven artifacts. This convergence allows fashion to serve as both a medium of personal empowerment and a platform for collective sustainability, reflecting an urgent shift toward more responsible forms of innovation.

Sustainable design principles have played a crucial role in redefining how wearable technologies are conceptualized and produced. Traditional approaches that focused primarily on usability and novelty are now being replaced by holistic frameworks grounded in environmental awareness and long-term responsibility. Concepts such as *cradle-to-cradle* and circular design emphasize longevity, modularity, and the recyclability of materials, promoting a life-cycle mindset that seeks to minimize waste and reduce ecological footprints (Gurova et al., 2020, Dulal et al., 2022, Gwilt et al., 2017, Pearl, Intriligator & Liu, 2025). By integrating these principles, designers are not only addressing ecological concerns but also fostering a new aesthetic of durability—one in which visible repair, adaptive reuse, and transparency of process become desirable qualities rather than flaws.

Furthermore, the development of sustainable wearables relies heavily on interdisciplinary and user-centered methodologies. Design processes informed by ethnography, engineering, and behavioral studies enable a deeper understanding of users' emotional and cultural relationships with technology (Lu & O'Reilly, 2024; Casciani, 2023, Pearl, Intriligator & Liu, 2025). The inclusion of users in participatory design stages ensures that products align with human needs rather than technological determinism. Such approaches reflect the growing influence of *responsible innovation* (Min, Shen & Ren, 2024; Le, Dang & Bui, 2024), where technological progress must be guided by ethical considerations, inclusivity, and the anticipation of long-term social consequences. In this sense, sustainable wearables extend beyond functionality—they become sites of dialogue between humans, machines, and environments.

The cultural dimension of wearables introduces another essential layer of meaning. Fashion technologies are not neutral artifacts; they embody narratives, identities, and cultural memories. Integrating traditional crafts, indigenous aesthetics, and regional materials into wearable designs fosters cultural preservation while promoting emotional attachment (Le, Dang & Bui, 2024, Singh, 2022, Versteeg, van den Hove & Hummels, 2020). This connection between innovation and heritage generates what could be described as *cultural sustainability*, the continuity of intangible values through material expression. In communities where artisanal practices coexist with modern technological interventions, wearable design becomes a hybrid language that negotiates between the local and the global, the ancestral and the futuristic.

Equally important is the embodied experience that wearables provide. Unlike static objects, these artifacts exist in dynamic interaction with the human body, shaping sensory perception and social behavior. The tactile qualities of materials, the responsiveness of embedded systems, and the aesthetic coherence between form and movement contribute to their emotional and cultural significance (2, Smelik, Toussaint, & Van Dongen, 2016; Versteeg, van den Hove & Hummels, 2020). Through this embodiment, wearables mediate identity and belonging, turning the body into both an interface and a canvas of expression. Whether through biometric sensors, smart fabrics, or solar panels, these technologies reflect a dialogue between inner and outer worlds—between the desire for connection and the need for autonomy.

Collaborative and co-design models have emerged as vital mechanisms for integrating cultural sensitivity into wearable design. Partnerships between designers, engineers, and artisans can lead to the creation of hybrid products that respect traditional knowledge while incorporating contemporary innovation (Le, Dang & Bui, 2024, Singh, 2022). Such collaborations also democratize technological access, decentralizing production and promoting inclusivity. In this sense, wearable design becomes an act of cultural mediation—where technology supports diversity rather than homogenization, and where communities contribute directly to the innovation process.
Despite these advances, several challenges persist. The tension between rapid technological change and sustainable design practices often leads to issues of e-waste, obsolescence, and inequitable access (Gurova et al., 2020, Dulal et al., 2022, Gwilt et al., 2017, Pearl, Intriligator & Liu, 2025). Additionally, the cultural appropriation of traditional motifs for market-driven purposes raises ethical concerns regarding ownership and authenticity. To address

these issues, designers must balance innovation with reflection, ensuring that technological progress does not compromise environmental integrity or cultural respect. The opportunity lies in developing frameworks that promote ethical production, material transparency, and participatory value creation (Bryan-Kinns et al., 2018; McMillan, 2019).

In summary, the relationship between wearable technologies, sustainable design, and cultural meaning is defined by the integration of technical innovation, environmental responsibility, and cultural awareness. Therefore, we notice that sustainability and cultural meaning intersect across three dimensions: material and production ethics (Gurova et al., 2020, Dulal et al., 2022, Le, Dang & Bui, 2024), user experience and emotional value (Lu & O'Reilly, 2024; Smelik, Toussaint, & Van Dongen, 2016; Versteeg, van den Hove & Hummels, 2020), and design approach through interdisciplinary and co-creative processes (Min, Shen & Ren, 2024; Le, Dang & Bui, 2024, Singh, 2022). Success in this field depends on cross-disciplinary collaboration, user-centered innovation, and a commitment to cultural and ecological resonance. Ultimately, wearable fashion's potential lies not only in what it does, but in what it represents—a vision of technology that sustains both the planet and the people who inhabit it.

Methodology

The methodological framework adopted in this study follows the principles of qualitative and exploratory research, structured according to the design development processes proposed by Löbach (2001), Baxter (2010), and Treptow (2013). These authors provide complementary perspectives on how product design should articulate functionality, aesthetics, and social meaning through systematic and user-centered stages. Löbach (2001) emphasizes the creative and cognitive dynamics of the design process, where form and function evolve in response to human needs and symbolic interpretation. Baxter (2010) contributes a methodological rigor based on structured planning, market analysis, and product specification, ensuring design feasibility and technical validation. Treptow (2013), in turn, situates these processes within the fashion system, stressing the importance of aesthetic coherence, symbolic representation, and material experimentation in product innovation.

The research process was divided into four main stages: (1) bibliographic research, (2) market and user analysis, (3) product design and prototyping, and (4) evaluation and validation. This structure ensured a holistic understanding of the relationship between technology, sustainability, and fashion aesthetics. Each stage was guided by specific tools and methods designed to integrate user perception, environmental responsibility, and technological functionality.

In the first stage, bibliographic research was conducted to map theoretical and technical foundations concerning renewable energy, wearable technology, and sustainable fashion design. Sources included scientific publications, technical reports from the International Renewable Energy Agency (IRENA), and theoretical frameworks from design authors. This stage allowed the definition of the main analytical axes: sustainability, usability, and aesthetic integration.

The second stage, market and user analysis, followed Baxter's structured approach to identifying opportunities for innovation and differentiation. Benchmarking was used to compare existing solar-powered bags, power banks, and sustainable accessories available in the Brazilian and international markets. This analysis revealed a design gap—most solar accessories prioritize performance but lack an urban, minimalist aesthetic suitable for daily use. Additionally, a user profile study was conducted through exploratory questionnaires to identify the needs, habits, and expectations of potential consumers. Personas were then created to represent these findings, such as *Mariana*, the digital marketing analyst seeking autonomy during urban commutes, and *Rafael*, the freelance designer balancing technology and sustainability in his professional life.

The third stage, product design and prototyping, was developed according to the methodological structure proposed by Löbach (2001), moving from conceptual abstraction to material realization. This stage was divided into subphases: (a) *informational design*; (b) *conceptual design*; (c) *preliminary planning*; and (c) *detailed design*. Tools such as functional analysis, semantic, syntactic, and pragmatic analysis (adapted from Silveira, 2018), style benchmarking, and mood boards were employed to translate the conceptual identity into tangible form. The process also incorporated alternative generation and selection matrices to evaluate prototypes based on criteria such as usability, material sustainability, ergonomic comfort, and visual coherence. The selected prototype combined a brim cotton fabric with a 3-watt photovoltaic panel, connected to a portable power bank compatible with universal USB charging, balancing efficiency, lightness, and durability.

The planning phase followed Baxter's (2010) model of product specification, ensuring that aesthetic, functional, and production parameters were consistent with market viability. Technical documentation included material definitions, cost estimation, and lifecycle considerations, integrating sustainability metrics such as recyclability and repairability. Ergonomic analyses were also performed to ensure comfort and practical usability in urban contexts, while aesthetic coherence was maintained through neutral colors, clean lines, and minimalist composition.

The construction of the prototype was guided by Treptow's (2013) understanding of fashion design as a process of experimentation and critical reflection. Sewing techniques and textile finishing were tested to ensure both visual refinement and mechanical stability of the embedded photovoltaic system. This stage highlighted the designer's role as mediator between creative intention and technical feasibility—balancing expressive aesthetics with energy functionality. Challenges such as panel fixation, wiring concealment, and material reinforcement were addressed through iterative prototyping and testing.

Finally, the evaluation and validation stage involved usability testing and failure analysis, based on the assessment methods of Mesacasa and Cunha (2015). Three users tested the prototype under real conditions, evaluating attributes such as comfort, finish, texture, and charging performance. The results revealed a high acceptance index (average of 91%), confirming the product's effectiveness and market potential. Minor adjustments were identified regarding internal organization and energy performance under low-light conditions, leading to design improvements in structure and material resilience.

Overall, the methodological path combined theoretical rigor, empirical observation, and creative experimentation. Grounded in Löbach's cognitive design model, Baxter's systematic planning, and Treptow's aesthetic and cultural lens, this study exemplifies how product design can integrate sustainable technologies into fashion without compromising symbolic and sensory value. The application of analytical tools, user research, and iterative prototyping enabled the creation of a solar-powered handbag that harmonizes functionality, sustainability, and contemporary urban aesthetics, positioning it as a viable contribution to the field of wearable technologies and sustainable fashion design.

Informational design stage

The informational design stage was essential to establish the conceptual, technical, and aesthetic foundations for the development of the solar-powered handbag. Through bibliographic research, market benchmarking, and user studies, this stage aimed to align the project with principles of functionality, sustainability, and user-centered design. The process involved mapping current consumer demands, identifying opportunities for innovation, and defining the environmental and ergonomic parameters that would guide the next phases of development.

The opportunity for this project emerged from the observation of contemporary lifestyles marked by urban mobility, extended work routines, and increasing dependence on electronic devices such as smartphones, headphones, and smartwatches. Despite the expansion of sustainable fashion and wearable technologies, the market still lacked a product that integrated renewable energy into a functional and stylish accessory for daily use. Most solar-powered products available were designed for outdoor or sports contexts, often prioritizing technical performance over aesthetics. This identified a clear market gap for an urban, elegant, and sustainable handbag capable of combining practicality, energy autonomy, and modern design.

This proposal addresses this gap by integrating a small photovoltaic panel and portable power bank into a versatile handbag suitable for daily use. The product unites the appeal of fashion design with environmental responsibility, aligning with the United Nations Sustainable Development Goals (SDG 7 – Affordable and Clean Energy) by promoting access to renewable energy in everyday life, and with SDG 12 – Responsible Consumption and Production, by encouraging sustainable material use and conscious consumer behavior. The handbag also carries strong commercial potential due to three converging trends: the expansion of the mobile device market, the increasing consumer preference for eco-friendly products, and the growing interest in portable, renewable technologies.

A benchmark analysis revealed that solar-powered backpacks and power banks dominate the market but are limited to niche audiences focused on outdoor activities. Their average prices range between R$500–R$1000[7] for solar backpacks and R$100–R$300 for power banks, while urban handbags without solar integration range from R$80–R$400. This positioning opened a space for innovation: a solar-powered handbag that balances style, functionality,

[7] The minimum wage in Brazil is R$ 1,518.

and affordability, appealing to the modern, environmentally conscious urban consumer.

Based on the market and user analyses, the following requirements were defined for the product:

- Functionality: ability to charge small electronic devices (phones, earphones, etc.) using solar energy.
- Aesthetics: a contemporary, versatile design suited for urban daily use.
- Sustainability: incorporation of renewable energy and low-impact materials.
- Ergonomics: comfortable wearability, long adjustable straps, and organized internal space.
- Technology: compatibility with multiple charging inputs and outputs.
- Market Appeal: a minimalist, modern visual language that resonates with connected, conscious consumers.

These requirements guided the design process from concept generation to prototype validation, ensuring that the handbag would meet both technical and emotional expectations.

A detailed market study was conducted to define the target audience for the solar handbag. We notice that the potential consumers are predominantly urban professionals and students aged 20 to 45 years, regardless of gender, with an average income between R$2,500 and R$8,000. They are digitally connected individuals who value sustainability, technological innovation, and practical design solutions. Their purchasing behavior is largely influenced by e-commerce platforms, social media, and sustainable fashion marketplaces, reflecting a preference for brands that embody ethical and ecological values.

To synthesize the consumer insights and guide design decisions, five representative personas were created based on user research and lifestyle data, each illustrating a key segment of the potential market (Table 1):

Table 1. Representative Personas of Potential Consumers for the Solar-Powered Handbag

Persona	Age / Occupation	Location	Income (R$)	Profile Summary	Key Need
Mariana	27 / Digital Marketing Analyst	São Paulo – SP	4,800	Works long hours, constantly using her phone for calls and social media. Supports sustainable brands and values multifunctional accessories.	Charge phone throughout the day without relying on outlets in cafés or coworking spaces.
Rafael	35 / Freelance Graphic Designer	Belo Horizonte – MG	5,500	Works remotely, moves around the city using public transport and bike. Seeks functional, sustainable accessories.	Functional bag that combines clean technology, style, and organization.
Bianca	22 / Architecture Student	Salvador – BA	3,500 (family)	Studies full-time, values trendy and eco-friendly designs, participates in environmental initiatives.	Practical and stylish bag for carrying notebooks and charging devices during the day.
Lucas	41 / Tech Entrepreneur	Curitiba – PR	9,000	Runs a startup, attends meetings and events, values sophisticated and innovative products with ESG alignment.	Professional accessory that reflects his modern lifestyle while ensuring device autonomy.
Juliana	30 / Content Creator and Environmental Activist	Florianópolis – SC	6,000	Produces content on sustainable fashion and low-impact living, always connected.	Solar handbag that aligns with her ethics and allows continuous content creation.

These personas guided the design strategy by aligning product features with user expectations and emotional values, reinforcing the handbag's positioning as a functional, aesthetic, and ethical innovation. The integration of solar technology into fashion thus transcends mere functionality, becoming a form of symbolic design that reflects the aspirations of a conscious, future-oriented generation.

Core benefit and style planning

The core benefit of the solar-powered handbag lies in its ability to provide users with portable energy autonomy, allowing them to recharge small electronic devices conveniently and sustainably through integrated solar technology. This solution directly addresses a common daily need—keeping devices charged during long commutes, outdoor activities, or extended workdays—without reliance on conventional power sources. By transforming solar energy into a practical feature embedded within a fashion accessory, the product offers both immediate functional value and symbolic meaning: it represents a shift toward cleaner energy and responsible consumption within everyday life.

Beyond this primary advantage, the handbag delivers complementary benefits that enhance user experience and reinforce its market positioning:

- a modern, minimalist design adaptable to various contexts,
- sustainable materials and renewable energy integration,
- universal charging compatibility for diverse devices, and

- competitive pricing within the urban fashion market.

Together, these elements strengthen the product's value proposition as a functional, aesthetically refined, and ecologically responsible accessory that aligns with the lifestyle of contemporary consumers—connected, mobile, and environmentally aware. The clarity of its central benefit—clean, portable energy—combined with secondary advantages ensures the handbag's distinction among competitors and contributes to its innovative character in the sustainable fashion segment.

Building upon this functional foundation, the style planning phase aimed to translate the identified opportunity into a visual and aesthetic identity capable of merging technological utility with contemporary urban fashion. Previous models of solar accessories—mainly technical backpacks for hiking or camping—guided the identification of gaps in visual language. These predecessors prioritized robustness, bright colors, and performance-driven materials, characteristics that proved unsuitable for professional and urban environments. Indirect competitors, such as handbags with USB ports, provided only symbolic references to practicality, lacking both energy autonomy and environmental commitment.

To counter this, the project proposed a hybrid design identity that embodies the balance between innovation and elegance. The envisioned brand communicates *clean technology*, *environmental awareness*, and *accessible urban style*, grounded in three pillars: functional innovation, minimalist aesthetics, and sustainability. Its visual expression is defined by neutral color palettes, simple silhouettes, and high-quality finishes, avoiding excessive graphics or vivid hues to maintain a timeless, sophisticated appeal.

A style benchmarking study was conducted using national and international sustainable fashion brands such as Fjällräven, XD Design, Notiluca, Rains, and Insecta Shoes. This analysis revealed recurring aesthetic principles: earthy or neutral color palettes, simplified geometries, visible material quality, and the use of design as a tool for ecological communication. These insights guided the creative direction of the solar handbag, establishing it as a refined and conscious solution that dialogues with sustainable fashion trends while maintaining a distinct urban identity.

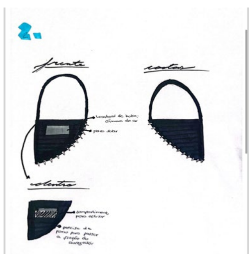
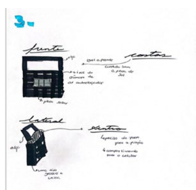
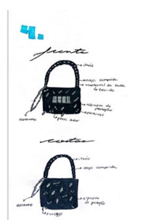
Parametric analysis of style was then applied to articulate the handbag's visual language relative to competitors. The proposed design emphasizes neutrality, balance, and material honesty, contrasting with the utilitarian excess of outdoor gear and the overly technical appearance of urban tech bags. The solar handbag's composition favors asymmetrical balance, smooth geometric rhythm, and coherence between visual and functional elements—achieving unity and clarity while highlighting its photovoltaic feature as both a functional and aesthetic focal point.

In summary, the style planning process consolidated the product's conceptual and symbolic alignment: a contemporary handbag that embodies autonomy, sustainability, and sophistication. Through its clean design and renewable functionality, we understand that the piece fulfills practical demands but also communicates cultural and ecological awareness—positioning fashion as an active medium for technological and environmental transformation.

Generation of alternatives and selection of the final design

During the ideation phase, nine visual and material alternatives for the solar-powered handbag were developed (Table 2). The initial concept proposed constructing the entire product from recycled inner tubes, a material that would strongly reinforce the sustainable commitment of the design and align it with the United Nations Sustainable Development Goals (SDG 12 – Responsible Consumption and Production). However, the material posed significant production challenges. The inner tube's high resistance and thickness made it extremely difficult to sew using a standard domestic sewing machine, compromising the product's manufacturability and scalability.

Table 2. Generation of alternatives

Piece 1	Piece 2	Piece 3	Piece 4	Pieces 5 – 9
				

Given these limitations, the project team decided to explore alternative materials that could maintain the aesthetic appeal and ecological intent while improving feasibility. The most effective solution was to adopt brim fabric — a plain-woven cotton-based textile — which offered strength, flexibility, and a high percentage of natural fiber content. This choice provided both environmental benefits and compatibility with available production tools, ensuring greater precision and finish quality.

Each of the nine conceptual sketches was then analyzed based on its visual potential, ergonomic usability, technical feasibility, and alignment with the project's aesthetic and functional goals (Table 3). The evaluation considered both the symbolic and pragmatic aspects of each design, following the principles of user-centered and sustainable design (Löbach, 2001; Baxter, 2010; Treptow, 2013).

Table 3. Comparative evaluation of alternative design concepts for the solar-powered handbag

Model	Main Material	Design Features	Advantages	Limitations	Decision
Piece 1	Inner tube	Graffiti-inspired design, short strap	Unique aesthetic	Difficult to sew, poor solar exposure	Discarded
Piece 2	Brim fabric (cotton)	Asymmetric shape, long strap	High solar exposure, easy production	None critical	**Selected**
Piece 3	Inner tube	Compact model	Resistant material	Incompatible with solar panel	Discarded
Piece 4	Flat fabric	Decorative metal accessories	Visually striking	Too niche, limited appeal	Discarded
Pieces 5–9	Inner tube	Various small or irregular forms	Experimental appeal	Wrong proportions, impractical	Discarded

The first model (Piece 1) featured an expressive visual identity inspired by urban graffiti and experimental color blocking. However, its use of inner tube material and short strap design made it impractical—the solar panel would remain under the user's arm, reducing sunlight exposure and energy capturing efficiency. The second model (Piece 2) was ultimately selected for production. Designed from the outset to use fabric instead of rubber, it presented a long strap that allowed the solar panel to remain exposed to light during use. Its asymmetric structure added a modern and distinctive character to the design while maintaining ergonomic comfort and functional coherence. This balance between innovation and usability made it the strongest candidate.

The third model (Piece 3) was excluded for the same reasons as the first—it relied on inner tube material and did not allow for proper solar panel integration. The fourth model (Piece 4) offered a promising alternative due to its flat fabric composition, yet it included numerous metallic embellishments such as eyelets, piercings, and safety pins, which gave it a niche, alternative aesthetic. Because the project aimed for a neutral, widely appealing visual identity, this design was deemed too stylistically restrictive.

The remaining models 5 through 9 were also discarded. Designs 5, 6, and 8 were too small to accommodate the photovoltaic panel selected for the project, while models 7 and 9 required solar panels of unavailable shapes and dimensions. Additionally, all five relied on inner tube material, reintroducing the same production and stitching constraints previously identified.

Nevertheless, the comparative analysis (Table 3) confirmed Piece 2 as the most balanced solution in terms of functionality, material feasibility, and aesthetic value. Its long strap design enhances solar capture efficiency, while the choice of brim fabric ensures sustainable, durable, and comfortable use. The final prototype thus embodies the project's vision: a product that unites technological innovation, sustainable materials, and contemporary fashion aesthetics into a coherent and accessible design.

Product planning and prototype development

The product planning phase focused on transforming the solar-powered handbag from concept to a functional prototype, ensuring technical feasibility, aesthetic coherence, and alignment with sustainable design principles. Based on Baxter (2010) and Löbach (2001), the process prioritized product quality, appropriate material selection, and integration of renewable technology within an accessible and durable design.

The analysis of product quality identified key factors that guided design refinement (Tabel 4): the unspoken desire for convenience in energy use, the basic need for personal storage, the excitement factor of technological novelty, and the performance expectation of reliability and comfort.

