

# Green Threads for a Sustainable Future: Eco-Friendly and Durable Clothing from Natural Fibers

Zeba Jamal\*, Akanksha Singh\*\*, Prachi Shukla\*\*\*,

Subject Matter Specialist (Home Science) \*\*, Assistant Professor\*, \*\*\*

Department of Apparel and Textile Science, College of Community Science\*

Krishi Vigyan Kendra Kotwa Azamgarh-I \*\*

Department of Human Development & Family Studies, College of Community Science\*\*\*

Acharya Narendra Dev University of Agriculture & Technology Kumarganj, Ayodhya

Corresponding Authors: Akanksha Singh, Dr. Zeba Jamal

E-mail: [singhakku3216@gmail.com](mailto:singhakku3216@gmail.com), [drzebamalnduat@gmail.com](mailto:drzebamalnduat@gmail.com)

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## Abstract

The global textile and fashion industry is one of the major contributors to environmental pollution due to excessive consumption of water, energy, chemicals, and non-renewable resources. The widespread use of synthetic fibers has intensified problems such as greenhouse gas emissions, textile waste accumulation, and microplastic pollution. In response to these environmental concerns, natural fibers have emerged as sustainable alternatives because they are renewable, biodegradable, eco-friendly, and possess excellent functional and comfort properties. This review paper provides a scientific overview of eco-friendly and durable clothing produced from natural fibers including cotton, hemp, flax, jute, bamboo, banana fiber, wool, and silk. The paper discusses the classification, environmental significance, durability, and performance characteristics of natural fibers along with recent advancements in sustainable textile processing technologies such as natural dyeing, enzymatic treatments, nanotechnology, and green chemistry approaches. The role of circular economy principles including recycling, reuse, and biodegradable textile systems in promoting sustainable fashion is also highlighted. Additionally, the review examines major challenges associated with natural fibers such as variability in quality, moisture sensitivity, wrinkling, and higher processing costs, while emphasizing future opportunities through biotechnology, smart textiles, and eco-friendly innovations. The study concludes that natural fibers have significant potential to support environmentally sustainable, durable, and ethically responsible fashion systems. The integration of advanced textile technologies, sustainable agricultural practices, circular economy models, and consumer awareness can help reduce the environmental footprint of the textile industry and contribute toward global sustainability goals.

## Introduction

The global fashion and textile industry has undergone unprecedented growth over the past few decades due to rapid industrialization, population expansion, urbanization, rising disposable incomes, globalization of trade, and continuously evolving consumer preferences. The textile sector is one of the largest manufacturing industries in the world and contributes significantly to economic development, international trade, employment generation, and industrial productivity. According to the World Bank, the fashion

industry employs millions of people worldwide and forms a substantial component of the global economy. However, despite its economic importance, the textile and apparel sector is increasingly recognized as one of the most environmentally damaging industries because of its intensive use of natural resources, chemicals, water, and energy (Niinimäki et al., 2020). Modern textile manufacturing involves multiple stages including fiber production, spinning, weaving, knitting, dyeing, finishing,

garment construction, transportation, retailing, usage, and disposal. Each stage contributes to environmental degradation through greenhouse gas emissions, wastewater discharge, chemical pollution, microplastic release, and excessive waste generation. The United Nations Environment Programme (UNEP) reported that the textile industry contributes nearly 10% of global carbon emissions and approximately 20% of global industrial wastewater production, making it one of the leading contributors to climate change and water pollution worldwide (UNEP, 2021). Textile processing industries consume enormous quantities of freshwater during dyeing, bleaching, washing, and finishing operations. Large volumes of chemically contaminated wastewater containing dyes, salts, heavy metals, surfactants, and toxic auxiliaries are often discharged into aquatic ecosystems without adequate treatment, severely affecting water quality, biodiversity, and human health. Synthetic fibers such as polyester, nylon, acrylic, and polypropylene dominate global textile production because of their affordability, easy mass production, versatility, durability, and low maintenance requirements. Polyester alone accounts for more than half of the total global fiber market (Textile Exchange, 2022). However, synthetic fibers are primarily derived from non-renewable petroleum-based resources and are associated with significant environmental concerns throughout their lifecycle. The extraction and processing of fossil fuels required for synthetic fiber production contribute substantially to greenhouse gas emissions and energy consumption. Furthermore, synthetic textiles are non-biodegradable and may persist in the environment for several hundred years after disposal, accumulating in landfills and natural ecosystems (Shen et al., 2010). One of the most alarming

environmental issues associated with synthetic textiles is microplastic pollution. During domestic laundering and industrial washing processes, synthetic garments release microscopic plastic fibers known as microplastics into wastewater systems. These microplastics eventually enter rivers, lakes, oceans, and food chains, where they are ingested by aquatic organisms and accumulate in marine ecosystems. Browne et al. (2011) demonstrated that synthetic textile fibers constitute a major source of marine microplastic contamination worldwide. Microplastics have been detected in fish, shellfish, drinking water, and even human tissues, raising serious concerns regarding ecological sustainability and public health. Additionally, the rapid growth of “fast fashion” has intensified textile waste generation because inexpensive, low-quality garments are frequently discarded after limited use, contributing to mounting landfill burdens and resource depletion.

In response to these environmental challenges, researchers, policymakers, industries, and consumers are increasingly focusing on sustainable textile systems based on renewable, biodegradable, and environmentally friendly materials. Natural fibers have emerged as promising alternatives to synthetic textiles because they are derived from renewable biological resources and generally possess lower ecological footprints. Natural fibers are biodegradable, recyclable, breathable, comfortable, and often require lower energy inputs during production compared to synthetic fibers (Kozłowski, 2012). Their ability to decompose naturally under appropriate environmental conditions reduces long-term environmental pollution and supports circular economy principles. Natural fibers have been used by human civilizations for thousands of years and

constitute the foundation of traditional textile cultures worldwide. Archaeological evidence suggests that ancient societies in India, Egypt, China, and Mesopotamia utilized cotton, flax, wool, silk, and other natural fibers for clothing, shelter, and domestic applications. Cotton textiles were extensively produced in ancient India and Egypt, while silk production flourished in China through sericulture practices developed over centuries. Wool from sheep and goats provided thermal protection in colder climates, whereas flax-derived linen became highly valued for its durability and comfort. These traditional fibers continue to hold cultural, economic, and technological significance in modern textile industries. Plant-based fibers such as cotton, hemp, flax, jute, bamboo, banana fiber, pineapple leaf fiber, coir, and ramie are increasingly attracting attention because of their sustainability potential. Hemp and flax cultivation require relatively fewer pesticides and less irrigation compared to conventional cotton farming, making them environmentally preferable alternatives. Similarly, agricultural waste-derived fibers such as banana and pineapple leaf fibers promote resource efficiency and waste valorization. Animal fibers such as wool and silk provide exceptional thermal insulation, moisture regulation, elasticity, and luxury characteristics while remaining biodegradable and renewable when produced sustainably.

Advancements in textile science, biotechnology, nanotechnology, and sustainable engineering have significantly improved the quality, functionality, and durability of natural fiber-based fabrics in recent years. Innovations in fiber extraction, enzymatic processing, bio-finishing, nano-coating, natural dyeing, and eco-friendly textile treatments have enhanced the performance properties of

sustainable textiles. Modern natural fiber garments can now provide wrinkle resistance, antimicrobial protection, ultraviolet shielding, moisture management, flame retardancy, and enhanced mechanical strength while maintaining environmental compatibility (Thilagavathi & Kannaian, 2010). Blending natural fibers with regenerated cellulose fibers and biodegradable polymers has further expanded their applications in fashion, sportswear, medical textiles, technical textiles, and smart wearable systems. The growing awareness regarding climate change, environmental degradation, ethical labor practices, and sustainable consumption patterns has accelerated the demand for eco-friendly fashion worldwide. Sustainable fashion movements encourage the use of renewable materials, ethical manufacturing processes, circular economy practices, recycling, and durable clothing systems. Consumers are increasingly seeking garments that combine environmental responsibility with comfort, aesthetics, and functionality. Eco-labels, sustainability certifications, and transparent supply chains are becoming important determinants of purchasing behavior in global textile markets. Governments and international organizations are also promoting sustainable textile transitions through environmental regulations, carbon reduction strategies, waste management policies, and circular economy initiatives. The United Nations Sustainable Development Goals (SDGs), particularly goals related to responsible consumption and production, climate action, clean water, and sustainable industrialization, strongly support the development of eco-friendly textile systems. Natural fibers align closely with these sustainability objectives because they contribute to reduced carbon emissions, biodegradability, renewable resource utilization, and rural economic

development. Despite their considerable environmental advantages, natural fiber textiles also face certain challenges related to variability in quality, moisture sensitivity, wrinkling, microbial susceptibility, and processing costs. Nevertheless, continuous scientific advancements and growing environmental awareness are helping overcome these limitations and expanding the future potential of sustainable natural fiber clothing.