Table 4. Product quality dimensions and design responses

Quality Dimension	Description	Design Response
Latent Desire	Desire for an integrated, always-ready energy source.	Built-in solar panel for continuous charging.
Basic Need	Storage capacity for everyday use.	Internal organization and ergonomic design.
Excitement Factor	Curiosity about an innovative, dual-function product.	Hybrid of fashion accessory and energy generator.
Performance	Durability, comfort, and reliable charging.	Reinforced seams and adjustable strap for sunlight exposure.

The chosen technology was a Tomate-brand photovoltaic panel, offering 3W of power at 6V and 1A current, with USB 5V output suitable for small electronic devices. The component’s compact dimensions and polycrystalline waterproof structure ensured resistance and easy integration into the fabric.

The prototype construction was the most significant and instructive phase (Table 5). It involved translating the conceptual design into a tangible product through pattern development, cutting, sewing, and integration of the photovoltaic system. Initial challenges included the precision of fabric alignment and seam reinforcement to sustain the solar panel's weight and maintain usability. Adjustments were made to the strap length and angle, optimizing solar exposure without compromising comfort.

Table 5. Prototype construction phases and technical insights

Stage	Description	Key Observations
Cutting and Patterning	Definition of geometric panels for balanced structure.	Required precise measurements for solar module fit.
Sewing and Assembly	Assembly using brim fabric and reinforcement stitching.	Reinforcement at strap bases improved load resistance.
Panel Integration	Installation of solar module and USB wiring.	Cable channeling achieved without visual interference.
Testing and Adjustment	Real-sunlight test and ergonomic evaluation.	40% phone charge in 90 min; high comfort feedback.

The brim cotton fabric was selected for its durability, tactile quality, and high cotton content—offering a balance between ecological responsibility and manufacturing practicality. The inner structure was adapted to hide wiring while maintaining accessibility to the USB output. The final model achieved visual balance, ergonomic efficiency, and energy autonomy consistent with its conceptual goal.

The final prototype (Figure 1) demonstrated the effective merging of fashion and technology, maintaining aesthetic simplicity while providing a tangible functional benefit. The long strap design enhanced solar exposure, and the minimalist geometry communicated modernity and efficiency. The product's sustainable narrative was reinforced using natural materials and renewable energy, highlighting its potential as a marketable and socially relevant innovation.

In summary, the prototyping process validated the solar-powered handbag as a feasible and meaningful design solution. The product achieves an effective synthesis of functionality, sustainability, and aesthetic clarity, transforming renewable energy into a wearable expression of autonomy and ecological awareness. Its successful prototype demonstrates the potential of sustainable fashion design to unite innovation, environmental responsibility, and consumer practicality in a single, coherent artifact.

Figure 1. Developed prototype

Usability testing and product evaluation

The usability testing and final evaluation of the solar-powered handbag aimed to assess its overall performance in terms of functionality, comfort, and user acceptance. Three participants between 22 and 27 years old tested the prototype in real conditions, providing both quantitative ratings and qualitative feedback (Table 6). The test followed the method proposed by Mesacasa and Cunha (2015), which considers aesthetic perception, ergonomics, and satisfaction as key indicators of design success.

Table 6. Usability evaluation and acceptance index for the solar-powered handbag (adapted from Mesacasa & Cunha, 2015)

Consumer	Finish	Comfort	Wearability	Shape /Design	Fabric/ Texture	Color	Purchase Intention	Acceptance Index (AI)	Comments
Ana (27)	5	5	5	5	5	5	5	**100%**	Innovative design, durable fabric, and effective solar functionality.
João (23)	5	4	4	5	5	5	5	**93.4%**	Practical for outdoor work; good finish; useful charging system.
Beatriz (22)	4	4	3	4	4	5	3	**80%**	Creative concept, lightweight, easy to use; weaker solar performance on cloudy days.

The results demonstrated a high overall acceptance index of 91%, indicating excellent approval from users in terms of design quality, comfort, and functionality. The main positive aspects highlighted were the innovative concept, practicality of solar charging, and material durability. Minor improvement points included increasing internal compartmentalization, reinforcing some seams, and optimizing solar efficiency under low-light conditions.

From an aesthetic perspective, the handbag met its design goals, presenting a minimalist and balanced form that integrates the solar panel discreetly into the surface without compromising visual harmony. The choice of neutral colors and geometric proportions contributed to a professional, gender-neutral appearance suited for urban contexts. Functionally, the product performed efficiently in outdoor environments, successfully charging small devices such as smartphones and wireless earphones. The system's dependency on sunlight, however, led to slower performance under cloudy or indoor conditions—an expected limitation for photovoltaic applications. Nonetheless, users considered this acceptable given the handbag's portability and ecological advantage. Technically, the prototype overcame earlier challenges related to panel fixation and cable concealment. Reinforced stitching and internal channeling improved both safety and aesthetics. The adjustments made during assembly confirmed the product's technical viability, balancing lightness, resistance, and user comfort.

In summary, the solar-powered handbag successfully achieved its goal of merging fashion, technology, and sustainability. It provides a functional and symbolic response to contemporary consumer needs, offering renewable energy integration in an elegant, urban design. Despite minor refinements needed for future iterations, the prototype demonstrates strong potential for commercial application and user adoption, standing as an innovative example of sustainable fashion design driven by practical utility and aesthetic coherence.

Final considerations

The development of the solar-powered handbag enabled not only the creation of an innovative and functional product but also a critical reflection on how design, technology, and sustainability can be coherently integrated to meet the needs of the contemporary consumer. The project followed a design methodology grounded in user-centered and sustainable design approaches, incorporating bibliographic research, market analysis, prototyping, and usability testing. From the identification of a clear market gap—the absence of urban accessories that combine energy autonomy, aesthetic appeal, and environmental responsibility—to the evaluation of results, every stage was conducted with methodological consistency and practical validation.

The results confirmed that the handbag effectively meets its general and specific objectives, providing a practical and symbolic solution for users with active urban lifestyles who rely on mobile devices throughout the day. The incorporation of solar energy as a functional element not only adds value to the product but also reinforces its symbolic dimension, representing independence, ecological awareness, and innovation. The usability testing showed strong acceptance, with users praising the design's comfort, material quality, and technological relevance.

From an aesthetic and technical standpoint, the handbag achieved a balanced and minimalist visual language aligned with contemporary fashion trends. Its neutral color palette and geometric silhouette contributed to a timeless appeal, while the discreet integration of photovoltaic components ensured both elegance and usability. Technical adjustments during prototyping—such as seam reinforcement, cable concealment, and strap redesign—resulted in a product that successfully balances form, function, and environmental purpose.

In conclusion, the project demonstrates the feasibility of developing fashion accessories that transcend aesthetics, providing real and sustainable solutions aligned with the principles of the UN Sustainable Development Goal 7 (Affordable and Clean Energy). It reinforces the relevance of fashion design as a strategic and transformative discipline, capable of fostering environmental awareness through everyday products. The solar handbag represents a tangible manifestation of design's capacity to address practical issues while promoting ecological responsibility and social innovation.

Ultimately, the study validates the handbag's potential for market introduction, particularly in urban and conscious consumer segments that value innovation and sustainability. The experience gained throughout this process highlights the role of applied design research in bridging creativity and environmental ethics, positioning fashion as a medium for positive change.

For future studies, it is recommended to explore new materials and technological integrations, such as flexible photovoltaic textiles or modular electronic systems, as well as expanded testing with larger user groups. These developments may enhance performance, broaden accessibility, and strengthen the handbag's role as a model for sustainable innovation in contemporary fashion design.

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CHAPTER XI

DESIGN AND APPLICATIONS OF FLEXIBLE PIEZORESISTIVE PRESSURE SENSORS FOR SMART TEXTILES

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Introduction

Wearable technologies have become an inseparable part of modern life, enriching user experience and comfort by integrating technology directly into clothing and the human body. These innovations, often referred to as wearable computers, smart garments, or wearable materials, are gaining increasing popularity and presence in daily life. The main purpose of wearable technology is to provide technological functionality while being seamlessly integrated into the body as part of everyday activities. Such devices serve a wide range of purposes, including health monitoring, fitness tracking, personal safety, and even merging fashion with technology.

Among these technologies, smart textiles represent one of the most promising and dynamic areas. These textiles incorporate embedded sensors and processors capable of sensing environmental conditions, communicating data, and monitoring the wearer's physical state. Such garments can collect biometric data, track movement, and, in some cases, even assist in medical diagnostics. Because of these capabilities, smart textiles have become particularly valuable in healthcare and sports applications. Ongoing research and technological development in this field offer new possibilities for wearable platforms, expanding the potential and market scope of smart clothing systems.

For clothing that integrates sensor technology, the choice of lightweight, flexible, and comfortable materials is of great importance to ensure both functionality and comfort. Therefore, conductive textiles and textile-based sensors made using these materials are among the preferred options for wearable applications. These sensors not only enhance the comfort of the user but also expand the functional range of clothing.

Conductive fibres, yarns, and fabrics used in textile production are ideal materials for these kinds of applications. Conductive textiles can be produced in various ways by using metallic threads that are naturally conductive, by adding conductive components during fibre spinning, or by coating fibres and fabrics with conductive polymers. Introducing conductive properties during the production process allows textile materials to interface with electronic systems, making them more adaptable to wearable technologies. This approach ensures that smart textiles are not only functional but also aesthetically pleasing and comfortable, encouraging users to adopt wearable technologies in daily life.

Piezoresistive materials and conductive inks play a critical role in the design of functional garments that are integrated into wearable technologies. Piezoresistive materials change their electrical resistance when pressure is applied, making them suitable for low-voltage, simple electronic circuits. They are also more cost-effective than many other alternatives. This book chapter presents information about flexible pressure sensors, focusing on sensors produced by applying piezoresistive and conductive inks onto textile surfaces.

State of the Art

Textile-based sensors have been developed to monitor the human body and various environmental parameters in real time. These sensors can be categorized into several groups such as strain, pressure, temperature, and humidity sensors, each designed for specific applications. For example, strain sensors monitor body movements, pressure sensors detect physical interactions, and temperature sensors track body and environmental heat variations.

Recent studies show remarkable progress in sensor technologies. In particular, the use of carbon-based inks has enhanced detection sensitivity and broadened application possibilities. Duan et al. (2023) investigated how carbon ink can improve sensing performance and the potential of combining it with other functional materials. Gilanizadehdizaj et al. (2022) developed flexible piezoresistive pressure sensor arrays using reduced graphene oxide and demonstrated their wide pressure range and low hysteresis. Similarly, Duan et al. (2022) reviewed flexible sensor matrices and highlighted the importance of expanding detection range. Gilanizadehdizaj et al. (2023) also examined how to optimize sensor sensitivity at both low and high-pressure levels.

The literature presents various fabrication techniques for textile-based sensors. Piezoresistive, piezoelectric, capacitive, and optical mechanisms are widely studied, each offering different benefits and fabrication routes. Studies by Edmison et al. (2002), Rendl et al. (2012), Chen et al. (2017a), Ahn et al. (2020), and Ullrich et al. (2020) focus on piezoelectric sensors; those by Sergio et al. (2002), Meyer et al. (2006, 2010), Holleczek et al. (2010), Zhang et al. (2011), and Hughes-Riley et al. (2019) on capacitive sensors; and Donati et al. (2014) on optical sensors. The piezoresistive materials used in this project contribute to this expanding field of research.

Piezoresistive materials are defined by their ability to change electrical resistance when mechanical pressure is applied (Borowski et al., 2015). They play a crucial role in micro-electro-mechanical systems (MEMS) such as force, pressure, and strain sensors, microphones, accelerometers, temperature, and chemical sensors (Saçu & Alçı, 2012). Their resistive behavior forms the core of the transduction mechanism in these devices. Piezoresistive pressure sensors are preferred due to their low cost, sufficient sensitivity, and low voltage requirements. These materials are available in various structures and forms, provided by multiple manufacturers.

Among them, carbon-filled polyethylene films stand out for their flexibility.

Tama et al. (2017) produced a textile-based pressure sensor using a sandwich structure composed of a piezoresistive film, conductive fabric, and conductive ink. The conductive fabric was thermally pressed onto both sides of the film, though short-circuit issues were observed due to silver particles from the conductive fabric merging into the piezoresistive layer under heat and pressure. Carvalho et al. (2017) developed pressure sensors using piezoresistive films with copper tape, woven, and knitted conductive fabrics as electrodes, comparing their performances. Gomes et al. (2018) used conductive silicone mixed with insulating silicone at different ratios to create piezoresistive surfaces of varying thicknesses. These were combined with conductive fabrics and inks for pressure sensor fabrication.

Carvalho et al. (2018) addressed earlier issues by testing different bonding materials, namely thermoplastic polyolefins, to improve layer adhesion. Their results showed that nonwoven adhesives provided better insulation between layers than mesh adhesives, resulting in lower voltage output. Birkocak et al. (2023) designed smart body protectors for karate, integrating small-scale textile-based pressure sensors using piezoresistive films and conductive fabrics, later scaled up for real testing. These sensors effectively detected impact forces.

The literature also includes a wide range of studies on conductive inks, which play an essential role in fabricating flexible sensors. Depending on the printing technique, these inks can offer superior sensitivity in circuit formation. Common methods include doctor blade coating (Castro et al., 2018), inkjet printing (Stempien et al., 2016; Bihar et al., 2017; Chen et al., 2017b), and film printing (Khirotdin et al., 2016; Wang et al., 2017; Ankhili et al., 2017; Noura et al., 2018; Zhou et al., 2018; Ran et al., 2018; Xu et al., 2019; Liu et al., 2019). Ankhili et al. (2017) highlighted the wash durability of printed electrodes, maintaining functionality after up to 50 washing cycles. Ran et al. (2018) analyzed how bending and washing affect electrical resistance, while Gomes et al. (2020) examined the wash resistance of different conductive inks printed on various fabrics (cotton, PES, PA, and blends) finding the best results with 100% cotton substrates. Castro et al. (2018) produced piezoresistive samples on polyurethane films using film printing, spray coating, and drop-casting techniques, analyzing resistance changes with a Wheatstone bridge circuit. Film-printed samples showed the highest sensitivity. Possanzini et al. (2019) compared mechanical and electrical behaviors of piezoresistive inks printed on four types of fabrics:

three knitted and one woven, finding higher sensitivity in elastic knits but greater stability in woven fabrics.

Gonçalves et al. (2016) fabricated pressure sensors using biocompatible thermoplastic composites and piezoresistive inks, achieving high mechanical strength and low hysteresis. Lagha et al. (2019) developed small-scale (1 cm^2) pressure sensors for automotive seating using conductive and piezoresistive inks. Carbonaro et al. (2021) created a textile-based pressure mapping system for monitoring sleeping posture and respiration, achieving 83.1% sensitivity and 93.6% accuracy. Saujanya et al. (2024) fabricated and characterized pressure sensors printed on PVC and transparent OHP films using piezoresistive and conductive inks containing graphene, nickel, and silver. Their results showed that nickel–graphite composites effectively detected strain and pressure under different mechanical deformations. Ali et al. (2024) studied PDMS-based flexible nanocomposite sensors containing varying percentages of multi-walled carbon nanotubes (MWCNTs) and analyzed their electrical and mechanical performance. Kang et al. (2024) developed a polymeric nanocomposite pressure sensor made of PDMS, silver nanoplates, and reduced graphene oxide using a blade-coating technique. The sensor exhibited excellent response (0.04 kPa^{-1} sensitivity), quick reaction time (286 ms), and strong hydrophobicity with a 137.2° contact angle. Fan et al. (2024)

investigated the mass production of ultrathin, fully printed pressure sensors using thermally processed graphene oxide (TGO) ink applied to polyimide films. These sensors showed a wide detection range up to 550 kPa, excellent repeatability over 6500 cycles, and good long-term durability.

Overall, these studies demonstrate the diversity and continuous progress in piezoresistive sensor technology. Although many works exist on pressure sensors using piezoresistive materials, studies that combine piezoresistive and conductive inks printed on textile surfaces remain limited. Understanding their behavior on different substrates offers a promising direction for future research.

Textile Sensors

Sensors are devices that can detect various physical stimulus and convert them into measurable electrical signals (Chun et al., 2018). These devices can sense a wide range of variables such as pressure, weight, light intensity, temperature, heat, and humidity, among others. Each type of sensor is specifically designed to accurately and efficiently detect the physical quantity it measures. Because of this, sensors are considered a fundamental component in many different fields of science and technology (Bosowski, 2015).

The main function of a sensor is to perceive a physical quantity or a material property and convert it into binary, single, or multi-dimensional electrical signals. These generated signals are then transferred to higher-level systems for further processing and analysis (Bosowski, 2015). Through this process, sensors play a critical role in various applications, particularly in automation, health monitoring, and environmental control systems.

In recent years, smart textiles have been developed through the integration of conventional sensors into textile materials. More recently, sensors have been directly fabricated from textile structures themselves. Textile sensors have been diversified to provide different functionalities and can be categorized according to their field of application and sensing capacity (Çelikel, 2020):

- Temperature Sensors: Devices that detect thermal changes and convert them into electrical voltage.
- Light Sensors: Devices that convert light energy into an electrical signal.
- Sound Sensors: Sensors that transform sound waves into electrical signals.
- Humidity Sensors: Sensors that measure absolute or relative humidity levels and convert them into voltage.
- Pressure Sensors: Devices that convert mechanical pressure into electrical signals.

- Strain Sensors: Sensors that detect mechanical strain and convert it into an electrical response.
- Chemical Sensors: Devices designed to detect the concentration or presence of chemical substances.
- Biosensors: Structures that identify biological components and generate corresponding signals.

Piezoresistive Pressure Sensors

Piezoresistive materials are special materials whose electrical resistance changes when they undergo mechanical deformation. These materials form the core component of piezoresistive sensors. The working principle of such sensors is based on converting the resistance change in the material into an output voltage (Figure 1) (Birkocak et al., 2023). The resistance value changes inversely with the applied force, making these sensors suitable for a wide range of applications, especially for detecting interactions between two contact surfaces (ALmassri et al., 2013).

The operating principle of a piezoresistive sensor can generally be expressed using a simple resistance variation formula. The change in resistance depends on the applied force and can be defined mathematically as shown in Equation (1).

$$R = \frac{\rho x L}{t x \omega}$$

(1)

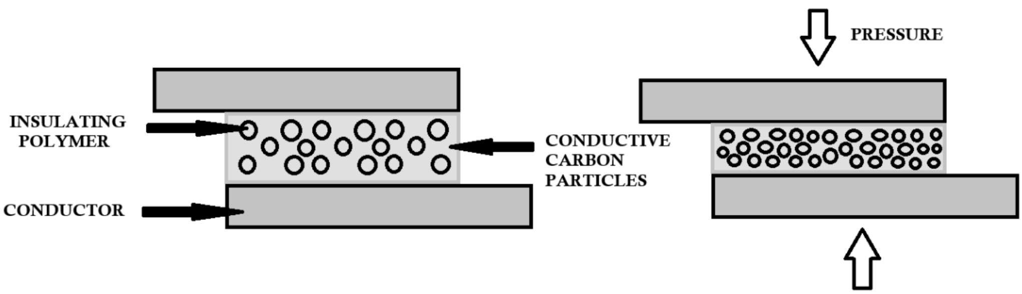
Where:

ρ: resistivity of the piezoresistor

L: length

ω: thickness

t: contact width



These sensors are particularly suitable for applications that require high sensitivity and accuracy. Their small size and low power consumption make them highly preferred in fields such as portable medical devices and energy-efficient industrial systems. The advantages offered by piezoresistive pressure sensors make them valuable not only for industrial and medical uses but also for environmental monitoring, automotive systems, smart wearable devices, and even aerospace applications. Therefore, the development of piezoresistive sensors remains at the center of research and innovation aimed at producing more precise and efficient devices.

Piezoelectric Pressure Sensors

The piezoelectric effect is based on the principle that certain materials generate an electric charge or voltage when mechanical pressure is applied to them (Toy, 2020). These materials can produce an electrical output that is directly proportional to the applied force or pressure, making them ideal for a wide range of applications. Owing to this property, piezoelectric materials can function both as sensors and as actuators, they can generate an electrical response when subjected to mechanical deformation or produce mechanical force when an electrical input is applied (Figure 2). This dual functionality places them within the category of smart materials (ALmassri et al., 2013).

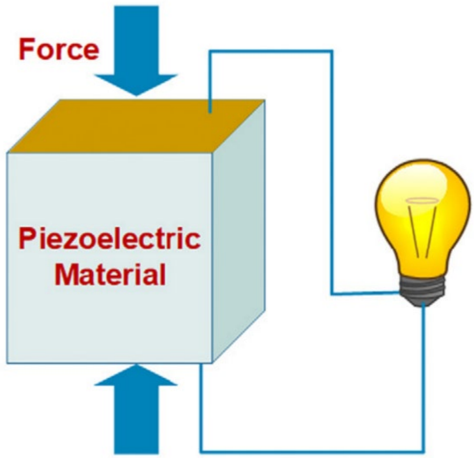


Figure 2. Pressure sensor based on the piezoelectric working principle

The main difference between piezoresistive and piezoelectric effects lies in their response to mechanical force: while piezoresistive materials exhibit a change in electrical resistance under applied pressure, piezoelectric materials directly generate a voltage because of deformation. This distinction defines their areas of application. Piezoresistive materials are typically used in pressure and strain sensors, whereas piezoelectric materials are preferred for energy harvesting, precision positioning, and high-frequency applications.

The wide range of applications of piezoelectric materials makes them indispensable in various fields, from medical devices and industrial monitoring systems to automotive technologies and consumer electronics.

Capacitive Pressure Sensors

Capacitive sensors consist of plate capacitors whose capacitance changes with the applied force. They operate based on variations in the distance between the plates, which allows for the design of dense sensor arrays and the capability to perform dynamic measurements. Capacitive pressure sensors are typically designed in a “sandwich” structure, where a dielectric layer is placed between two conductive electrodes (Figure 3) (Chen and Yan, 2020).

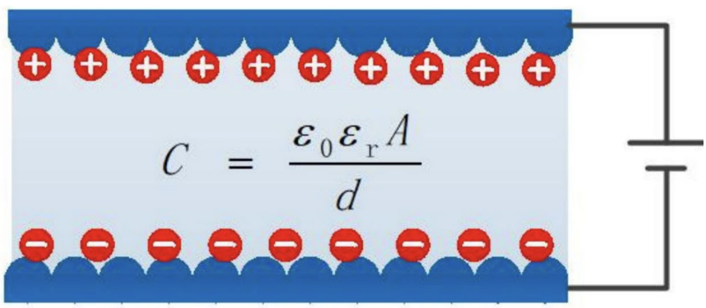


Figure 3. Pressure sensor based on the capacitive working principle (Su et al., 2022)

The capacitance value, C, can be calculated using Equation (2) (Su et al., 2022):

$$C = \frac{\epsilon_0 \epsilon_r A}{d} \quad (2)$$

The basic operating principle of these sensors depends on the vacuum permittivity ϵ_0, the relative permittivity of the dielectric layer ϵ_r, the effective area of the electrodes A, and the distance between the electrode plates d. When pressure is applied, the elastic deformation of the soft material within the sensor alters these parameters, thereby changing the capacitance. Such variations define how the sensor responds under pressure and help optimize its performance for different applications.

Fabrication of Piezoresistive Pressure Sensors

In this study, piezoresistive and conductive inks were used for sensor fabrication. The piezoresistive ink (Nanopaint, Portugal) has a carbon-based composition and can be applied using the film-printing technique. Its high elasticity and flexibility, combined with its ability to cure at low temperatures, make it ideal for printing on textile surfaces. These properties, particularly its excellent stretchability and sensitivity to resistance changes under applied pressure, offer significant advantages for the fabrication of flexible and large-area sensors.

The conductive ink (Nanopaint, Portugal) used in this study is a silver-based, flexible material suitable for a variety of applications, including wearable electronics, sensors, and medical devices. It is characterized by high flexibility and stretchability, allowing the printed layers to adapt to body movements. Its high solid content provides a denser coating during application, enhancing electrical conductivity and improving the performance of wearable devices. Additionally, the ink's high viscosity allows better control of flow during the printing process, enabling the formation of sharper and more detailed printed patterns. These features make it particularly suitable for use in wearable technology and medical applications.

For sensor fabrication, a 100% PES plain-weave fabric with a polyurethane (PUR) coating was used as the substrate. Printing stencils were prepared using a 70-mesh polyester gauze, compatible with the screen-printing equipment.

The sensor structure was designed as shown in Figure 4. First, the conductive ink was applied onto the substrate fabric and cured. Then, the piezoresistive ink was printed as the upper layer, followed by a final curing step to obtain the complete sensor. The conductive ink layers were fixed at 100 °C for 20 minutes, while the piezoresistive ink layers were fixed at 100 °C for 8 minutes.

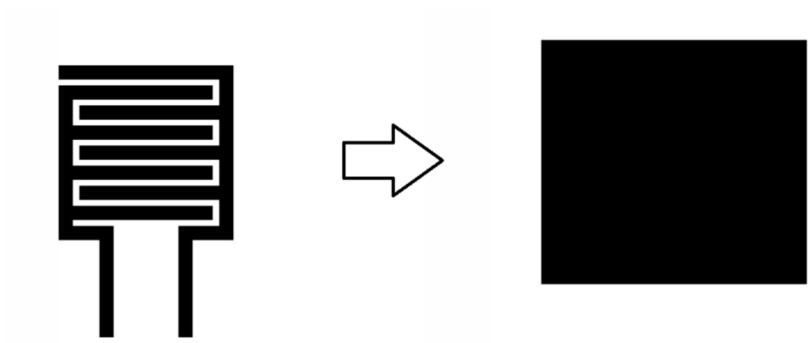


Figure 4. Structure of the piezoresistive sensor

The functionality of the produced piezoresistive textile pressure sensor was evaluated using a 289/FVF Fluke True-RMS digital multimeter to determine whether it operated effectively as a pressure sensor. To ensure stable electrical connections during measurements, snap fasteners made of conductive material were attached to the connection points of the sensor circuits (Figure 5).

Figure 5. The fabricated piezoresistive textile pressure sensor

Changes in the electrical resistance of the produced sensors were observed in relation to the applied force. During measurements with the multimeter, the resistance value was first recorded under no load, and then pressure was applied manually using a finger. A noticeable change in resistance under applied force confirmed the piezoresistive behavior of the sensor (Figure 6).

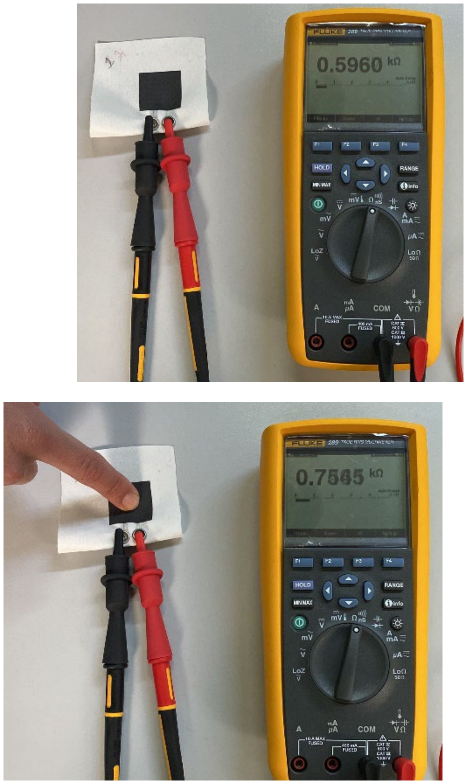


Figure 6. Observation of resistance changes under applied force using a multimeter

Conclusions

This book chapter presented an overview of textile-based pressure sensors and provided experimental results obtained from the development of textile pressure sensors using piezoresistive and conductive inks. Textile pressure sensors hold strong potential for applications in wearable technology, health monitoring systems, and smart clothing. They can be used to track users' physical activities, monitor health conditions, and even support rehabilitation processes.

The findings from this study offer valuable insights into future phases of the project, particularly for the further development and commercialization of textile sensor technologies. In upcoming research, it is recommended to explore different textile substrates for sensor fabrication and to use a dedicated sensor interface for more accurate measurement of resistance variations. Additionally, structural and material enhancements are suggested to improve sensor performance and broaden its application areas.

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CHAPTER XII

ELECTRONIC TEXTILE-BASED WEARABLE ANTENNAS: DESIGN, FABRICATION, AND APPLICATIONS

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1. Introduction

The 21st century has witnessed a paradigm shift in personal electronics, moving from portable devices to truly wearable systems. This evolution is driven by the convergence of miniaturized electronics, the Internet of Things (IoT), and a growing demand for personalized health, fitness, and communication solutions. Wearable technology is no longer confined to rigid accessories like smartwatches and fitness bands, as the frontier has now advanced toward smart textiles, which are fabrics integrated with electronic functionality. These intelligent garments promise to seamlessly embed technology into the fabric of our daily lives, enabling continuous, unobtrusive monitoring and interaction (Cho et al., 2022; Meena et al., 2023). From biometric data collection in athletes' jerseys to real-time location tracking in first responders' uniforms, smart textiles represent a transformative platform for next-generation human-centric applications. Furthermore, the rapid development of flexible and conductive materials, such as conductive yarns, polymers, and printable inks, has paved the way for scalable integration of antennas and sensors directly into garments (Eghan et al., 2025; Islam et al., 2024; E. Tetik & Tetik, 2017). These e-textile systems are expected to play a critical role in advancing personalized healthcare and resilient communication networks.

Central to the functionality of any wireless wearable system is the antenna, the key component responsible for transmitting and receiving electromagnetic (EM) signals. To achieve true integration with the human body while maintaining user comfort, conventional rigid antennas, typically fabricated from metals like copper on substrates such as FR-4, are often unsuitable. This limitation has led to the emergence of e-textile-based antennas, commonly referred to as e-textile antennas (Ejaz et al., 2023; Salama et al., 2025; E. Tetik & Antepli, 2018; M. Yang et al., 2024). A textile antenna is a radiating element fabricated either partially or entirely from textile materials, employing conductive threads, yarns, or fabrics for the radiating structure and conventional textile substrates (e.g., cotton, polyester) as the dielectric layer. These antennas offer an ideal balance between flexibility, wearability, and EM performance. E-textile antennas are widely recognized as a foundational technology for enabling robust wireless communication in smart garments. By replacing rigid components with flexible, lightweight, and conformal alternatives, they bridge the critical gap between high-performance electronics and the dynamic, deformable nature of the human body. This paves the way for the seamless development of fully integrated systems, such as Wireless Body Area Networks (WBANs), where on-body sensors and communication modules interact wirelessly without compromising comfort, mobility, or aesthetics. Moreover, their unobtrusive form factor allows for discreet integration in everyday clothing, supporting applications in healthcare monitoring, emergency response, military operations, and athletic performance tracking (P. Chen et al., 2023a; Jiang et al., 2019; E.

Tetik & D. Tetik, 2018). Ongoing research also focuses on enhancing their mechanical durability, washability, and resilience to bending and stretching, which are essential for real-life usage (Karimi et al., 2018a; Mai A R Osman et al., 2012; Yao et al., 2021). As materials science and fabrication techniques continue to evolve, e-textile antennas are expected to become a cornerstone of next-generation wearable electronics and pervasive computing systems.

While adopting textile materials in antenna design offers a unique set of advantages, it is also known to present significant challenges when compared to traditional rigid counterparts. A balanced understanding of these trade-offs is crucial for successful design and implementation. The primary benefits of textile antennas stem directly from their material properties. They are inherently flexible and conformable, allowing them to bend, stretch, and adapt to the dynamic curvature of the human body. This directly translates to enhanced user comfort, which is a critical factor for long-term wear. Furthermore, they possess a low profile, enabling discreet integration within garments without adding bulk or weight. Perhaps most importantly, their compatibility with standard textile manufacturing processes, such as weaving, knitting, sewing, and embroidery, allows for scalable and cost-effective production of smart clothing (Mantash et al., 2012; Monne et al., 2018; Salvado et al., 2012). Despite these advantages, textile antennas face several performance and reliability challenges. The most prominent drawback is often their lower radiation efficiency, which is primarily caused by the higher electrical resistance of conductive yarns and the inherent dielectric losses of textile substrates compared to traditional materials. In addition, their performance is highly sensitive to environmental factors; variations in humidity, exposure to perspiration, and mechanical deformations (such as bending or stretching) can significantly affect the antenna's resonant frequency and impedance matching (El Gharbi et al., 2025; Wang et al., 2015). Bonefačić and Bonefačić investigated embroidered textile antennas and examined how environmental moisture affects their communication and sensing performance. The results demonstrated that increased humidity leads to detuning of the antenna’s resonant frequency, reduced radiation efficiency, and degraded impedance matching (Bonefačić & Bartolić, 2021). Corchia et al. evaluated the durability of wearable antennas fabricated from nonwoven conductive fabrics under repeated washing and ironing cycles. The authors observed that mechanical and thermal stresses led to increased surface resistance and noticeable shifts in the antenna’s resonant frequency, ultimately reducing radiation efficiency (Corchia et al., 2018). Finally, ensuring long-term durability, particularly maintaining performance after repeated cycles of washing, abrasion, and flexing, remains a critical research challenge that must be addressed before textile antennas can be widely deployed in real-world applications (Ventura et al., 2022).

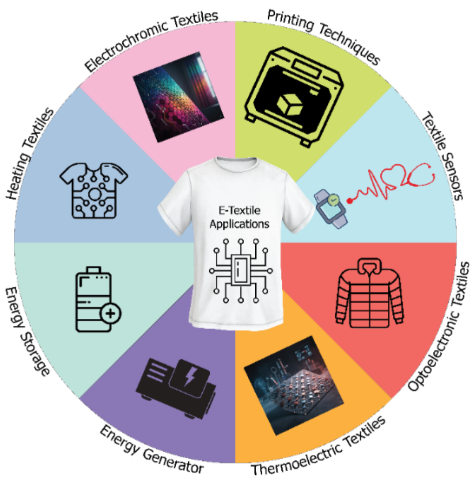

Figure 1. Application areas for wearable e-textile materials

To provide a clearer understanding of current research trends and practical applications, this chapter includes overviews and visual comparisons of textile antenna designs. Fig. 1 illustrates various application domains of e-textile antennas, highlighting their integration into multifunctional wearable systems. These applications encompass health monitoring through wearable sensors, smart garments for continuous biometric tracking, and energy-harvesting textiles designed to power low-consumption electronics (Carneiro et al., 2020; Du et al., 2022; Matijevich et al., 2020; G. Tetik & Tetik, 2020; Yamada, 2022). Additionally, emerging trends such as flexible batteries, wireless charging modules, and printed electronic circuits demonstrate how textile antennas are enabling the seamless convergence of sensing, communication, and energy management within next-generation smart fabrics (J. Chen et al., 2016; Elmoughni et al., 2019; Hashemi et al., 2020; E. Tetik, 2022).

This chapter aims to provide a comprehensive and structured overview of the field of electronic textile-based antennas. The chapter begins by exploring the materials used for both conductive and substrate layers, detailing their EM properties. Following this, we delve into the various fabrication techniques, such as embroidery, weaving, and printing, and provide a comparative analysis. The subsequent section focuses on the design and simulation of textile antennas, with special attention to the critical effects of on-body placement, bending, and environmental conditions. Then, it addresses the methodologies for characterization and performance measurement, both in free space and in on-body scenarios. It also showcases various application areas, including healthcare, military, and IoT. Finally, the chapter concludes by summarizing the key challenges facing the field and discussing promising future research directions that will shape the next generation of wearable wireless technology.

2. Fundamental Concepts and Theoretical Background

An effective textile antenna design necessitates a multidisciplinary understanding that combines classical EM theory, antenna design principles, and the distinct material properties of e-textiles. Unlike conventional antennas fabricated on rigid substrates such as FR4 or Rogers materials, textile-based antennas must operate effectively on flexible, porous, and anisotropic media. On the other hand, these unconventional substrates introduce additional design constraints related to dielectric inhomogeneity, mechanical deformation, and variable conductivity due to the use of conductive yarns or coatings. In this regard, before moving on to the practical aspects of prototyping and real-life deployment, it is essential to develop a solid theoretical foundation. This includes a review of fundamental antenna parameters—such as input impedance, return loss, bandwidth, radiation efficiency, and gain—as well as an understanding of wave propagation in deformable and lossy media. Furthermore, the EM interaction between textile fibers and conductive elements must be explored, particularly how these interactions affect resonant behavior, surface current distribution, and overall radiation characteristics. The basic theoretical concepts governing antenna behavior is given and the structure and compositions of e-textiles are described. In addition, emphasis is placed on how the unique mechanical and electrical properties of textile materials influence antenna performance, reliability, and integration within wearable systems.

2.1. Antenna Fundamentals

An antenna is fundamentally a transducer that converts guided electrical signals from a transmission line into radiated EM waves in free space, and vice versa. Its performance is quantified by a set of critical parameters that dictate its effectiveness in a wireless communication system. While these principles apply to all antennas, their interpretation is particularly nuanced for textile antennas due to their flexible nature and interaction with the human body. Key performance characteristics such as resonant frequency, bandwidth, directivity, and gain take on unique considerations in the context of textile-based antennas. The resonant frequency (f_r), which typically corresponds to the point where the antenna's input impedance becomes purely real, is strongly influenced by the antenna’s physical dimensions. However, for textile antennas, this frequency can shift dynamically due to external factors like mechanical deformation (e.g., bending, stretching) and environmental conditions such as humidity or sweat absorption, which alter the effective electrical length. Bandwidth, defined as the range of frequencies over which the antenna maintains satisfactory impedance matching (commonly where $S_{11} < -10$ dB), can benefit from the inherently low dielectric constant of textile substrates, enabling wider operational ranges. Directivity and gain—both measures of how effectively an antenna radiates energy in a preferred direction—are similarly impacted by material limitations. While directivity depends on the antenna's geometry, gain is also a function of efficiency, which often suffers in textile implementations due to resistive losses in conductive threads and dielectric losses in the fabric substrate (Karimi et al., 2018b; Mukai et al., 2019; Nikbakhtnasrabadi et al., 2021; Sanjari et al., 2016). These parameters must be carefully considered and optimized when designing wearable antennas, especially for applications that demand both mechanical adaptability and reliable EM performance.

2.2. E-Textile Structures

E-textiles can be said to be fabrics created by the integration of electronic components or containing natural electronic properties. For textile antennas, they form both the conductive radiating elements and the dielectric substrate. Conductive yarns are the fundamental building blocks for creating conductive paths in a textile structure. They can be produced through various methods, such as twisting staple fibers with fine metal wires (e.g., stainless steel, copper), coating non-conductive polymer yarns with a conductive layer (e.g., silver, nickel), or using intrinsically conductive polymers. The choice of yarn involves a trade-off between conductivity, mechanical flexibility, durability, and cost. While metal-based yarns offer lower resistance, they can be stiffer and more prone to breaking under repeated stress (Marterer et al., 2024).

Dielectric Constant (ε_r) or Relative Permittivity: This parameter indicates a material's ability to store electrical energy in an electric field. The dielectric constant of the substrate directly influences the resonant frequency and physical size of the antenna; a higher ε_r allows for greater miniaturization. Common textiles like cotton, polyester, and wool have a low dielectric constant (typically $\varepsilon_r \approx 1.5–2.0$), which results in physically larger antennas but can improve bandwidth. A major challenge is that the ε_r of many textiles is highly sensitive to moisture content and physical compression.

Loss Tangent (tan δ) or Dissipation Factor: This parameter quantifies the amount of energy from the EM wave that is absorbed and dissipated as heat within the dielectric substrate. A high loss tangent leads to poor radiation efficiency and lower antenna gain. Natural fibers like cotton and wool are particularly susceptible to absorbing moisture, which dramatically increases their loss tangent and degrades antenna performance. Synthetic materials like polyester and polytetrafluoroethylene generally exhibit lower losses and are often preferred for high-performance applications.

Correct analysis and optimization of these parameters ensure the desired design results, thus providing high efficiency from the designed e-textile-based antennas.

3. Materials for Textile Antennas

The performance, reliability, and manufacturability of a textile antenna are fundamentally designated by the materials chosen for its construction. Unlike conventional antennas built on standardized rigid substrates, textile antennas utilize a diverse range of materials that must balance EM performance with mechanical requirements such as flexibility, durability, and user comfort. This subsection details the two primary components: the conductive materials used to form the radiating elements and the dielectric fabrics that serve as the substrate.

3.1. Conductive Materials

The selection of conductive materials is a fundamental aspect of textile antenna design, as these materials form the radiation patch, transmission lines, and ground plane; these are the components directly responsible for electromagnetic performance. The electrical, mechanical, and chemical properties of the chosen conductor strongly influence not only the radiation efficiency and impedance stability but also the wearability, comfort, and lifetime of the overall system. These materials must exhibit low electrical resistance to minimize signal loss and ensure high radiation efficiency, while also withstanding mechanical deformation, such as bending, stretching, and repeated washing cycles encountered during daily use. In addition, factors such as surface roughness, thickness uniformity, and adhesion to the textile substrate can significantly impact current distribution and, consequently, antenna performance. Therefore, the development and optimization of conductive materials for e-textile applications involve a delicate balance between electrical conductivity, mechanical flexibility, and environmental durability. These materials can be broadly categorized into three groups: Metal-Based Conductors, Conductive Polymers and Inks, and Carbon-Based Materials.

3.2. Dielectric Substrate Materials

The non-conductive textile that serves as the antenna's substrate plays an equally critical role. It provides mechanical support, and its dielectric properties (the dielectric constant and loss tangent) directly influence the antenna's resonant frequency, bandwidth, and efficiency. The choice of fabric involves a trade-off between comfort, cost, and EM performance. Natural fabrics like cotton, denim, and felt are often chosen for their breathability and low cost. However, they are hygroscopic, meaning they readily absorb moisture from the environment or perspiration. This absorption drastically increases their dielectric constant and loss tangent, causing significant detuning of the antenna's resonant frequency and a sharp decrease in radiation efficiency. In contrast, synthetic fabrics such as polyester, nylon, and polytetrafluoroethylene are hydrophobic and exhibit more stable and lower-loss dielectric properties, making them preferable for high-performance applications where consistency is key. Ibáñez-Labiano et al. (2020) presented a systematic dielectric characterization of several non-conductive fabrics commonly used in wearable applications. The study measured key electromagnetic parameters, such as the dielectric constant and loss tangent, under different environmental conditions. It was demonstrated that natural fabrics like cotton exhibit strong variability in their dielectric properties due to moisture absorption, which can lead to frequency detuning and reduced radiation efficiency. In contrast, synthetic fabrics such as polyester showed more stable behavior, making them preferable for consistent antenna performance. The results highlight the necessity of accurately modeling the dielectric properties of textile substrates to ensure reliable design and simulation of wearable antennas(Ibanez-

Labiano & Alomainy, 2020). This variability requires a critical step in the design process, such as characterizing and modeling the dielectric properties of the substrate. Unlike uniform industrial substrates, textiles are anisotropic, porous, and non-homogeneous. Their EM properties can vary with fabric weave, density, compression, and environmental conditions. Therefore, accurate characterization using techniques like the waveguide method or free-space measurement is essential for reliable antenna simulation and design. These measured properties must then be accurately modeled in EM simulation software to predict the antenna’s real-world performance before fabrication (Zhang et al., 2022).

4. Fabrication and Manufacturing Techniques for Textile Antennas

The translation of a simulated antenna design into a functional, reliable physical prototype is a critical step governed by the choice of fabrication technique. Unlike the standardized photolithography used for rigid printed circuit boards, textile antenna manufacturing employs a diverse set of methods adapted from the textile and printing industries. The selection of an appropriate technique is a crucial decision that directly influences the antenna's performance, cost, durability, and scalability. This choice is intrinsically linked to the materials used; for instance, yarn-based techniques are suitable for conductive threads, while printing methods require specialized conductive inks. This section explores the primary fabrication methods, categorizing them into yarn-based integration, surface deposition, and hybrid assembly techniques.