This review paper aims to provide a comprehensive scientific overview of eco-friendly and durable clothing produced from natural fibers. The paper discusses the classification and properties of natural fibers, environmental benefits, durability and performance characteristics, sustainable textile processing technologies, circular economy approaches, industrial challenges, and future prospects in sustainable textile development. The study highlights how natural fibers can contribute to the creation of environmentally responsible, economically viable, and socially sustainable fashion systems for the future.

## 2. Natural Fibers and Their Classification

Natural fibers are fibers obtained from naturally occurring biological and mineral sources. These fibers are renewable, biodegradable, and environmentally preferable alternatives to synthetic materials because they originate from natural ecosystems and can decompose through biological processes after disposal. Natural fibers have been used by humans since prehistoric times for the production of clothing, ropes, fishing nets, baskets, household textiles, and shelter materials. Their versatility, availability, comfort properties, and ecological compatibility

continue to make them highly important in contemporary textile industries. Natural fibers are generally classified according to their origin, chemical composition, and structural characteristics. Broadly, they are divided into three major categories: plant fibers, animal fibers, and mineral fibers. Each category possesses distinct physical, chemical, and mechanical properties that determine its suitability for different textile applications.

**Plant Fibers:** Plant fibers are primarily cellulose-based fibers obtained from different parts of plants including seeds, stems, leaves, fruits, and husks. Cellulose is the principal structural component of plant cell walls and provides strength, flexibility, and durability to plant fibers. Plant fibers are widely used in textile industries because they exhibit good tensile strength, moisture absorption capacity, breathability, biodegradability, and thermal comfort (Kozłowski, 2012). Based on their botanical origin, plant fibers are further categorized into seed fibers, bast fibers, leaf fibers, fruit fibers, and stalk fibers.

**Seed Fibers:** Seed fibers develop around plant seeds and are generally soft, fluffy, and highly spinnable. Cotton is the most important and widely used seed fiber in the global textile industry. Cotton fibers are composed predominantly of cellulose and are valued for their softness, absorbency, comfort, and versatility. Cotton fabrics provide excellent breathability and skin compatibility, making them highly suitable for clothing applications. However, conventional cotton cultivation often requires large quantities of water, pesticides, and fertilizers, leading to environmental concerns. Organic cotton farming practices are therefore increasingly promoted as sustainable alternatives. Kapok is another seed fiber obtained from the seed pods of the kapok tree (*Ceiba*

*pentandra*). Kapok fibers are lightweight, hollow, and water-resistant, making them useful in insulation materials, stuffing, and specialized textile applications.

**Bast Fibers:** Bast fibers are extracted from the phloem or inner bark of dicotyledonous plants. These fibers are generally long, strong, and durable because of their high cellulose content and well-developed fiber structure. Bast fibers are increasingly recognized as sustainable textile materials due to their low environmental requirements and excellent mechanical properties. Hemp (*Cannabis sativa*) is one of the oldest textile fibers known to humanity. Hemp fibers possess exceptional tensile strength, abrasion resistance, ultraviolet protection, and antimicrobial properties. Hemp cultivation requires relatively low pesticide use and moderate water consumption, making it environmentally sustainable. Modern textile technologies have improved the softness and flexibility of hemp fabrics, expanding their use in fashion apparel and technical textiles. Flax (*Linum usitatissimum*), used to produce linen fabrics, is another highly durable bast fiber. Linen textiles exhibit excellent moisture absorption, thermal conductivity, breathability, and resistance to wear. Flax cultivation generally requires fewer agrochemicals than cotton production, enhancing its sustainability profile. Jute is an inexpensive bast fiber commonly used in packaging, sacks, carpets, geotextiles, and eco-friendly composites. Ramie, kenaf, and nettle fibers are additional bast fibers with promising applications in sustainable textiles and bio-composite industries.

**Leaf Fibers:** Leaf fibers are extracted from the leaves of monocotyledonous plants and are generally coarser and stiffer than bast fibers. Sisal, abaca, pineapple leaf fiber, and agave fibers belong to this category.