4.1. Yarn-Based Integration Techniques

Yarn-based integration techniques involve embedding conductive yarns directly into the textile structure, resulting in antennas that are not merely attached to, but structurally integrated within the fabric itself. This production approach aligns with the primary goal of wearable systems: achieving mechanical and aesthetic harmony between electronic and textile components. By integrating the conductive elements at the yarn level, these methods ensure improved flexibility, breathability, and user comfort, while minimizing the risk of delamination or detachment that can occur with surface-mounted techniques. Furthermore, since these antennas are formed as part of the textile's construction process, they offer enhanced mechanical durability, maintaining stable electrical properties even under continuous bending, stretching, and washing cycles. Such characteristics make yarn-based integration an attractive route for developing long-lasting, washable, and conformal antennas suitable for everyday use in wearable communication systems and smart garments.

Embroidery: This is one of the most popular and versatile methods for fabricating textile antennas. Using computer-numerical-control (CNC) embroidery machines, conductive yarn is stitched onto a non-conductive fabric substrate to form a precise, high-resolution pattern. Embroidery offers excellent repeatability and is suitable for complex geometries such as meanders, spirals, and slot antennas. The final conductivity of the embroidered pattern can be controlled by adjusting parameters like stitch density and stitch type. While it provides robust and well-defined conductive traces, the dense stitching can locally increase the stiffness of the fabric (Abbas et al., 2019; Angelaki et al., 2024).

Weaving and Knitting: These are fundamental textile manufacturing processes where conductive yarns are incorporated into the fabric during its creation. In weaving, conductive yarns are interlaced as warp or weft threads to form planar conductive sheets, ideal for ground planes or simple dipole structures. In knitting, conductive yarns are interloped, resulting in an inherently stretchable structure. Knitted antennas are particularly promising for applications requiring high conformability and movement, such as in performance sportswear. While these methods produce truly integrated and flexible electronics, achieving the high precision required for complex, high-frequency antenna geometries can be more challenging compared to embroidery (Januszkiewicz & Nowak, 2024).

4.2. Surface Deposition and Printing Techniques

Additive manufacturing methods involve depositing a layer of conductive material onto the surface of a textile substrate. They are particularly well-suited for rapid prototyping and large-scale production. The success of these techniques heavily depends on the ink formulation, its interaction with the porous and uneven textile surface. In addition, process parameters such as curing temperature, printing resolution, and deposition thickness play a critical role in determining the final electrical conductivity and mechanical stability of the printed patterns. Since textiles are inherently flexible and stretchable, ensuring strong adhesion between the conductive layer and the fabric is essential to prevent cracking or delamination during bending or repeated washing. Moreover, optimizing these techniques enables the creation of high-frequency antenna structures with precise geometries, which is vital for achieving consistent electromagnetic performance in wearable systems.

Screen Printing is a cost-effective and scalable fabrication method that enables the deposition of thick, highly conductive layers on textile substrates, making it ideal for wearable antenna applications. Despite challenges such as ink bleeding and adhesion on porous fabrics, it remains a mature and reliable technology for mass production. A study by Arulmurugan et al. demonstrated a screen-printed denim-based antenna with high gain, wide bandwidth, and safe SAR levels, confirming the method's suitability for wearable biomedical devices (Arulmurugan et al., 2024; Hasni et al., 2021).

Inkjet printing is a digital, non-contact technique that precisely deposits conductive nano-inks onto fabrics, enabling high-resolution patterns and rapid prototyping with minimal material waste. Although it offers excellent design flexibility, challenges include ink formulation, absorption into textile fibers, and the need for post-processing to enhance conductivity, as the resulting thin layers typically exhibit higher resistance (Whittow et al., 2014).

4.3. Lamination and Comparative Analysis

This category encompasses fabrication approaches in which pre-existing conductive layers are assembled onto textile substrates, followed by a comparative evaluation of all previously discussed integration techniques. In lamination-based fabrication, conductive elements such as metal foils or conductive fabrics are physically bonded to the textile using adhesives, heat, or pressure, forming a stable conductive interface. This approach is particularly attractive due to its simplicity, reproducibility, and compatibility with conventional textile processing methods. It enables the creation of antennas with precisely defined geometries and excellent surface conductivity, especially when using metallic foils like copper or aluminum. Furthermore, lamination allows the integration of multilayer antenna structures, including shielding and ground planes, which are often challenging to achieve with yarn- or ink-based methods. However, since the conductive layer and the textile are joined through an adhesive interface, issues such as loss of flexibility, reduced air permeability, and degradation of adhesion strength under repeated mechanical stress or laundering can limit its long-term reliability. Hence, while lamination is ideal for prototyping and laboratory evaluation due to its speed and uniformity, additional optimization in adhesive formulation and substrate compatibility is often required for wearable and washable applications (Nowak et al., 2024).

5. Design and Simulation of Textile Antennas

The design of a textile antenna is a multifaceted and iterative process that extends beyond the conventional rules of antenna engineering. It requires a delicate balance between achieving desired electromagnetic performance and accommodating the practical constraints imposed by textile materials, manufacturing techniques, and the dynamic on-body environment. Unlike rigid antennas designed with well-defined, isotropic materials, textile antenna design must account for material inhomogeneity, flexibility, and significant environmental interaction. This chapter explores the common antenna structures adapted for textiles, the indispensable role of computational simulation in the design cycle, and the unique challenges that must be addressed to create functional and reliable wearable wireless systems.

While numerous antenna designs exist, a few key topologies have proven particularly suitable for textile implementation due to their planar structure, ease of fabrication, and performance characteristics. The microstrip patch antenna is arguably the most widely used topology. Its layered structure (a conductive patch separated from a larger conductive ground plane by a dielectric textile substrate) is inherently low-profile and conformal. This makes it ideal for seamless integration into clothing. Its performance is highly dependent on the substrate's dielectric properties, and it is relatively simple to fabricate using techniques like embroidery, printing, or lamination. Monopole and dipole antennas are also common, especially for their simple linear structures which are easily realized with a single conductive thread via embroidery or weaving. The monopole, requiring a ground plane for operation, often utilizes a textile ground or leverages its proximity to the body in its design. For applications demanding compactness and reduced backward radiation towards the user, the Planar Inverted-F Antenna (PIFA) is an excellent choice. Its shorting pin and compact resonant structure help mitigate the effects of body loading, making it a preferred topology for on-body communication systems like WBANs (Aliakbarian et al., 2021; Mai A. Rahman Osman et al., 2011).

6. Characterization and Performance Measurements

Following the design and fabrication stages, a rigorous characterization process is essential to validate the antenna's performance against simulation results and to quantify its viability for real-world applications. For textile antennas, this process extends beyond standard electrical testing to include an evaluation of their performance under mechanical stress and in their intended on-body environment. A comprehensive measurement protocol is crucial for understanding the antenna's true capabilities and limitations. This section outlines the key experimental procedures used to characterize textile antennas, from fundamental electrical properties to their robustness and on-body operational effectiveness.

6.1. Electrical Characterization

The initial and most fundamental step in antenna characterization is the measurement of its input reflection coefficient, denoted as S_{11}. This measurement is performed using a Vector Network Analyzer (VNA) and provides critical information about the antenna's performance, including its resonant frequency, impedance matching, and operational bandwidth. By analyzing the S_{11} plot, a designer can quickly verify if the antenna is resonating at the intended frequency and how efficiently it accepts power from the feed line. A common industry standard is to define the bandwidth as the frequency range where S_{11} is below -10 dB. A significant practical challenge in this process is establishing a reliable and repeatable connection between the flexible textile antenna and the rigid coaxial port of the VNA. Custom fabric fixtures, carefully soldered connectors, or conductive adhesives are often required to ensure a stable interface that does not introduce significant measurement errors.

6.2. Radiation Property Measurement

While the VNA confirms how well the antenna accepts power, it does not reveal how that power is radiated into space. Tests are performed in an anechoic chamber to measure the antenna's radiation characteristics such as radiation pattern, gain, and efficiency. This specialized room is lined with radiation-absorbent material that eliminates EM reflections, thus simulating a "free-space" environment. Inside the chamber, the textile antenna is placed on a turntable while a reference antenna measures the radiated fields at various angles. This process maps the antenna's 3D radiation pattern, identifying the direction of maximum radiation and revealing its directivity. The measured gain provides a practical measure of the antenna's ability to concentrate power in a specific direction, while the radiation efficiency quantifies how much of the input power is successfully radiated versus being lost as heat in the materials. For flexible textile antennas, mounting the sample without affecting its performance is a key consideration; typically, low-dielectric-constant foam supports are used to maintain the antenna's intended shape during testing (Kim et al., 2025; Mikulić et al., 2022).

6.3. Mechanical Durability Tests

For a textile antenna to be a viable product, it must maintain acceptable performance after being subjected to the mechanical stresses of everyday use, wear, and maintenance. Mechanical durability tests are designed to quantify this robustness. These evaluations typically involve subjecting the antenna to multiple cycles of a specified stress and measuring its electrical performance before, during, and after the test period. Among these, key tests include bending and stretching, in which custom-built rigs repeatedly flex or elongate the antenna to simulate human movement. This helps identify failure points in the conductive traces and assesses the stability of the resonant frequency under dynamic deformation. In addition to mechanical wear, practical usability demands resilience against regular maintenance, which is assessed through washability and abrasion tests. Antennas are subjected to standardized domestic laundry cycles to evaluate the durability of the materials, and the integrity of the feed point connection. Similarly, abrasion tests simulate the friction and wear that occur when the garment rubs against other surfaces. The results of these tests are critical for material selection and for establishing the expected operational lifetime of the smart garment (Rotzler et al., 2021; Xu et al., 2019).

6.4. On-Body Performance Tests and Protocols

Ultimately, a wearable antenna must function correctly when placed on the human body. As established, body loading significantly alters antenna performance, making on-body testing the definitive validation step. These tests are conducted by attaching the antenna to a human test subject in its intended location (e.g., chest, arm, back) and measuring its performance, typically its reflection coefficient using a portable VNA. To ensure repeatability and comparability across different studies, standardized test protocols are essential. These protocols define the antenna's placement, the posture of the test subject (e.g., standing, sitting), and a series of prescribed movements (e.g., walking, arm bending). Measurements are often taken in both static (stationary) and dynamic (moving) scenarios. The data gathered from on-body tests provide the most accurate insight into the antenna's real-world behavior and are crucial for confirming its suitability for a specific WBAN or other wearable communication application (Ali et al., 2022; Mulaparti et al., 2023).

7. Application Areas

The unique advantages of textile antennas, such as flexibility, seamless integration, and user comfort, have initialized a wide and growing range of applications previously impossible with traditional rigid electronics. By transforming everyday clothing into active communication nodes, this technology is poised to revolutionize industries ranging from healthcare to defense. Their conformability to complex body surfaces and ability to maintain performance under mechanical stress make them especially attractive for wearable applications. Furthermore, textile antennas offer opportunities for unobtrusive integration, enabling continuous sensing and communication without affecting the aesthetics or comfort of garments. This chapter examines the most important and promising application areas where textile-based wearable antennas serve as a key enabling technology, focusing on wearable health monitoring systems, sports and performance analysis, military and security applications, the Internet of Things (IoT) and smart home textiles, and Wireless Body Area Networks (WBANs).

7.1. Wearable Health Monitoring Systems

Perhaps the most impactful application of textile antennas is in the field of personalized healthcare. They are driving a paradigm shift from episodic clinical measurements to continuous, ambulatory health monitoring. By integrating antennas into smart shirts, bandages, or other garments, it becomes possible to wirelessly transmit real-time physiological data collected by on-body sensors. For example, textile antennas are used in systems for long-term electrocardiogram (ECG) and electroencephalogram (EEG) monitoring, allowing patients to remain comfortable at home while their vital data is sent to healthcare providers. Similarly, they are crucial for emerging non-invasive technologies like continuous glucose monitoring, where a skin-patch sensor needs to reliably transmit data to a smartphone or a dedicated receiver. The comfort and discretion of these systems significantly improve patient compliance and enable the collection of long-term data essential for early diagnosis and management of chronic diseases.

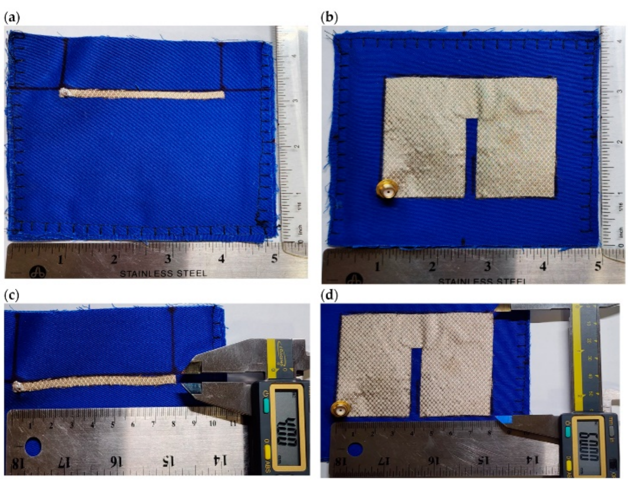

Figure 2. Wearable antenna design: (a) bottom view, (b) top view, (c) patch plane, and (d) ground plane (Nguyen & Green, 2025). Licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Nguyen and Green present the design, fabrication, and characterization of a wearable e-textile antenna specifically developed for continuous health monitoring systems. The work demonstrates how conductive textile materials can be integrated into garments to form a flexible, low-profile antenna that maintains performance under mechanical deformation. The authors perform both simulation and experimental validation to assess antenna performance metrics such as resonant frequency, bandwidth, and radiation efficiency. Fig. 2 (reproduced from Nguyen & Green, 2025) in their work illustrates the detailed antenna design, including (a) the bottom view, (b) the top view, (c) the patch plane, and (d) the ground plane, providing a clear visualization of the structural and functional aspects of the proposed textile antenna (Nguyen & Green, 2025).

7.2. Sports and Performance Analysis

In the competitive world of sports, data-driven insights are key to optimizing performance and preventing injuries. Textile antennas integrated into athletic apparel provide a platform for collecting and transmitting a wealth of biomechanical and physiological data without hindering an athlete's movement. Smart clothing equipped with inertial measurement units and textile strain sensors can provide real-time data about the athlete's posture, gait or swing mechanics to the coach using integrated antennas. This allows for immediate feedback and targeted adjustments. Furthermore, these systems can monitor vital signs like heart rate, respiration, and core body temperature during intense activity, helping to prevent overexertion and ensuring the athlete is performing at their peak physiological condition (Rum et al., 2021; K. Yang et al., 2024).

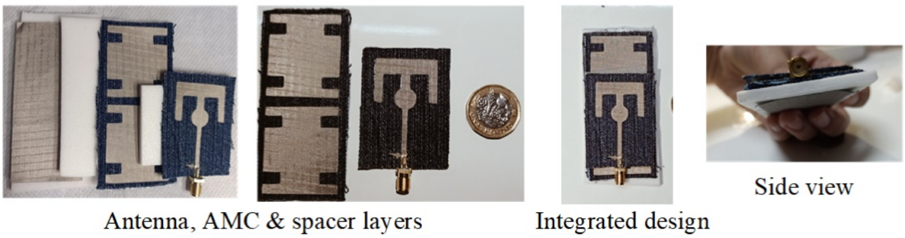

Figure 3. Views of the fabricated prototype (reproduced from Ejaz et al., 2023, "A High Performance All-Textile Wearable Antenna for Wristband Application," Micromachines, 14(6), 1169). Licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

In this context, Ejaz et al. presented a high-performance all-textile wearable antenna designed for wristband applications operating in the 2.45 GHz ISM band (Ejaz et al., 2023). The proposed antenna was fabricated entirely from flexible and conductive textile materials, ensuring both comfort and stable electromagnetic performance under bending and on-body loading conditions. Simulation and experimental analyses confirmed its robust impedance matching, high radiation efficiency, and minimal detuning when worn on the wrist, demonstrating its suitability for continuous sports monitoring and fitness tracking. Fig. 3 (reproduced from Ejaz et al., 2023) shows different views of the fabricated prototype, highlighting its compact and conformal structure optimized for wearable use.

7.3. Military and Security Applications

For modern soldiers and first responders, reliable and unobtrusive communication systems are essential for mission effectiveness, situational awareness, and personal safety. Traditional whip or rigid antennas, while functional, are often cumbersome, prone to mechanical damage, and can compromise the user's stealth and mobility. Textile antennas, by contrast, offer the ability to embed communication and sensing capabilities directly into uniforms, tactical vests, or helmets—resulting in a low-profile, flexible, and covert alternative that enhances operational efficiency in the field. These integrated systems can support a variety of functions, including intra-squad voice and data communication, GPS/GNSS-based positioning, and real-time transmission of biometric data such as heart rate or stress indicators to command centers (Harshini et al., 2024; S et al., 2024). Recent studies have demonstrated the viability of such systems under realistic military conditions. For example, Celenk et al. developed an all-textile cavity-backed SIW antenna designed for military badge integration, achieving high gain and excellent on-body performance even under mechanical deformation. Similarly, meanderline-pattern antennas fabricated on denim substrates have been proposed for position identification and tracking in tactical operations, combining flexibility with reliable radiation characteristics (Çelenk & Tokan, 2022). Research projects led by the European Space Agency (ESA) have further explored textile-based communication modules for satellite and field communication systems, emphasizing durability, low specific absorption rate (SAR), and environmental resilience.

Figure 4. Fabricated photograph of the Koch fractal antenna on jeans cloth. Reproduced with permission from The Electromagnetics Academy under the terms of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/).

By integrating these antennas seamlessly into garments, soldiers can maintain constant connectivity without the encumbrance of external equipment, reducing the risk of entanglement and improving ergonomics. Moreover, the combination of textile antennas with sensors, GPS modules, and body networks establishes a foundation for smart soldier systems, enabling real-time situational awareness, health monitoring, and mission data exchange. As material technologies and fabrication methods advance, such textile-based communication infrastructures are expected to play a pivotal role in next-generation defense and emergency response systems. A miniature Koch fractal wearable antenna designed for military applications operating in the VHF band has been proposed and experimentally validated by Poonkuzhali et al (Poonkuzhali et al., 2016). The antenna is fabricated directly onto a denim textile substrate, demonstrating a low-profile, flexible design suitable for seamless integration into military garments. Detailed electromagnetic simulations and experimental measurements are presented to assess its resonant frequency, impedance matching, and radiation characteristics under realistic usage conditions. Fig. 4 (reproduced from Poonkuzhali et al., 2016) illustrates the fabricated prototype of the antenna, showing both its compact structure and textile integration, emphasizing its potential for wearable communication systems in defense scenarios.

7.4. Internet of Things (IoT) and Smart Home Textiles

The application of textile antennas extends beyond wearable devices into the broader ecosystem of the Internet of Things (IoT) and smart environments. Everyday textile objects can be transformed into intelligent, connected devices. For instance, an antenna woven into a smart curtain could communicate with a home automation system to open or close based on ambient light levels or a user's schedule. A smart carpet with an integrated antenna array could function as a system for presence detection, fall detection for the elderly, or even indoor localization. The large surface area available on these textiles can be leveraged to design electrically large and efficient antennas, potentially enabling them to act as passive RF energy harvesters or data relays within a smart home network.

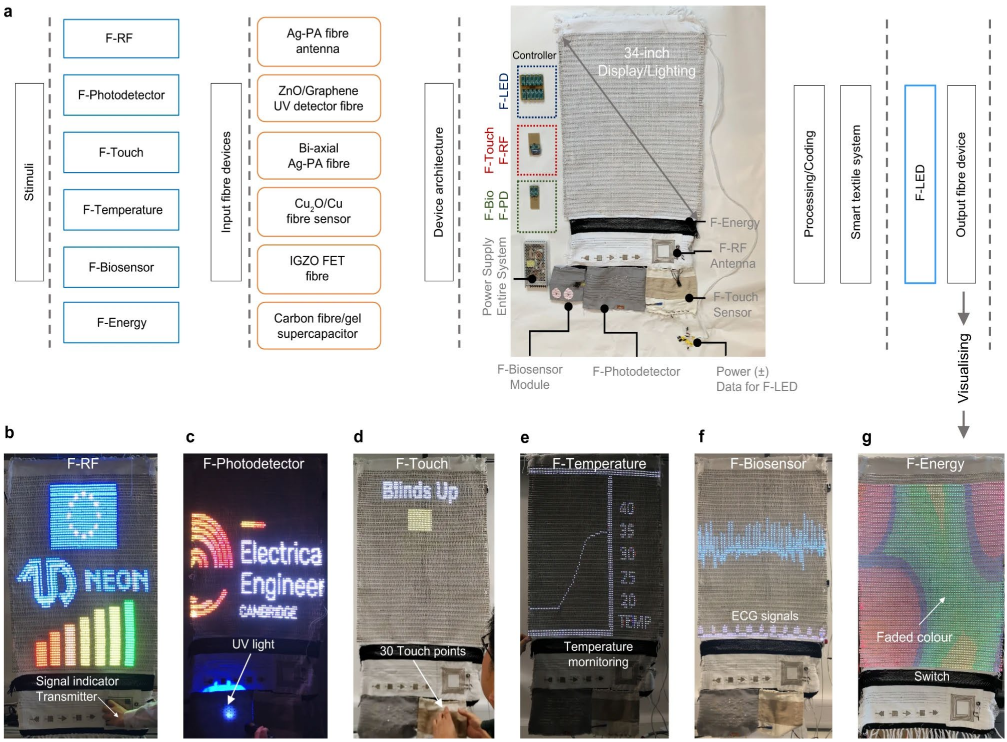

Figure 5: Design of smart textile display system from material to system level. Reproduced with permission from Choi et al. (2022) under the terms of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/).

Choi et al. developed a smart textile lighting/display system for smart home and IoT applications, integrating multifunctional devices such as F-LEDs, F-energy storage units, F-temperature sensors, F-RF antennas, F-biosensor modules, F-photodetectors, and F-touch sensors, as illustrated in Fig. 5 (reproduced from Choi et al., 2022). These devices are woven into the fabric using a modular "Lego-like" design, enabling easy expansion and customization. The system is designed to enable real-time monitoring and visualization of various environmental and physiological parameters. The prototype demonstrates long-term stability and responsiveness, illustrating its potential for integration into everyday textiles to enhance user interaction and comfort (Choi et al., 2022).

7.5. Wireless Body Area Networks (WBANs)

The Wireless Body Area Network (WBAN) is the core technological framework that underpins many of the applications discussed above, particularly in health and sports. A WBAN is a short-range wireless network of sensors worn on or implanted in the body, which communicate with each other and with a central hub. Textile antennas are the physical "nodes" of this network, providing wireless links for this on-body communication. For instance, in a comprehensive health monitoring system, a textile antenna on a wristband (communicating with a pulse oximeter) might send data to a central antenna on a chest-worn garment, which then relays the aggregated data to an external device like a smartphone. Designing antennas that can reliably establish communication links around the complex and dynamic environment of the human body is the primary function of textile antennas within the WBAN architecture(Adam et al., 2021; Preethichandra et al., 2023).

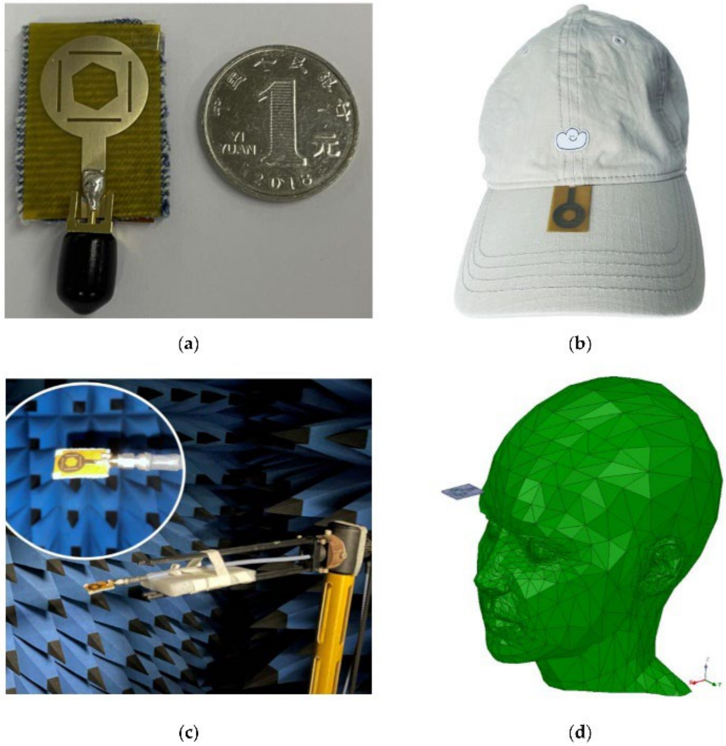

Figure 6. (a) Wearable antenna; (b) Antenna integrated into a peaked cap; (c) Radiation pattern measured in free space; (d) Human head model. Reprinted from Chen, P.; Wang, D.; Gan, Z. "Flexible and Small Textile Antenna for UWB Wireless Body Area Network," Micromachines, 2023, 14(4), 718. Licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Chen et al. presented a flexible and compact ultra-wideband (UWB) textile antenna specifically designed for Wireless Body Area Network (WBAN) applications. The antenna was fabricated on a denim substrate using conductive fabric, achieving a lightweight and conformal structure suitable for wearable use. The researchers performed both free-space and on-body measurements to evaluate the antenna's impedance stability, gain, and radiation characteristics under realistic conditions. As shown in Fig. 6 (reproduced from Chen et al., 2023), the prototype was integrated into a peaked cap, demonstrating its seamless integration capability and stable radiation performance even in proximity to the human head model. The experimental results confirmed that the antenna maintained consistent performance across the UWB range, highlighting its potential for continuous health monitoring and personal communication systems within WBAN environments (P. Chen et al., 2023b).

8. Conclusion

This chapter has provided a comprehensive examination of electronic textile-based antennas, charting a course from fundamental concepts and materials to advanced applications and future challenges. It has been established that textile antennas are not merely flexible substitutes for their rigid counterparts but represent a distinct class of technology that bridges the disciplines of electromagnetic engineering, material science, and textile manufacturing. The chapter has explored the diverse palette of conductive materials, and highlighted the critical role of textile substrates, whose dielectric properties present both opportunities and challenges. Furthermore, the discussion of fabrication techniques, including weaving, knitting, sewing, embroidery, and printing, has demonstrated the myriad ways in which radiating structures can be seamlessly integrated into fabrics. Central to this chapter has been the emphasis on the unique design and characterization challenges inherent to this field: the profound effects of body loading, mechanical deformation, and environmental sensitivity. These factors necessitate a co-design approach in which the antenna and its wearable context are treated as inseparable components. Looking forward, the potential of textile-based antennas is closely tied to the future of ubiquitous computing and human-centric technology. Their role is expected to expand beyond simple data transmission, becoming integral components of multifunctional smart textile systems capable of simultaneously sensing, communicating, and even harvesting energy. The advent of 5G and 6G communications, with their demands for higher frequencies, ultra-low latency, and massive connectivity, will introduce both new opportunities and significant challenges, driving innovation in wideband and miniaturized textile antenna designs. To fully realize this vision, the research community must continue to address persistent hurdles related to durability, washability, and scalable, cost-effective manufacturing. As these challenges are gradually overcome, textile antennas are poised to become the invisible yet essential threads that seamlessly connect us to our data, our environment, and each other, transforming clothing from a passive covering into an active, intelligent interface and making technology an integral, almost imperceptible part of human experience.

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CHAPTER XIII

DIGITAL TRANSFORMATION OF TEXTILES AND FASHION THROUGH ARTIFICIAL INTELLIGENCE

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Introduction

In the digital era, the importance of concepts such as sustainability and resilience is undeniable, and every effort made to protect our world—our livable environment—and its natural resources is of great significance. In this context, digital transformation (DT) is indispensable in our lives and in the sectoral context, where the concepts of "speed", "waste reduction", and "resilience" are such critical key factors. The authors prioritize digital transformation in terms of efficient use of resources, reduction of waste, effective transformation of existing resources, protection of the world, and minimization of carbon footprint points. In this framework, this chapter attempts to explain the concept of digital transformation and systematically present its applications in the textile and fashion industry.

DT is a multidimensional phenomenon that brings fundamental changes to the structure, business strategies, and operational practices of organizations producing goods and services in an engineering context, going beyond being merely a technological process. (Cavalcante et al., 2025; Weiner et al., 2025; Bermeo-Giraldo et al., 2025). Strategic innovation in the business model has led to significant departure from traditional production methods, and consumer expectations have also changed (Bermeo-Giraldo et al., 2025). As in other sectors, digital transformation in the textile and fashion industry has capital-based objectives such as providing competitive advantages, increasing profitability, and generating new revenue streams (Çavuşlar, 2025). In addition to the operational benefits of digital transformation, such as shortening efficiency in production, reducing costs, improving quality, and improving delivery times, there are also strategic benefits such as ensuring customer satisfaction and enabling the production of sustainable and durable products (Çavuşlar, 2025).

DT encompasses four different dimensions (Chirumalla et al., 2025). The first of these is the Awareness Dimension, which refers to the maturity of organizational strategies that reference the cultural dimension of the phenomenon and is directly related to employee competence. Once the need for transformation is accepted, resources are mobilized. The second dimension is the Readiness Dimension, which also addresses the investment perspective of infrastructure other than organizational culture and structure, emerges as a critical stage where the feasibility of moving towards DT goals is examined. Technology Selection & Relevance Dimension is the third dimension. It is the dimension of determining digital technological features and integrating them into the process, supported by external resources. It usually works in a way specific to the organization. The Operations Dimension is the fourth dimension, incorporating production system design as a factor. It involves the real-time execution of the technologies selected in the previous dimension. As can be understood from the entire model, DT is an adaptation-based phenomenon that requires top management support and the participation of highly competent employees, can develop through stakeholder collaborations, and can be sustained through data storage and security (Çavuşlar, 2025).

To gauge the scope of academic research on the topic (title, abstract, and keywords) the terms “digital transformation” and “textile” or “fashion” were queried in two major citation databases, Scopus and Web of Science (WoS). As shown in Figure 1, publication volume increased in WoS until 2021 and continues to grow at a high rate in Scopus.

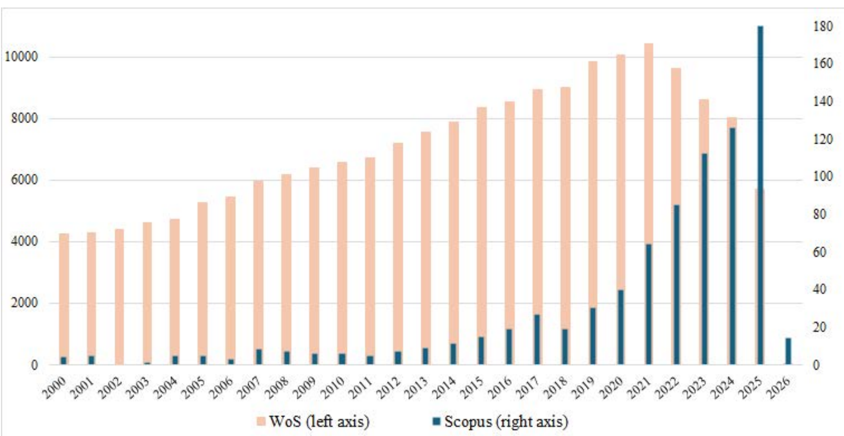

Figure 1. Number of documents published by keywords (Created by authors from WoS and Scopus data-November 2025)

Indeed, it is clear that the keywords related to the topic cannot be limited to digital transformation. Because Industry 4.0 and Industry 5.0 are stages of the comprehensive process defined as digital transformation. And the technologies used in these stages have been comprehensively examined in bibliometric analyses in the literature. Under the overarching framework of digital transformation, we have moved from Industry 4.0, which aims to increase efficiency and achieve full automation using technology, to Industry 5.0, which uses Industry 4.0 tools and focuses on sustainability and resilience (Nahavandi, 2019). The technologies used in this context are presented in Figure 2. Which technology will be applied is highly dependent on the sector and the organization applying the technology (Tang, 2021).

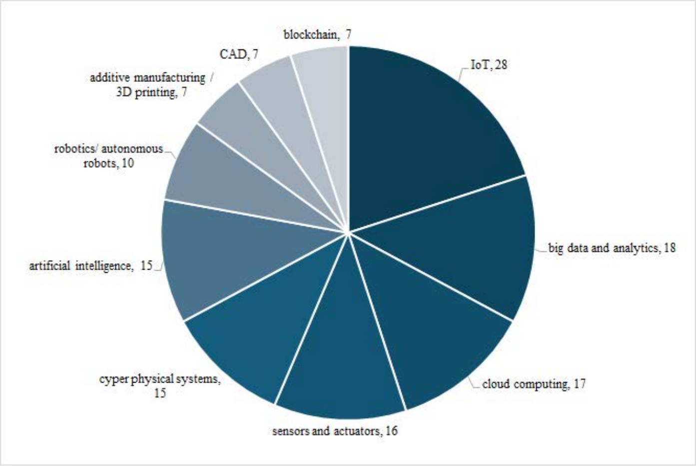

Figure 2. Technologies used in digital transformation (Created from the data given in Orisadare et al., 2025)

As shown in Figure 2, the application area of technologies enabling artificial intelligence (AI) is also quite broad. AI can be used in design, trend analysis, forecasting, supply chain management, quality control, smart material development, marketing, and personalized recommendation systems, even in customer service. This covers the entire process of the textile product, from the beginning of its journey as a fiber to the end of its wear life, during which it maintains its durability, performance, and functionality throughout its period of use. The aim of this study is to demonstrate the artificial intelligence applications through concrete examples.

Methods

This study is a theoretical secondary data analysis study. Within this framework, the subject was evaluated by reviewing scientific sources, which are secondary data sources related to the subject in the field. In this study, this analysis was used to compile the results of research on the subject and to present the results of existing research in a comparative framework with other research. The conceptual analysis method used here was employed to access existing information on digital transformation and artificial intelligence applications in the textile and fashion industry, and existing documents were compiled and analyzed. During the data collection phase, scientific journals, scientific books, and platforms presenting specific examples of textile and fashion brands implementing digital transformation with artificial intelligence were utilized.

This enabled a systematic review of original literature and current applications.

AI Applications in Textiles and Fashion

In recent years, AI has provided indispensable applications in manufacturing, construction, the raw material industry, and information technologies. The essential aim of usage of AI applications in these industries is to save time, resources, and energy to promote green and sustainable industrial growth. These applications have driven digital transformation in textile and fashion industries, as in every branch of industry. To comprehend the context of this digital transformation, it will be beneficial to consider the current volume of AI applications used in the sector and the accelerated increase of their usage day by day.

Although digital transformation requires a significant initial investment, corporate businesses are aware that every day they remain distant from digital transformation creates a disadvantage in terms of both sustainability and resilience, as well as maintaining their competitive strength by responding quickly and effectively to customer demands. As a result, they have taken and continue to take steps related to DT. This section attempts to explain application examples related to the use of AI in DT.

Applications in quality control

The processes required to produce a textile product are numerous and complex, resulting in many defects occurring during the journey of the raw material to the final product reaching the consumer—in the broadest sense, clothing. There are many different types of defects that can occur in the intermediate forms from fiber to yarn, the yarn itself, the bobbin, weaving preparation, weaving, knitting, dyeing, printing, and finishing processes (Ozek et al., 2025). Traditional machine learning, deep learning, hybrid and adaptive AI technologies can be used in defect quality control (Ozek et al., 2025). There are various fabric types used in garment designs. And all of them have different defects. Clear definition and classification of these defects free from noise can be performed by AI technologies (Wong and Jiang, 2018; Jiang and Wong, 2018). A basic defect detection unit for fabrics includes a camera, frame grabber, detection algorithm system, lighting system, and software. The camera captures the image, the frame grabber captures individual frames, the detection algorithm processes them, and classification is performed. Lighting is important for accurate detection at the correct angle. The data is then stored in the software for later use (Nair and Trivedi, 2024).

Color control has also been a subject of study. The light scattering and absorption properties of each fiber are different. Furferi et al. (2016) aimed to obtain the best reflectance data for non-existent blends by using Kubelka-Munk theory and artificial neural networks together with artificial intelligence to determine the best spectrophotometric color in all fibers and fiber blends.

Applications in design

The first studies on the subject date back to the 2000s. Hsu and Wang (2005) studied the use of data mining to determine body measurement systems in garment production. The study is important in terms of providing reference points and establishing standard body patterns and rules to enable manufacturers to produce garments easily. The use of AI in design facilitates fabric selection, pattern creation, and color combination decisions for designers, enabling the exploration of innovative creative possibilities (Değirmenci, 2024). Refabric is an AI tool used in the design field that generates usable outputs, enables businesses to design using their own fabrics, is based on visual-focused modules (meaning it can prepare prompts by uploading images), and serves a process that speeds up the work of design teams. Refabric enables designers to use their time more efficiently by allowing them to focus on more creative work, and it also has the ability to quickly create new designs by learning the fabric's texture, drape, and other characteristics through training modules (DTS Tasarım Merkezi, 2025a).

Polytropon, an integrated artificial intelligence software that enables fashion industry businesses to digitally create, transform, test, plan, and monitor all stages of their products throughout the entire product lifecycle; covers all stages from pattern design and automatic pasting to product life cycle management, 3D design and development (Browzwear), automated photography solutions (Orbitvu), and store planning and visualization. With VIZOOphysX™, material digitization can now be performed with fabrics that are not physically available (VIZOO, 2025). It is possible to obtain output from a process where the physical properties of the fabric are digitally created based on the fabric composition and integrated into the design, which can be integrated with 3D Apparel CAD software (DTS Tasarım Merkezi, 2025b; Browzwear, 2025).

Applications in fashion sales

In the fashion industry, businesses are striving to improve product quality and efficiency in order to advance in a global competitive market that has maintained its intensity for years, and are making efforts to improve all stages of the industry with AI-supported tools (Sharma et al., 2025). Sales support units featuring AI-powered customer representatives, where customers can visually see personalized styles on their preferred body types using smart mirrors, and AI-based fashion influencers with millions of followers (Boğday Sayğılı and Dilber, 2024) are a few examples that can be given regarding the fashion sales sector. Brands also use AI-powered sentiment analysis to understand their customers' emotions (Sher, 2026). Nike is one of the pioneering brands in this regard. H&M has also reported on the management and secure storage of personal data, robust data security practices, and ensuring the ethical use of artificial intelligence and data-driven digital technology (H&M Group, 2024). AI methods can be used to predict tendencies or preferences for apparel and sales demand. An intelligent forecasting approach for new products led brands to plan or review their designs according to customer demands (Tsao et al., 2023).

Applications in sustainability and waste management

The use of AI in industrial waste management presents itself as a strategic necessity that will fundamentally transform operational paradigms in the Anthropocene era. Beyond efficiency gains, the focus is on optimizing complex waste collection, transportation, and disposal processes through the application of advanced AI-powered predictive analytics and decision support tools (Samuels, 2025; Tang, 2023).

The benefits of using AI in waste management are multifaceted. Operationally, when collection logistics are optimized with algorithms, vehicle mileage and idle time are minimized, and transportation costs show a significant reduction. This leads to a decrease in greenhouse gas emissions. It aligns with environmental sustainability requirements and supports global carbon neutrality goals (Faiz et al., 2024). Furthermore, AI supports provide transparency and traceability throughout the life cycle by enabling continuous monitoring, verification, and automatic reporting of waste streams. This traceability is critical for compliance with regulations and for providing verifiable contributions to the circular economy (Šajn, 2022).

The rapid, accurate, and highly efficient separation of heterogeneous waste streams has been facilitated by AI systems (Lu and Chen, 2022). Compared to traditional manual or mechanical separation methods, it offers unique advantages in the separation of post-consumer textile products, particularly for determining fiber composition and dye type, thanks to advanced sensors and machine learning (Robinson et al., 2024). As a result, recovered materials are of high purity, and secondary raw material values increase. Consequently, the integration of artificial intelligence into all areas of waste management transforms waste management from a logistical challenge into a technological leap that is fundamental to achieving a true circular economy.

The Smart Tag system enables the identification of waste, the issuance of digital waste identities, the sorting and transfer of waste using QR tags, its collection, recycling, tracking, and monitoring, culminating in a digitally traceable process that ends with data analysis and reporting (Sayıt, 2025). This traceability is possible in practice with the Digital Product Passport (DPP). The DPP is a tool proposed by the European Commission to increase transparency and circularity, enabling the sharing of product information throughout the entire value chain, from raw material extraction to recycling (Telfort and Valialii, 2025). The DPP provides material composition and origin information for each product and significantly improves separation procedures by providing comprehensive information about the life cycle.

Conclusion

Considering all results, it is evident that artificial intelligence, machine learning, and along with other digital technologies such as IoT, blockchain hold significant potential for transformation in both the textile and fashion industry and supply chain management in a broader context. However, realizing this potential requires high costs, and sometimes corporate resistance creates obstacles to this potential, necessitating the careful management of human-machine collaboration.

While Industry 5.0 emphasizes creating human- and planet-centered value, the importance of culture is once again coming to the fore in this process that places people at the center. It is crucial that employees, consumers, and collaborators are involved in the process with sufficient readiness and competence. Furthermore, it is important to continuously engage with various platforms and networks to create new collaboration networks. It would be appropriate for artificial intelligence developers and implementers to be in constant communication, so that requests can be evaluated as quickly as possible, deficiencies can be addressed, and adaptation can be accelerated. Critical issues include which data will be stored where and how, with whom it will be shared, and what investments are required in relation to these facts. This situation requires robust infrastructure. It should not be overlooked that none of these stages can be realized without top management support.

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CHAPTER XIV

ANALYZING THE CONCEPT OF FAST FASHION THROUGH DIGITAL ETHNOGRAPHY: INSIGHTS FROM INSTAGRAM AND YOUTUBE

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Introduction

Consumption is conceptualized in contemporary societies not merely as the fulfillment of an economic need, but also as a multi-layered social practice through which individuals express their identities, negotiate their social positions, and produce cultural meanings. Giddens and Sutton (2016: 192) defines consumption as goods, energy, resources, and services made available for people's use and service, while Bauman (1999: 40-41) emphasizes that in modern consumer societies, individuals use consumption practices to display not only products but also their identities, lifestyles, and social visibility. According to Sassatelli (2007), consumption is a cultural system in which social values are produced through objects; in this system, individuals invest not only in objects but also in the narratives, images, and symbolic meanings that those objects represent. In this context, consumption has become more visible, accelerated, and performative, particularly due to the impact of digitalization; social media platforms have become dynamic spaces where individuals display, reinterpret, and compare their consumption practices. Fast fashion, which is at the center of this transformation, has emerged as a concrete reflection of the value system established by consumer culture through speed, innovation, accessibility, and visual appeal. Therefore, fast fashion is not just an economic sector; it has become a cultural phenomenon that directly shapes individuals' identity performances, the circulation of their

aesthetic preferences, and the interactions they establish through social media in the digital age.
Fast fashion is a phenomenon that stimulates consumption through a business model based on the design-production-sales cycle, aims to create a constant desire to purchase among consumers, reorganizes marketing criteria accordingly, and has significant negative social and environmental impacts.
As a business model, it has certain characteristics such as ensuring the continuous growth of capital to maximize capital profit, leaving traditional fashion behind, offering greater agility, and delivering new products more frequently and faster (Niinimäki et al., 2020). Unfortunately, it has created ecological and social problems in addition to economic ones. Fast fashion, which has become one of the most defining features of contemporary consumer culture, operates at a relentless pace, unlike traditional fashion cycles that once revolved around seasonal collections. Fast fashion brands encourage consumers to buy and consume clothing at an unprecedented rate by offering new designs on a weekly or even daily basis. This change has been driven not only by supply chain logistics and various global developments, but also by cultural and technological changes that have reshaped people's relationships with clothing, trends, and self-presentation. Scholars have emphasized that fast fashion represents a profound restructuring of the temporal, economic, and symbolic logic of the fashion system (Joy et al., 2012). Rather than durability, craftsmanship, quality, or

longevity, fast fashion prioritizes novelty, “disposability,” and speed; these are qualities that closely align with the concepts of ‘speed’ and “constant consumption” in digital media culture.

The environmental damage caused by fast fashion is gradually increasing. The massive piles of clothing on the shores of Ghana and in the Atacama Desert (Yıldırım, 2024) reveal this damage. In the last decade, researchers focused on this damage in academic documents. The textile and fashion industry is one of the world's most resource-intensive and environmentally polluting sectors. It is responsible for increased carbon footprints, excessive water use from farms to factories, chemical pollution, and the exponential growth of textile waste filling landfills (Niinimäki et al., 2020). By 2030, global textile waste is estimated to reach 130 million tons (Matthews, 2024). Social harms are also closely linked to these ecological concerns. Furthermore, production chains are built on precarious labor, low wages, unsafe working conditions, and the exploitation of workers (especially women and children).

Culturally, fast fashion promotes excessive consumption by spreading the idea that clothes are easily replaceable and inherently temporary. The constant need for “something new” fuels cycles of impulsive purchasing driven by trends rather than personal expression or long-term value, emotional consumption, and identity performance. These structural harms are intensified by various dynamics of social media (Leaver et al., 2020). Social media platforms are increasingly playing a central role in shaping fashion meanings, consumption habits, and aesthetic expectations, elevating values such as capturing the moment, novelty, staying current, and remaining visible. Shopping videos, unboxing posts, and “get ready with me” themed content are presented as fun, highly interactive, and socially rewarding activities, normalizing patterns of excessive consumption. The algorithms of these platforms prioritize content that generates high engagement, thereby continuously reinforcing these dynamics.

Although the social and environmental harms mentioned above are becoming more widespread day by day, it should not be forgotten that social media is a battleground for these and similar issues. The number of posts criticizing waste and labor exploitation, exposing environmental damage, and promoting sustainability is steadily increasing. Activist accounts, sustainable fashion influencers, and critical commentators use the same digital tools, such as hashtags, to draw attention to and question the norms of fast fashion. Hashtags such as #slowfashion and #sustainablefashion, which are alternatives to the concept of fast fashion, encourage consumers to evaluate the longevity and circularity of fast fashion products and their responsible consumption, raising awareness in this area by drawing attention to alternative aesthetic and ethical frameworks (Jung and Jin, 2016). Thus, social media both reinforces and questions fast fashion culture. Conflicting values coexist on social media, creating a layered discourse environment. This complexity and the dynamism of digital environments make these platforms an important arena for understanding how users negotiate their identities, responsibilities, and desires regarding fast fashion.

To meaningfully analyze these dynamics, digital ethnography has emerged as a productive methodological approach. Digital ethnography extends the principles of traditional ethnography to online environments where social life (especially Gen Z's life) is increasingly unfolding (Pink et al., 2016). Unlike traditional ethnography, which requires physical presence in a community (Kartarı, 2017; Saka, 2021), digital ethnography examines interactions, narratives, and symbolic practices in digital spaces such as social media feeds, comment sections, hashtags, and video narratives. Digital ethnography provides a holistic approach to culture through various offline or online applications shaped by digitalization, given the internet's pervasive and undeniable impact on daily life (Varis, 2014). It provides access to places that cannot be physically reached and, with the advent of the virtual environment, provides information about the change and transformation of individuals' forms of interaction. Digital ethnography is also referred to by other concepts such as virtual, cyber, discourse, and internet-connected ethnography (Varis, 2014). Kozinets also defined it as netnograhpy, a technique that transfers ethnographic techniques to the digital realm (Yıldırım and Şimşek, 2013: 229). Digital ethnography makes it possible to examine the essence of social change and transformation (Hine, 2017). It acknowledges that digital environments are not separate from “real life,” but rather an integral part of it, serving as spaces where individuals construct their identities, share their experiences, and participate in collective meaning-making processes.

Digital ethnography offers a wide range of advantages for examining the concept of fast fashion, just as it does for other concepts, at an increasing rate of use. It allows researchers to observe how people express their defined perceptions and attitudes through visual or textual content. Furthermore, because anonymity is preserved, it easily captures various emotional dimensions (such as excitement, desire, and anger) that might be difficult to access through quantitative or qualitative interviews. Finally, it places fashion consumption within broader social and cultural contexts such as beauty standards, body politics, environmental concerns, and economic constraints.

A growing number of scientific studies are applying digital ethnography to examine phenomena on social platforms, demonstrating the method's flexibility and depth. For example, Leaver et al. (2020) conducted a digital ethnographic study on Instagram to explore visual cultures and identity performances among influencers and other users, revealing how Instagram's aesthetic norms shape self-presentation and cultural value. In the context of fashion, Rocamora (2018) examined fashion bloggers and influencers using digital ethnographic methods, revealing how digital media reshapes fashion communication, gatekeeping, and consumption. While these studies do not focus directly on fast fashion, collectively they show how digital ethnography captures the interaction between platform capabilities, user practices, and cultural production.

Furthermore, digital ethnography is particularly well-suited for investigating hashtag cultures. Hashtags serve as discursive markers that bring together diverse forms of expression, enabling researchers to track thematic clusters, participation patterns, and value negotiations within large volumes of content (Highfield and Leaver, 2016). In fast fashion contexts, hashtags not only categorize clothing and trends but also articulate ethical stances, collective concerns, and emerging forms of digital activism. Posts shared with hashtags such as #slowfashion or #sustainablefashion, alternatives to the #fastfashion tag, highlight concerns about sustainability, conscious consumption, or second-hand alternatives.

YouTube offers an equally rich site for digital ethnographic inquiry. Its video-based format enables deep narrative engagement, emotional expression, and community-building. Studies have shown that YouTube comment sections function as participatory arenas where viewers share experiences, debate ethical issues, or reinforce consumption norms (Burgess and Green, 2018). In the case of fast fashion, haul videos often elicit a mix of admiration, critique, and reflective commentary.

Viewers negotiate complex feelings—desire for new clothing, awareness of sustainability concerns, or skepticism toward influencer sponsorships—making YouTube an important space for understanding the affective and moral dimensions of fast fashion consumption.
Given these dynamics, digital ethnography offers a unique opportunity to examine not only what people say about fast fashion, but also how they enact, negotiate, and experience it within their daily digital practices. The interaction of visuality, narrative, algorithmic mediation, and social participation create a multi-layered cultural environment that cannot be adequately captured by purely quantitative approaches.

The primary objective of this study is to analyze consumer perceptions of “fast fashion” within the context of consumption through digital ethnography on social media. Given that most people use social media and conduct most of their consumption via e-platforms today, this study was conducted to examine consumption related to the fast fashion field, considering that social media is the best environment for analyzing people's perceptions, attitudes, and behaviors regarding consumption.

Moreover, the study aims to clarify how individuals interact around the concept of “fast fashion” on social media, whether they are aware of the concept of “fast fashion” or its alternatives, and what attitudes and behaviors they adopt in relation to these concepts.

Methodology of Study

Ethnography is an important approach in qualitative research. Ethnography is concerned with the discovery and description of the cultures or cultural phenomena of group of people (Christensen, Johnson and Turner, 2015: 411). This study aims to understand the online cultural representations of fast fashion and users' perceptions of this phenomenon, as well as the attitudes and behaviors shaped around it, by examining content produced on Instagram and YouTube using digital ethnography methods. The study analyzes how fast fashion is normalized or aestheticized through social media, or conversely, how it is criticized by examining consumption tendencies within user interactions on posts and in the comments section. The research problem defined for this study focused on the question of how individuals (as consumers) perceive the fast fashion industry. An attempt was made to reveal awareness of the environmental damage caused by the products of this industry, as well as the effort and resources invested.

To this end, the study method first involved conducting a brief bibliometric analysis on the subject. Bibliometric analysis, which is an analysis based on quantitative measurement, mapping, and interpretation of scientific publications related to the research topic, aimed to understand which other concepts or research areas publications containing the concept of fast fashion were shaped around. The keywords encountered in this analysis was associated with the keywords selected for digital ethnography.

For the bibliometric analysis, the Dimensions.ai, a comprehensive research information platform that comprehensively indexes academic publications, research outputs, and scientific data, was utilized. The number of publications found using the keywords “fast fashion” was searched with title and abstract restrictions, and the resulting document counts were classified according to research areas using ANZSRC (Australian and New Zealand Standard Research Classification) codes and presented graphically.

The research is queried with the keywords “fast fashion,” “sustainable fashion,” “slow fashion,” “ethical fashion,” and “eco fashion” in topics (title, keywords, and abstracts) of the documents indexed in WOS (Web of Science) and Scopus (Elsevier Abstract and Citation Database) databases. Studies published after 2020 were considered. A three- field plot Sankey diagram was plotted to display the year-by-year variation of key terms across the examined databases.

Publications made after 2020 with the keyword "fast fashion" in Scopus (Elsevier Abstract and Citation Database) were searched using title-abstract-keywords filters, and a bibliometric network map was created using VOSviewer (Visualization of Similarities) with the exported data. Additionally, a treemap chart was created using the other keywords found in the top 5 most cited studies from 2025 in Scopus that used the keyword "fast fashion." This analysis is important for determining which concepts the concept of fast fashion is associated with.

To achieve the main objective of the study, the digital ethnography technique, which is the best method for observing social media participation and interactions, was utilized. Digital ethnography offers a holistic approach through various online and offline applications shaped by digitalization, in contrast to traditional ethnography, which requires spending extended periods of time in the research field as an observer. In contrast to digital ethnography, traditional ethnography requires the researcher to be physically present within the community as a participant observer. Because the focus of ethnography is to define culture from the perspective of the individual within the group. This technique focuses on both the internal and external perspectives of a culture. As qualitative research, the researcher must use this perspective in a balanced manner to conduct a valid study (Christensen, Johnson and Turner, 2015: 412). Digital ethnography provides insight into the changes and transformations in how individuals interact with the virtual environment around a concept. One of the difficulties in collecting data through participant observation in classical ethnographic data collection methods is that the researcher's presence creates a "reactivity" effect that causes behavioral changes in group members (Christensen, Johnson and Turner, 2015: 414). In this study, we focused on the concept of "fast fashion." Two social media platforms were chosen for investigation: Instagram and YouTube. Labels (hashtags) determined according to the topic of the study were #fastfashion and alternatives such as #slowfashion, #sustainablefashion, #ecofashion, and #ethicalfashion. The number of posts made using these labels and the form of interactions were first analyzed. Positive and negative comments made under posts were analyzed to examine perceptions. Individuals' awareness of the effects of fast fashion was examined through examples from Instagram and YouTube. Therefore, as data was collected from these sources, it was analyzed according to the identified themes, patterns, and meanings. As Christensen et al. (2015) stated, meaning was extracted from the collected data, and the data was checked for validity throughout the process.

The number of posts related to the labels on Instagram was obtained by typing the label into the search button and counting the results. On YouTube, a project was created via the Google Cloud Console web address. After enabling the YouTube Data

API v3 service, an API key was generated. Requests were sent to the API via Python to obtain the number of keywords (labels). No interaction or messaging occurred with any users who shared posts/videos or interacted under these posts. Anonymity was maintained. No ethical were committed in the analysis of public posts/videos and comments.

The limitation of the research is that the number of posts mentioned for both social media platforms used is based on the values visible on the platforms' user interface and may change over time.

Results and Discussion

Bibliometric analyses results

First, the bibliometric analysis was conducted to conceptualize how the academic reflections of keywords related to the subject. The analysis shows the number of documents related to the keyword “fast fashion” obtained from the dimensions.ai platform according to research areas and codes, as shown in Figure 1. “35 Commerce, Management, Tourism and Services” ranks first with the highest number of publications, followed by “46 Information and Computing Sciences” and “40 Engineering.” The “44 Human Society” field ranks 10th in terms of publication count. Commerce and management, which covers the purchase, sale, distribution, marketing, logistics, and pricing of fast fashion consumer goods, includes various studies that will benefit enterprises that implement fast fashion as a business model. Research related to the field of information and computing sciences, which includes artificial intelligence applications that facilitate the workflows of businesses implementing fast fashion, points to more sustainable studies that require both less time and resources. Research in the field of engineering focuses on sustainability, the consumption habits of different generations, green synthesis, and the sectoral effects of recycling. Human society, which includes topics such as consumer behavior, labor market analysis, social sustainability goals, and supply chain, appears with fewer publications.

According to Giddens (2013: 639), technological developments experienced worldwide, particularly since the second half of the twentieth century, have transformed the appearance of telecommunications as a means of transmitting information, sound, and images remotely, along with the development of the internet. Accordingly, it can be said that these advances have increased awareness in the fields of information and computing research and have also influenced consumer behavior.

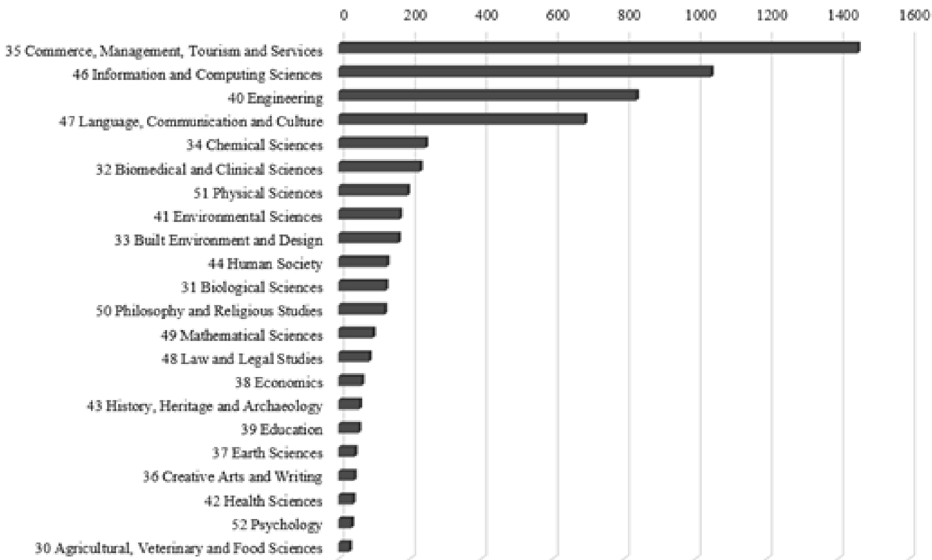

Figure 1. Number of documents vs ANZSRC Research fields (Reproduced by authors from dimeasions.ai data)

The three-field plot Sankey diagram in Figure 2 denotes the documents published in two databases according to years. The first field was the keywords searched in Scopus or WoS. The second field was years, and the last one was the database type. The thicker the rectangle or line, the greater the number of documents. As seen, fast fashion and sustainable fashion terms are the most common keywords among others. Moreover, Scopus includes significantly more documents than WoS for all keyword terms. The number of publications containing the keyword “sustainable fashion” in 2024 and 2025 are also at the highest level.

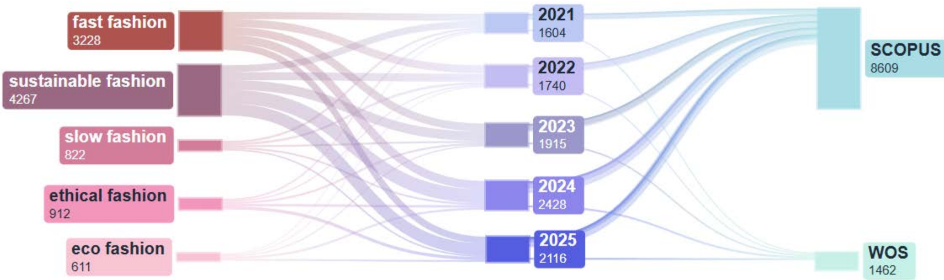

Figure 2. Sankey diagram illustrating the annual distribution of fast-fashion-related keywords and their flow into Scopus and Web of Science databases (Created by authors)

The bibliometric network map presented in Figure 3 was created to identify other keywords co-occurred with the keyword “fast fashion” in the academic field. The network map was formed with seven clusters and 35 themes. The economy-marketing-social media cluster includes “greenwashing,” “luxury,” “Instagram,” and “generation Z.” This structure shows that fast fashion is discussed in terms of marketing practices, generation Z consumption behaviors, the impact of social media, and brands' greenwashing. This cluster is supported by the fact that a visual-based platform such as Instagram plays a decisive role in fashion consumption. The terms “clothing industry,” “purchase intention,” “generation Z,” and “consumption behavior” are concentrated in the sustainable consumption and environmental impact cluster. This cluster shows that a large portion of the research focuses on the environmental costs of fast fashion, sustainable consumption trends, and consumers' purchase intentions. In the circular economy–fashion industry cluster, themes such as “sustainable development,” “fashion industry,” “recycling,” and “state of the art” are at the forefront. The interactions in this cluster refer to the transformation of the fashion industry and circular economy approaches. The concepts of “recycling” and “textile industry” form the sustainable fashion–slow fashion–sustainability cluster. This structure reveals the intensity of the slow fashion movement, which stands in opposition to fast fashion, sustainable production practices, and sustainability-focused fashion industry research. “E-commerce” and “ethics” within the retail–digitalization–consumer behavior cluster reflect consumers' access to fashion products in the digital environment, the effects of online shopping in the context of sustainability, and ethical consumption debates. The small gender-clothing cluster points to how fast fashion is linked to gender studies, while the theme corporate social responsibility is rarely used in conjunction with other themes, forms the final cluster.

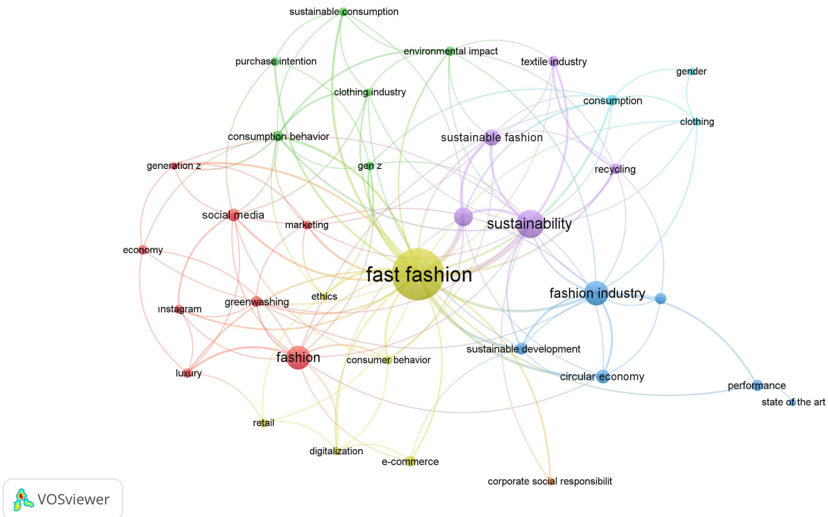

Figure 3. Bibliometric network map of keywords (Created by authors)

Figure 4 gives the treemap chart of keywords of 5 top cited articles in Scopus related to fast fashion and sustainable fashion keyword terms. One of the largest blocks in documents related to fast fashion, “polyester”, is one of the most important topics of discussion in fast fashion. Both its low cost and ease of production indicate its widespread use in fast production processes. The concept of “textile waste” emphasizes the high-volume waste problem arising from fast fashion's culture of excessive consumption. According to Giddens (2013: 995), consumption emphasizes the goods, services, energy, and resources consumed by human societies and institutions, but it can also damage the environmental resource base with negative effects and, at this point, bring patterns of social inequality to the fore.

The literature highlights the growing environmental burden, especially with short-lived products ending up in the trash. The position of "rapid fabrication" in the treemap represents mass and accelerated production processes, one of the fundamental characteristics defining fast fashion. This theme is frequently examined for its negative impacts on both labor and the environment. The concept of "artificial intelligence (AI)" refers to how new digital technologies are used in the industry for demand forecasting, production optimization, and customer behavior analysis. AI is considered a critical tool, particularly for trend forecasting and inventory management. The concept of "sustainability" shows the intensity of sustainability debates within fast fashion itself and a critical view of the concept of fast fashion.

The boxes on the sustainable fashion side show that the literature deals more with environmental, ethical, and transformation-focused themes. The concept of "sustainability" stands out as the most dominant keyword in the treemap and forms the basic principle of sustainable fashion. Research has generally focused on reducing resource use, nature-sensitive production processes, and ethical consumption practices. The transformation of the textile industry production chain, sustainable supply chains, and environmentally friendly materials show that sustainable fashion is being addressed at an industrial level. The fact that the "circular economy" concept appears as a distinct block in the map shows that sustainable fashion, unlike fast fashion, emphasizes closed-loop models based on the reuse, repair, and recycling of products. It is a concept frequently referenced in the literature. Indeed, today people are confronted with various dimensions of "manufactured risk" created by the impact of their own knowledge and the technology they have produced on the natural world (Giddens, 2013: 1006). This situation is increasingly drawing attention as a significant problem, both environmentally and sociologically. "Digital transformation" is addressed in the context of traceability, transparent production, and data-driven decision-making. This theme stems from brands' use of tools such as blockchain and digital supply chain tracking. As a primary search term, fashion occupies a significant space in the sustainability field and demonstrates that the concept of fashion is being redefined through alternative production and consumption models beyond fast fashion.

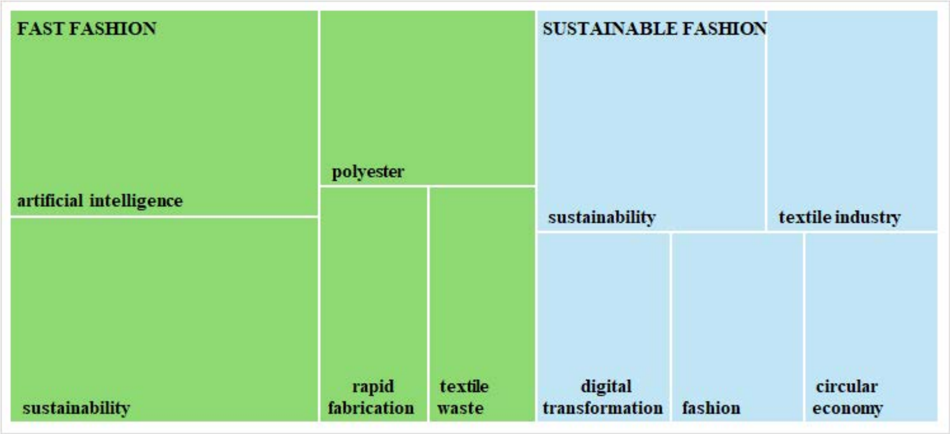

Figure 4. The treemap chart of keywords of 5 top cited articles in Scopus related to fast fashion and sustainable fashion (Created by authors)

Digital ethnographic analyses results

In this neoliberal era, where people are constantly bombarded with advertisements and messages emphasizing the need to be "stylish," "trendy," "stay on trend," and "keep up with fashion," and where constant pressure is exerted on people to consume, the questions that need to be addressed sociologically in this study are: what is the perception of fast fashion on Instagram and YouTube, what are people's attitudes, and how do these attitudes influence people's behavior in purchasing fast fashion goods? Jean Baudrillard emphasizes in his text The Consumer Society that consumption encompasses all of life. Consumers go from one object to another, making chain purchases (Baudrillard, 1998, 18-20). This chapter examines how Instagram and YouTube social media platform users position themselves around the concept of fast fashion as consumers and how they interpret this phenomenon through discourse.

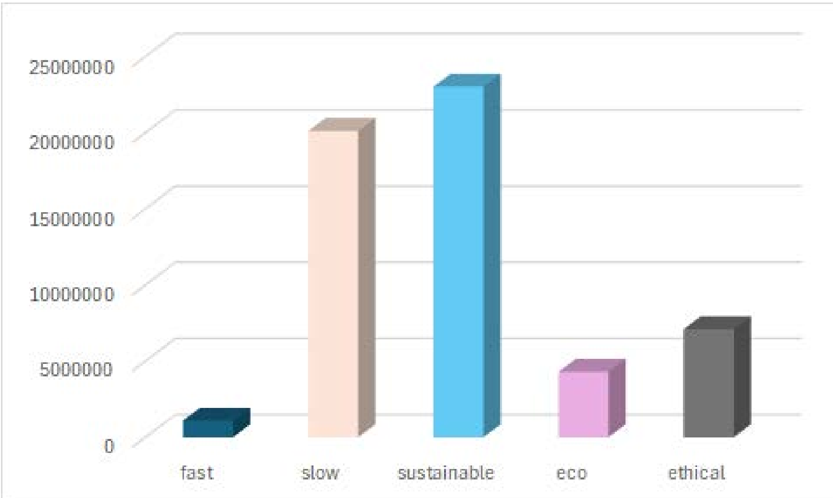

Figure 5. Number of posts in Instagram with labels #fastfashion, #slowfashion, #sustainablefashion, #ecofashion, and #ethicalfashion (Created by authors)

Figure 5 shows the number of hashtags scanned on the Instagram platform. While there were few posts published with the #fastfashion hashtag, many posts were shared with the hashtags #fastfashionalternatives, #fastfashionrevolution, #fastfashionisdead, and #fastfashionawareness. This situation alone indicates a critical view of the concept of fast fashion on Instagram. According to the results, hashtags typically appear under visual or video posts highlighting the dark side of fast fashion, including statistical data, footage of activists' actions, environmental damage, and labor exploitation. Institutions, organizations, non-governmental organizations (NGOs), and secondhand stores are often the primary originators of the posts. The objectives were converged around raising awareness, providing training/certification, making sales, calling to action, and emphasizing savings. A certain portion of those creating the posts aim to sell recycled or upcycled products. It can be said that posts aimed at spreading minimalism or ecological thinking are in the majority. There are posts promoting hand-knitted products as an alternative to industrial fast fashion products and posts aimed at selling secondhand or vintage-style clothing. There are positive and supportive comments from individuals under posts related to the topic. On the one hand, there is a post about the opening of Shein's first physical store in France, one of the fast fashion brands, while on the other hand, a post about clothing forests in France is attracting great interest. Accounts creating posts to raise awareness about the concept of fast fashion have between 50 and 450K followers, while fast fashion brands have between 30 and 70 million followers. Therefore, although the total number of posts for the hashtags examined in the study exceeds 55.5 million, considering the number of Instagram users (1.74 billion monthly active users in January 2025 (Datareportal, 2025)) and interactions, it is evident that this figure corresponds to a topic area within a small circle of interaction.

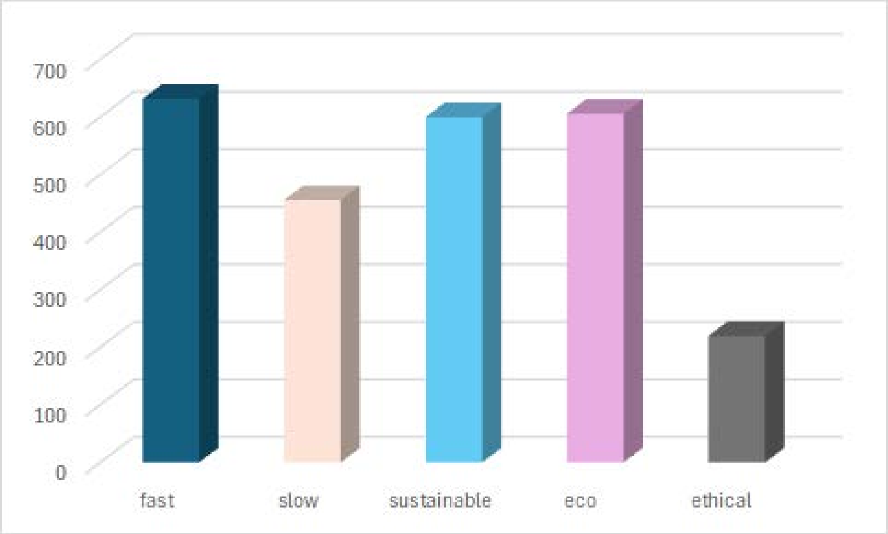

Figure 6. Figure 5. Number of posts in YouTube with labels #fastfashion, #slowfashion, #sustainablefashion, #ecofashion, and #ethicalfashion (Created by authors)

When examining Figure 6, it is evident that the number of videos on YouTube, according to the labels, is significantly lower than on Instagram. However, although content production on YouTube is less than on Instagram, the interactions occurring under the videos are of a larger volume. Videos published on YouTube on topics such as what fast fashion is, its true cost, its dark side, its ugly reality, its environmental impact, its life cycle, labor exploitation, and how the industry is killing the world have received between 10 million and 1.5 million views. There are 11,125 comments under the video with 10 million views. The one with 1.5 million views has 725 comments. While the vast majority of comments are positive, there are also pessimistic comments suggesting that the world will not change and that even if everyone watched these videos, some people would still consume fast fashion products. Positive comments encourage video content creators and advise them to make more videos, argue that this type of content should be shown to children in schools, claim that the video made them cry, touched them deeply, and changed their perspective, and call for a boycott to raise awareness. The channel owner with the highest number of subscribers among the top 10 most-watched videos (TedEd) has 2,244 comments from around the world.

Conclusion

Fast fashion has become one of the most defining elements of today's consumer culture; it has profoundly shaped not only purchasing behaviors but also individuals' identity formation processes, desires, and social visibility strategies. This study aims to reveal how fast fashion is represented on two powerful digital platforms such as Instagram and YouTube, how it is interpreted by users, and the discourses surrounding it. Through the digital ethnography method, the natural discourses, interaction practices, emotional responses, and perspectives on consumption produced by users around fast fashion were directly observed; thus, the dynamics of everyday digital culture regarding fast fashion were understood in detail.

The findings show that the fundamental appeal of fast fashion, such as affordable prices, variety, and rapid trend cycles, is intensely reinforced by digital platforms. The large number of users following fast fashion brand accounts points to this. Bauman (2013: 221) emphasizes that new technologies do not simply respond to a need. Demand for new products comes after they are launched on the market. As Bauman points out, with the emergence of digital technologies and the expansion of their areas of use, new product brands are launched on the market first, and then demand follows. Therefore, digital platforms can also generate intense interest in consumer products. Perhaps, as Bauman states (2013: 222), people have become "consumers of expertise."

Instagram's visually-centered structure, users' clothing posts, its occasional use as a shopping site, rapid trend transformations, and influencer guidance (by convincing the individual that any product to be consumed is also designed for their own personal use) have turned fast fashion into an aesthetic norm. These posts trigger individuals' desires for short-term happiness, validation, and belonging, normalizing consumption behaviors. However, although limited to a small interaction space on Instagram, the existence of a sustainability-focused counter-narrative has been identified through scanned hashtags. Posts with hashtags such as #slowfashion, #sustainablefashion, and #ethicalfashion are concentrated in digital spaces created by users striving to raise environmental awareness. However, these discourses remain less visible within the platform's overall trend-focused algorithmic structure. Aesthetic and speed-focused algorithms limit the spread of sustainability discourses and lead to fast fashion content becoming more dominant.

In this context, Baudrillard's “simulated image of society” comes to mind (Slattery, 2020:473). While criticizing the values and superficiality of society during that period, Baudrillard highlights the striking impact that the control power of mass media has on society. The power of symbols in these tools has permeated every area of social life (Slattery, 2020: 473-474). Similarly, it can be argued that fast fashion is spreading everywhere through contents and algorithms on digital platforms, which are extensions of internet technologies representing new media today. As Daniel Bell stated in “The Coming of the Post-Industrial Society,” the use of new technologies has increased in all areas of today's society, and computers, the internet, and communication in a global context have become highly developed and widespread (Slattery, 2020: 467-468). At this point, it has been possible to see the symbols and meanings produced and used by many individuals on digital platforms.

YouTube, unlike Instagram, offers a more argumentative, reflective, and emotionally profound discourse space. While “haul” videos make fast fashion appear appealing, the comments beneath these videos clearly reveal users' internal conflicts, environmental concerns, and reactions to labor exploitation. The bibliometric findings of the study are also consistent with the digital ethnography results. Themes that are the focus of academic literature, such as “environmental sustainability,” “textile waste,” “consumer behavior,” “greenwashing,” and “circular economy,” are echoed in different ways in the discourse of YouTube and Instagram users. This situation shows that academic discussions are finding resonance in the social sphere; users' awareness of sustainability, ethical consumption, and environmental sensitivity is increasing.

Using the digital ethnography method, users' discourses, emotional expressions, everyday performances, and perceptions of fast fashion consumption could be observed in their natural state in the digital environment. This method revealed that social media platforms are not only spaces for sharing information but also dynamic public spaces where identity performances and social debates take place.

Ultimately, it is clear that sociologists, who provide the most rational answer to the question of how we can live together and reveal various phenomena in their raw form in the construction of healthy societies, and engineers, who work to raise awareness for the protection of the environment, the creation of a sustainable environment, and the development of responsible consumption among individuals, must collaborate. Analyzing the concept of fast fashion via digital platforms is considered to be an interdisciplinary field of study with one aspect relating to sociology and another to engineering. In this context, this study is one of the pioneering works that will shed light on the field.

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CHAPTER XV

MAPPING THE FASHION PERSONALIZATION LANDSCAPE: A SYSTEMATIC REVIEW AND THEMATIC NETWORK ANALYSIS (2021–2025)

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Abstract

This study examines the evolution of fashion personalization between 2021 and 2025, highlighting its technological, cultural, and behavioral dimensions. Using a mixed-methods approach, it combines bibliometric mapping (VOSviewer®) and thematic network analysis (IRaMuTeQ®) based on 73 peer-reviewed articles from the Web of Science. Results indicate a growing academic interest since 2023, with research concentrated in technologically advanced countries such as China, the United States, and Germany. Six thematic clusters reveal two main research axes: a technological one, focused on AI, algorithmic design, and virtual environments; and a human-centered one, emphasizing identity, inclusivity, and sustainability. Findings suggest that personalization has evolved from a marketing tool into a socio-technical paradigm that merges creativity, data, and ethics. The study contributes by mapping the field's conceptual structure and proposing directions for interdisciplinary research in digital innovation and sustainable fashion.

Keywords: fashion personalization, artificial intelligence, bibliometric analysis, thematic networks, technology.

Introduction

Over the past decade, the convergence of artificial intelligence (AI), data analytics, and digital culture has profoundly reshaped the global fashion industry. As consumers increasingly seek individualized, immersive, and emotionally resonant experiences, personalization has emerged as a defining paradigm of contemporary fashion. It reflects not only technological evolution but a cultural and economic transformation—one that repositions fashion as an ecosystem of interactive, data-informed relationships between brands, products, and users. The integration of AI and machine learning has enabled brands to predict preferences, tailor recommendations, and generate virtual fittings in real time, establishing personalization as both a strategy of differentiation and a central mechanism for reimagining design, production, and consumption.

This paradigm shifts from mass production to individualized creation signals a broader restructuring of value within the fashion system. Once driven by aesthetic innovation and trend cycles, the industry now operates through algorithmic intelligence, predictive modeling, and behavioral analytics. Virtual try-on technologies, generative design platforms, and co-creation interfaces enable consumers to participate actively in product development, redefining authorship and authenticity in fashion design. Consequently, personalization is no longer a peripheral marketing tactic but an operational and epistemological principle that governs how fashion communicates identity, emotion, and cultural belonging in digital contexts.

Simultaneously, personalization intersects sustainability and ethics, reshaping how the industry conceives responsibility and consumption. By aligning production with real-time consumer data, personalization promises to reduce waste, minimize returns, and foster longer product lifecycles. Yet, this same data dependency introduces new ethical challenges related to surveillance, algorithmic bias, and privacy. The tension between technological optimization and human agency has become central to contemporary debates on digital fashion. As personalization technologies increasingly mediate emotional and social dimensions of consumption, they raise fundamental questions about individuality, transparency, and inclusivity in algorithmic environments.

From a sociocultural perspective, personalization reflects a deeper shift toward participatory and identity-based consumption. Digital natives, particularly Generation Z, demand not only functional fit but symbolic resonance—expecting fashion to reflect their values, emotions, and social positioning. The rise of the metaverse, augmented reality (AR), and avatar-based shopping has further blurred the boundaries between material and digital fashion, making personalization a key medium for self-expression. Within this hybrid ecosystem, fashion functions as both product and performance: a continuously adaptive interface between self and society, shaped by data and co-authored by users.

Despite its transformative potential, the literature on fashion personalization remains fragmented, with limited integration between technological, behavioral, and cultural perspectives. Previous research has advanced isolated insights into specific applications—such as AI-driven recommendation systems, consumer experience modeling, and virtual fitting technologies—but lacks a comprehensive understanding of how these developments interrelate within the broader fashion innovation landscape. This theoretical dispersion has hindered the consolidation of personalization as a coherent research field, calling for a systematic synthesis that can clarify its evolution, thematic diversity, and interdisciplinary implications.

Accordingly, this study offers three main contributions to the field of fashion and technology studies:

1. It provides a theoretical synthesis of how personalization has evolved as a socio-technical construct, articulating its intersection with creativity, identity, and digital ethics.
2. It integrates bibliometric mapping with thematic network analysis, employing VOSviewer® and IRaMuTeQ® to uncover both structural and semantic relationships across five years of research (2021–2025).
3. It identifies the central research axes and conceptual clusters that define current scientific discourse on fashion personalization, bridging quantitative evidence with qualitative interpretation to build a comprehensive framework of understanding.

Therefore, the main objective of this study is to analyze and interpret the scientific production on fashion personalization published between 2021 and 2025, combining bibliometric and thematic analyses to map its evolution, disciplinary intersections, and conceptual trajectories. By doing so, the study seeks to provide an integrated perspective on how personalization functions as a technological, cultural, and ethical paradigm in the contemporary fashion system.

The paper is structured into six main sections. Following this introduction, Section 2 presents the literature review, situating personalization within broader debates on digital transformation, AI, and consumer behavior in fashion. Section 3 details the methodological procedures adopted for data collection and analysis. Sections 4 and 5 report the results of the bibliometric mapping and thematic network analysis, respectively, highlighting the structural and conceptual evolution of the field. Finally, Section 6 offers concluding reflections and future research directions, emphasizing the implications of personalization for innovation, sustainability, and human-centered design in the digital era.

Literature review

Over the past five years, personalization has emerged as one of the most transformative forces in the fashion industry, driven by the convergence of artificial intelligence (AI), data analytics, and changing consumer expectations (Guo et al., 2023; Sharma et al., 2021; Sun, 2025; Nobile & Cantoni, 2023; Chen et al., 2019). Fashion brands and digital platforms are increasingly adopting personalization strategies to deliver unique and emotionally resonant experiences, using technology not only as a tool for differentiation but also as a central mechanism for redefining design, production, and consumption processes

(Subaranjani et al., 2024; Asaro, 2025; Gaikhe et al., 2025; Yu et al., 2019; Sun et al., 2018). This movement marks a paradigmatic shift from mass production to data-informed customization, where technology mediates the interaction between consumers and products at an unprecedented level of detail.

AI and data-driven systems play a fundamental role in this transformation. Recommendation engines, generative design tools, and deep learning models enable brands to analyze vast sets of information regarding consumer preferences, body measurements, and stylistic choices, producing highly tailored product suggestions and virtual try-on experiences (Lu et al., 2022; Jain, Paul & Shrivastava, 2021; Chen et al., 2019). Such systems have proven effective in improving customer satisfaction and purchase confidence by personalizing both the aesthetic and functional dimensions of fashion consumption (Ding et al., 2023; Ma, Kim & Lee, 2022). Simultaneously, online customization platforms have democratized access to design processes, allowing consumers to co-create products by selecting materials, colors, and fits through 3D CAD environments and virtual fitting technologies that offer real-time feedback (Sharma et al., 2021; Sun, 2025; Gaikhe, 2025; Ma, Kim & Lee, 2022). This participatory dynamic repositions consumers as active agents in the creative process, generating a sense of authorship and personal meaning in their fashion choices (Kent, 2017; Jain, Paul & Shrivastava, 2021; Ma, Kim & Lee, 2022).

Recent research also highlights the growing integration of emotional and social data into personalization systems. By analyzing user interactions on social media—such as likes, comments, and visual content—brands can infer affective responses and incorporate them into product development and recommendation algorithms (Asaro, 2025; Sun et al., 2018; Ma, Kim & Lee, 2022). Emotional AI and sentiment analysis contribute to refining these systems, enabling fashion companies to anticipate preferences and establish deeper emotional connections with users (Suleman et al., 2025; Ma, Kim & Lee, 2022). This shift suggests that personalization now operates not only at the functional level, addressing fit or style, but also at the symbolic level, where emotional resonance and identity play decisive roles in consumer-brand relationships (Ma, Kim & Lee, 2022).
From a consumer perspective, personalization significantly enhances engagement, satisfaction, and loyalty, particularly among Generation Z and digital-native audiences who value individuality and authenticity in their consumption experiences (Sun, 2025; Subaranjani et al., 2024; Asaro, 2025; Suleman et al., 2025; Ma, Kim & Lee, 2022). Studies show that consumers exposed to personalized

recommendations tend to perceive higher enjoyment and trust in digital fashion platforms, translating into stronger long-term commitment to brands (Ma, Kim & Lee, 2022). Moreover, the logic of co-creation fosters a participatory environment in which consumers become collaborators in design, reinforcing their sense of ownership over products and amplifying emotional attachment (Kent, 2017; Jain, Paul & Shrivastava, 2021; Ma, Kim & Lee, 2022). Social media and influencer marketing further accelerate this dynamic, shaping preferences and driving the demand for customizable fashion products (Asaro, 2025; Suleman et al., 2025; Ma, Kim & Lee, 2022).

However, despite these benefits, literature also identifies a range of challenges associated with the implementation of personalization in fashion. While personalization tends to increase satisfaction, improve fitness, and reduce return rates, it also introduces technical and ethical concerns, particularly regarding data integration, privacy, and algorithmic transparency (Sun, 2025; Subaranjani et al., 2024; Gaikhe et al., 2025; Yu et al., 2019; Lu et al., 2022; Ma, Kim & Lee, 2022). The process of balancing scalability and uniqueness remains one of the most complex aspects of sustainable on-demand production (Sun, 2025; Ma, Kim & Lee, 2022). Additionally, the heavy reliance on user data for personalization exposes fashion companies to issues of consent, data protection, and algorithmic bias, which can compromise consumer trust if not properly managed (Suleman et al., 2025; Ma, Kim & Lee, 2022).

In summary, the evolution of personalization in fashion represents both a technological advancement and a cultural reconfiguration of the fashion system. On one hand, it empowers consumers to participate in the creative process and strengthens emotional bonds with brands; on the other, it challenges the industry to reconcile innovation with ethical, technical, and sustainability demands. As the literature suggests, the future of fashion personalization depends not only on the sophistication of AI and data analytics but also on the industry's ability to maintain human meaning and individuality within increasingly automated systems (Ma, Kim & Lee, 2022; Li et al., 2020). Therefore, given the rapid technological evolution and the fragmented nature of existing studies, there is a pressing need for a systematic literature review that consolidates the findings of the past five years, offering an integrated understanding of how personalization in fashion has developed across technological, cultural, and consumer-driven dimensions.

Methodology

Regarding its methodological characterization, this study is classified as basic research, since it does not aim for the direct replication or practical application of the investigated content (Gil, 2008) but rather contributes to the theoretical and scientific development of fashion studies related to personalization technologies. In terms of objectives, it is an exploratory-descriptive study (Marconi & Lakatos, 2011) with a mixed-methods approach (Gil, 2008), combining quantitative and qualitative analyses. The quantitative stage describes bibliometric patterns derived from the dataset, while the qualitative stage explores the conceptual and thematic relationships among studies through thematic network analysis (Attride-Stirling, 2001).

To achieve the proposed objectives, a systematic literature review was conducted under the scoping review framework, which aims to provide an initial indication of the extent, range, and nature of existing research on a given topic (Arksey & O'Malley, 2005; Paré et al., 2015). The review followed six main steps: (i) identification of the database to be analyzed; (ii) definition of search keywords; (iii) execution of the search; (iv) screening of titles, abstracts, and keywords; (v) exclusion of unrelated studies; and (vi) full-text screening of the remaining documents.

The bibliographic search was conducted exclusively in the Web of Science database (Martín-Martín et al., 2021), selected for its broad coverage of high-impact international journals and consistent metadata structure for bibliometric analysis. The search strategy employed two markers combined through the Boolean operator “AND,” aiming to retrieve studies that contained both the technological and domain-specific terms:

1. *“Personalization”*
2. *“fashion”*

Thus, the final search expression was “Personalization” AND “fashion”, applied to titles and abstracts. Only peer-reviewed scientific articles written in English and published within the last five years (2021–2025) were included. The search was performed in October 2025, encompassing studies available up to September 2025. As a result, 73 articles were retrieved and selected for further analysis after screening and duplicate removal.

The bibliometric phase of the study was conducted using the software VOSviewer®, which allows the creation and visualization of bibliometric networks. This quantitative analysis explored the relationships among authors, institutions, countries, and keywords, identifying intellectual and collaborative structures within the field.

Subsequently, a qualitative thematic analysis was performed using IRaMuTeQ®, employing textual data from the abstracts of the retrieved articles. Following the approach of Attride-Stirling (2001), the procedure involved generating word clouds and dendrograms of classification to summarize and visualize key themes emerging from the corpus.

The thematic network construction followed six complementary stages adapted from Attride-Stirling (2001) and Soares Júnior et al. (2023):

(i) data coding;
(ii) identification of emerging themes;
(iii) construction of thematic networks;
(iv) exploration of interconnections;
(v) synthesis of central themes through word clouds; and
(vi) interpretation of recurring conceptual patterns.

This dual bibliometric–thematic strategy provided an integrated understanding of how personalization in fashion has been addressed in the scientific literature of the last five years, combining quantitative mapping with qualitative thematic interpretation.

Bibliometric analysis

Regarding the chronological development of research on fashion personalization, Figure 1 illustrates the chronological distribution of the 73 articles analyzed between 2021 and 2025. The data reveal a gradual increase in the number of publications over the five-year period, suggesting growing academic interest in personalization within the fashion domain.

After an initial decline from 13 articles in 2021 to 11 in 2022, the number of studies began to rise consistently, reaching 12 in 2023 and showing a sharp increase in 2024 (17 articles) and 2025 (20 articles). This upward trend indicates that personalization might have become a consolidated topic of inquiry in fashion research, reflecting broader shifts in consumer behavior, technological adoption, and the integration of data-driven approaches in design and retail practices.

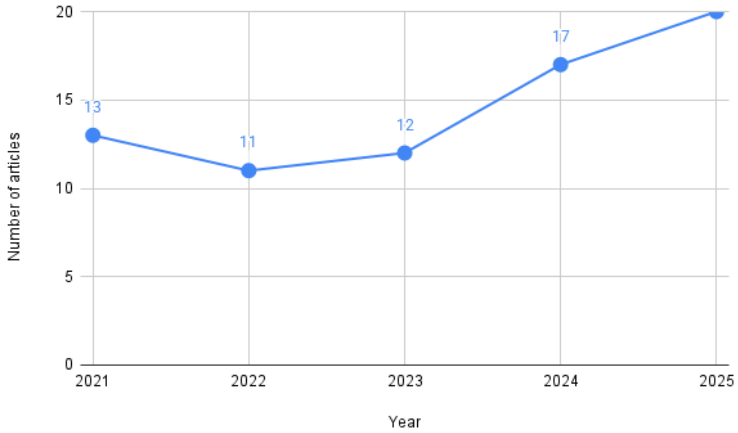

Figure 1. Chronological development of research on fashion personalization

The progressive growth observed from 2023 onwards aligns with the post-pandemic acceleration of digital transformation in fashion, particularly with artificial intelligence (AI), virtual fitting technologies, and recommendation systems (Wanick & Bazaki, 2023; Najib & Chakor, 2024). This trend suggests that scholars are increasingly addressing personalization as both a technological innovation and a cultural response to the demand for individuality and sustainability in fashion consumption.

The bibliometric analysis identified a total of 269 authors associated with the 73 selected articles. However, most of them appeared only once in the dataset, indicating a fragmented authorship pattern in the field. Among those with more than one contribution, Yini Chen from the Department of Apparel, Merchandising, Design and Textiles, Washington State University (USA) stood out as the most prolific author, with two publications and a total link strength of 253, suggesting moderate collaboration within the network.

At the institutional level, the Hong Kong Polytechnic University emerged as the most productive organization, contributing four documents and accumulating 30 citations, followed by Yonsei University (South Korea) with three documents and seven citations, and Ghent University (Belgium) with two documents but a notably higher 19 citations, indicating greater academic impact. Other relevant institutions included Purdue University (USA) and Washington State University (USA), each with two publications, highlighting a transnational concentration of research in East Asia and North America.

Regarding the geographical distribution (Figure 2), the studies originated mainly from China (19 documents, 97 citations), the United States (14 documents, 204 citations), and Germany (7 documents, 40 citations). These were followed by Italy (6), South Korea (5), and Finland (4), evidencing a predominance of research activity in technologically advanced economies with strong innovation ecosystems. The citation impact of India (81 citations), despite its lower publication volume (4 documents), suggests emerging academic visibility and potential regional leadership in the study of technology-driven personalization.

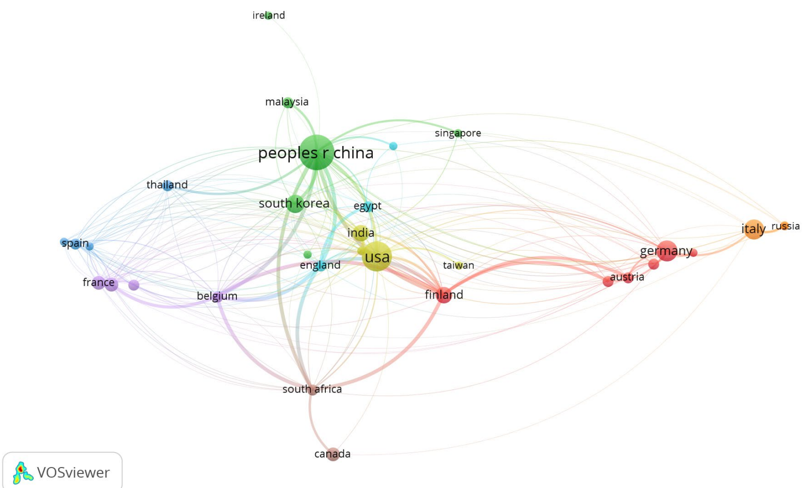

Figure 2. Geographical distribution of scientific publications on fashion personalization

This global pattern reveals that investigations on fashion personalization are primarily concentrated in countries with robust fashion industries and advanced research infrastructures, reflecting the intersection between technological development and creative economies. The dominance of Chinese and American institutions also mirrors the broader digital transformation of the fashion sector, where AI-based recommendation systems, data analytics, and consumer behavior modeling are driving personalization as both a technological and cultural paradigm.

The analysis of publication sources revealed that research on fashion personalization is disseminated across a diverse set of journals, reflecting its interdisciplinary nature (Table 1). Eight journals presented at least two documents within the analyzed period, covering areas that range from fashion and consumer behavior to psychology, information systems, and sustainability.

Table 1. Main journals publishing research on fashion personalization (2021–2025)

Source	Documents	Citations	Total Link Strength
Sustainability	3	19	32
Frontiers in Psychology	2	23	34
Journal of Fashion Marketing and Management	2	10	20
Journal of Retailing and Consumer Services	2	10	19
International Journal of Human–Computer Interaction	2		18
Textile Research Journal	2	15	18
ACM Transactions on Information Systems	2	17	15
Journal of Global Fashion Marketing	2	4	14
Others	56		

Among these, Sustainability emerged as the most productive source, publishing three articles that collectively received 19 citations, followed by Frontiers in Psychology, with two articles and 23 citations, the highest citation impact among the identified journals. This finding highlights the growing concern with sustainability and psychological dimensions in understanding personalization practices, particularly in how consumers engage with customized fashion products and digital experiences.

Other recurrent publication venues include the Journal of Fashion Marketing and Management, the Journal of Retailing and Consumer Services, and the Textile Research Journal, each contributing two studies. These journals reinforce the link between personalization, marketing strategies, and technological innovation in the fashion industry. Additionally, the ACM Transactions on Information Systems and the International Journal of Human–Computer Interaction reflect the computational and user-centered aspects of personalization, suggesting that fashion-related personalization research is increasingly grounded in data science, artificial intelligence, and digital interface design.

Overall, the dispersion of studies across both social science and technology-oriented outlets underscores the multidisciplinary character of the topic. It demonstrates that fashion is no longer confined to aesthetic or design discussions but is increasingly positioned at the intersection of consumer psychology, digital technology, and sustainability—a convergence that mirrors the broader transformation of the fashion ecosystem in the digital era.

The four most cited and influential articles in the dataset provide a clear picture of how personalization has been conceptualized and operationalized in recent fashion research. Table 2 summarizes the most prominent studies in terms of citation impact and total link strength.

Table 2. Most cited documents addressing personalization in fashion (2021–2025), showing leading studies that bridge consumer behavior, artificial intelligence, and technological innovation

Author (Year)	Main Focus	Citations	Total Link Strength
Jain (2021)	Digital clienteling and co-creation in hyper-personalized fashion services using the Technology-Based Reasoned Action (TBRA) model	54	12
Jin (2021)	The role of 4th Industrial Revolution technologies in addressing hyper-personalization, sustainability, and productivity challenges in fashion	44	26
Micu (2022)	Development of an AI-driven on-site customer profiling and hyper-personalization system (OSCPHPS) for in-store marketing	24	5
Ding (2023)	Template-guided outfit generation (TOG) model for personalized fashion recommendations and compatibility prediction	21	13

The most cited work in the corpus, by Jain (2021), adopts a service innovation perspective, extending the Technology-Based Reasoned Action (TBRA) model to explore the effects of customer innovativeness, attitudes, and involvement in co-creating hyper-personalized digital services. This study positions personalization as both a technological and behavioral phenomenon, emphasizing customer participation and co-creation as mediating forces in digital fashion transformation.

Similarly, Jin (2021) situates personalization within the broader framework of the Fourth Industrial Revolution (4IR), identifying hyper-personalization, sustainability, and productivity as three central goals reshaping fashion's production and consumption logics. By comparing cases across global industries, the study concludes that successful personalization relies less on technological availability and more on business model innovation aligned with unmet consumer needs—thereby linking personalization to strategic management and systemic adaptation.

Micu (2022) approaches personalization from a technological systems design perspective. Through the prototype of an AI-based on-site customer profiling and hyper-personalization system (OSCPHPS), the study explores how real-time data collection and emotion recognition can improve customer experience and sales performance. This work exemplifies the integration of machine learning, behavioral analytics, and retail strategy, signaling the ongoing convergence between computer science and fashion marketing.

Finally, Ding (2023) advances the discussion toward algorithmic personalization, proposing the Template-Guided Outfit Generation (TOG) framework. By modeling both user-item interaction and outfit compatibility, the study introduces a sophisticated mechanism for generating customized outfit recommendations using public datasets such as Fashion and Polyvore. The high precision scores reported in this study underscore the growing efficiency of AI-based personalization systems and their ability to merge aesthetic reasoning with data-driven modeling.

Collectively, these articles demonstrate the evolutionary trajectory of personalization research in fashion—from conceptual frameworks of co-creation and consumer participation (Jain, 2021) to highly technical implementations of AI-driven recommendation systems (Ding, 2023). The findings reveal a gradual shift from human-centric to hybrid human–machine models of personalization, where creativity, algorithmic intelligence, and ethical considerations converge to redefine the future of customized fashion experiences.

In summary, the bibliometric analysis reveals that research on fashion personalization has evolved rapidly over the past five years, consolidating itself as a multidisciplinary and globally distributed field. The increasing number of publications since 2023 demonstrates the growing relevance of personalization as a response to the digitalization of fashion and the consumer demand for individualized experiences. Although authorship remains fragmented, institutional and geographic patterns point to strong leadership from technologically advanced countries—particularly China, the United States, and European nations—supported by universities with established programs in fashion technology and digital innovation. The diversity of publication venues, spanning from sustainability and psychology to information systems and marketing, further underscores the convergence between design, data, and human behavior. The most cited works in the corpus show a clear methodological and conceptual evolution, moving from behavioral and co-creation models toward AI-based, algorithmic approaches to personalization. Altogether, these results highlight a paradigm shift in fashion studies, where personalization operates not merely as a marketing strategy or design trend, but as a core framework for understanding the intersection of technology, creativity, and identity in contemporary fashion research.

Thematic network analysis

The qualitative stage of the study, performed through Descending Hierarchical Classification (CHD) in IRaMuTeQ, generated six distinct thematic classes (Figure 3). Together, these classes represent the conceptual landscape of personalization in fashion, capturing both the technological and sociocultural dimensions of the topic. Each cluster was interpreted and named according to the prevalence and co-occurrence of terms, resulting in a coherent set of thematic networks that reflect the multidimensional nature of the field.

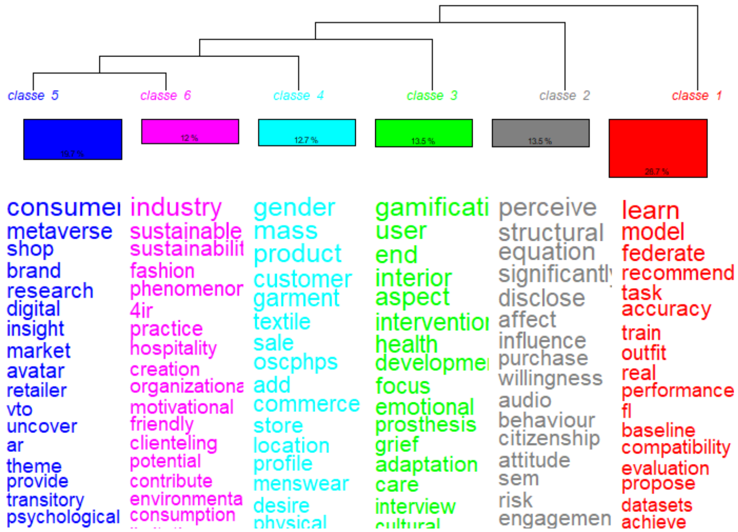

Figure 3. Descending Hierarchical Classification (CHD) dendrogram of fashion personalization studies, showing six thematic classes that represent the main conceptual domains of the field (2021–2025)

The largest cluster (in red) revolves around terms such as learn, model, federate, recommend, accuracy, train, outfit, and dataset. This class represents the technological and computational backbone of personalization, emphasizing the development and training of machine learning and federated learning models for recommendation systems. Studies in this network address how algorithms generate personalized fashion suggestions, optimize outfit compatibility, and improve performance metrics through real datasets (e.g., iFashion and Polyvore). Conceptually, this cluster illustrates the data-driven turn in fashion research, where personalization transcends aesthetics to become a function of predictive analytics, computational modeling, and user–system interaction.

The second cluster (in gray) gathers terms such as perceive, structural equation, attitude, affect, behaviour, engagement, and risk. This network represents a psychological and behavioral dimension of fashion personalization. It captures studies that apply structural equation modeling (SEM) and similar quantitative frameworks to examine how perceptions of personalization influence consumer trust, purchase intention, and emotional engagement. The recurrence of terms like citizenship and willingness suggests a growing concern with ethical consumption and self-expression, linking personalization to identity formation and digital consumer citizenship.

The third cluster (in green) features terms like gamification, user, intervention, health, emotional, prosthesis, grief, and adaptation. This class introduces an experimental and affective perspective, exploring how gamified and immersive systems can enhance user interaction in digital fashion environments. Some studies within this network relate to prosthetic design, adaptive fashion, and emotional computing, signaling a crossover between fashion, healthcare, and digital well-being. The prominence of development and focus terms indicates the consolidation of user-centered methodologies that extend personalization beyond commerce, positioning it as a tool for inclusion, therapy, and empowerment.

The fourth cluster (in cyan) is dominated by terms such as gender, mass, product, customer, garment, menswear, and profile. It represents research on mass customization, inclusive design, and gender representation in digital fashion. The recurrence of store, commerce, and location also suggests links to omnichannel retail strategies, indicating how personalization operates across physical and virtual spaces. This thematic network underscores the social and ethical challenges of algorithmic design, where issues of gender inclusivity, body diversity, and product adaptation are negotiated within data-driven systems.

The fifth cluster (in blue) includes terms such as consumer, metaverse, shop, brand, digital, avatar, research, retailer, and VTO (Virtual Try-On). This class encapsulates discussions around consumer experience in immersive and metaverse-based retail ecosystems. The focus on insight, market, and theme suggests that personalization here is explored as a narrative and experiential construct, where virtual identities, avatars, and augmented reality technologies mediate new forms of shopping and self-representation. This class highlights the fusion of fashion, gaming, and social media, portraying digital fashion as both a laboratory of innovation and a mirror of post-digital consumer identity.

The final cluster (in magenta) is characterized by terms like industry, sustainable, phenomenon, hospitality, organizational, clienteling, environmental, and consumption. This network reflects the sustainability-oriented discourse surrounding personalization, emphasizing how customized production models, eco-conscious digital tools, and circular practices are reshaping the fashion industry. The appearance of 4IR (Fourth Industrial Revolution) and creation connects this class to organizational innovation and the potential of personalization to reduce waste, improve resource efficiency, and enable responsible consumption. It reveals a conceptual alignment between technological advancement and ethical transformation.

Taken together, the six classes reveal a cohesive and interconnected thematic structure. The field of fashion personalization operates along two main axes:

(1) A technological axis, encompassing algorithmic development, virtual

environments, and gamified user experiences (Classes 1, 3, and 5); and

(2) A human-centered axis, focused on psychology, identity, and sustainability (Classes 2, 4, and 6).

This dual structure suggests that personalization in fashion is both a technological process and a cultural practice—a space where data, emotion, and ethics intersect. The thematic convergence identified in the CHD dendrogram highlights a shift from static notions of consumer targeting to dynamic systems of co-creation and adaptive design, marking personalization as a central paradigm in the digital transformation of fashion.

Final considerations

Over the past five years, the intersection of fashion and technology has given rise to personalization as one of the most significant transformations in industry's history. This study aimed to consolidate and interpret the scientific production on fashion personalization between 2021 and 2025, identifying its technological, cultural, and behavioral dimensions. Methodologically, the research adopted a mixed approach that combined bibliometric and thematic analyses. The bibliometric mapping, conducted through VOSviewer®, enabled the identification of publication patterns, authorship networks, and geographical concentration of research, while the qualitative stage, based on IRaMuTeQ® and Descending Hierarchical Classification (CHD), revealed conceptual and symbolic relations among key themes in the field.

The results show a rapid expansion of research on personalization in fashion, with a clear acceleration after 2023. The bibliometric evidence indicates a fragmented but growing academic community, with significant contributions concentrated in technologically advanced countries such as China, the United States, and Germany. The diversity of publication venues—ranging from *Sustainability* and *Frontiers in Psychology* to *Journal of Fashion Marketing and Management*—demonstrates that the topic has become inherently interdisciplinary, bridging fashion studies, data science, consumer psychology, and sustainability. The thematic analysis revealed six interrelated clusters representing two dominant axes: a technological axis focused on algorithmic design, virtual environments, and AI-driven systems, and a human-centered axis addressing identity, inclusivity, emotion, and ethical transformation. Together, these findings depict personalization not merely as a market trend but as a structuring paradigm in the digital evolution of fashion.

Conceptually, the study concludes that fashion personalization has evolved from an operational strategy to a complex socio-technical system. Initially driven by efficiency, customization, and competitiveness, it now functions as a mechanism of meaning production, where algorithmic intelligence and human creativity coexist. Personalization in fashion embodies a new form of authorship, one mediated by data but rooted in emotional resonance, cultural identity, and ethical reflection. It redefines the boundaries between producer and consumer, giving rise to a hybrid space of co-creation in which users participate in shaping products, aesthetics, and even the values of fashion itself.

From an epistemological standpoint, personalization consolidates a theoretical convergence between consumer culture studies and computational design. The field has moved from describing how personalization technologies work to question their implications for subjectivity, representation, and sustainability. The balance between automation and individuality has emerged as a defining tension: while AI systems enable deeper customization, they also risk standardizing identities and reinforcing algorithmic biases. This ambivalence highlights personalization as both an enabler of creative freedom and a potential mechanism of control—reflecting the paradoxes inherent to contemporary digital consumption.

In practical terms, personalization can be understood as a central pillar of the Fourth Industrial Revolution within fashion, promoting the integration of data-driven design, emotional analytics, and circular production models. The literature points to a gradual but decisive reorientation of the fashion system toward adaptive, user-centered, and sustainable frameworks. Yet, this transformation remains incomplete. Despite advances in predictive modeling, generative design, and virtual fitting technologies, challenges persist regarding data transparency, user privacy, and the ethical governance of AI. The long-term sustainability of personalization depends on how fashion companies reconcile innovation with humanistic values—ensuring that personalization serves as a form of empowerment, not surveillance.

Looking ahead, future research should pursue three main directions. First, there is a need for theoretical integration, combining perspectives from fashion studies, cognitive science, and digital ethics to develop models that capture the relational and affective nature of personalization. This involves advancing conceptual frameworks that explain not only *how* personalization technologies operate but *why* they shape identity, emotion, and social behavior. Second, future studies should explore methodological innovation, incorporating multimodal data analysis, user experience ethnography, and computational simulations to better understand personalization as both a design process and a cultural system. Such approaches could deepen our comprehension of hybrid creativity between humans and algorithms.

Finally, an important research agenda concerns the social and environmental governance of personalization technologies. Future investigations should address the ethical and ecological implications of hyper-personalized fashion—particularly how data-driven systems affect labor, diversity, and sustainability across global production chains. Building inclusive datasets, transparent AI frameworks, and cross-cultural analyses will be essential to ensure that personalization contributes to equity and responsible innovation. In this sense, the future of fashion personalization lies not only in algorithmic sophistication but also in its capacity to humanize technology, fostering creativity, diversity, and ethical awareness in the digital age.

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