Pineapple leaf fiber (PALF) has recently gained attention in sustainable fashion because of its high tensile strength, lightweight characteristics, and biodegradability. Fibers extracted from agricultural waste such as pineapple leaves promote circular economy principles and waste valorization. Banana fiber obtained from banana pseudostems is another eco-friendly textile material with good mechanical properties, moisture absorption, and biodegradability. Bamboo fibers are also increasingly used because of their softness, antimicrobial properties, and moisture management capabilities.

**Fruit and Husk Fibers:** Coir fiber extracted from coconut husks is known for its resilience, water resistance, and durability. Coir is primarily used in mats, brushes, ropes, mattresses, and geotextiles, although innovations are expanding its use in sustainable composites and technical textiles.

**Animal Fibers:** Animal fibers are protein-based fibers obtained from animals such as sheep, goats, silkworms, rabbits, alpacas, camels, and llamas. These fibers consist mainly of keratin or fibroin proteins and exhibit excellent elasticity, insulation, softness, and moisture regulation properties (Gulrajani, 2010). Wool is the most important animal fiber used in textile manufacturing. Wool fibers possess natural crimp, elasticity, flame resistance, and thermal insulation properties. Wool garments provide warmth even under damp conditions because wool can absorb significant moisture without feeling wet. Merino wool, cashmere, mohair, and alpaca fibers are highly valued for their softness and luxury characteristics. Silk is produced by silkworms during cocoon formation and is valued for its luster, smoothness, drape, and tensile strength. Silk fibers consist mainly of fibroin protein coated with



sericin gum. Sustainable sericulture practices are increasingly being adopted to improve the environmental performance of silk production. Other specialty animal fibers include angora from rabbits, camel hair, yak wool, and qiviut from musk oxen. These fibers are generally used in luxury textiles because of their exceptional softness and insulation properties.

**Mineral Fibers:** Mineral fibers are naturally occurring inorganic fibers obtained from geological sources. Asbestos is the most well-known mineral fiber and was historically used because of its heat resistance and durability. However, asbestos exposure is associated with severe respiratory diseases and cancers, leading to strict restrictions on its use in textiles and construction materials worldwide. Certain mineral-based fibers such as basalt fibers are currently being explored for technical and industrial applications because of their high strength and thermal stability. However, mineral fibers have limited applications in clothing due to comfort and safety considerations. Natural fibers vary considerably in their physical, chemical, and mechanical properties depending on plant species, animal breed, climatic conditions, cultivation methods, harvesting techniques, extraction processes, and post-processing treatments. Their structural composition determines important characteristics such as tensile strength, elongation, flexibility, moisture absorption, thermal insulation, biodegradability, and durability. Understanding these properties is essential for optimizing fiber selection, textile engineering, and sustainable apparel development.

### 3. Environmental Significance of Natural Fiber-Based Clothing

The growing environmental crisis associated with conventional textile

manufacturing has accelerated the transition toward sustainable fibers and eco-friendly apparel systems. Natural fibers are increasingly recognized as environmentally sustainable materials because they originate from renewable biological resources and possess high biodegradability. Unlike synthetic fibers such as polyester, nylon, and acrylic, which are derived from non-renewable petroleum resources, natural fibers decompose naturally under appropriate environmental conditions and therefore reduce long-term environmental pollution (Shen et al., 2010). The biodegradation of cellulose and protein-based fibers occurs through microbial action, resulting in lower ecological persistence compared to synthetic textiles that remain in landfills for centuries. One of the major environmental advantages of natural fibers is their lower carbon footprint during production. Plant fibers absorb atmospheric carbon dioxide through photosynthesis during cultivation, thereby contributing to carbon sequestration. Studies indicate that fibers such as hemp and flax exhibit negative or near-neutral carbon balances because their cultivation requires relatively fewer chemical inputs and less irrigation compared to conventional cotton cultivation (Cherrett et al., 2005). Hemp cultivation, for example, improves soil fertility, suppresses weed growth naturally, and requires minimal pesticide application. Similarly, flax cultivation consumes considerably less water and fertilizer than cotton, making it one of the most environmentally sustainable textile crops.

The production of synthetic textiles contributes substantially to greenhouse gas emissions due to energy-intensive polymer manufacturing processes. Polyester production alone accounts for significant fossil fuel consumption and carbon

emissions globally (Niinimäki et al., 2020). In contrast, natural fibers generally require lower energy inputs during extraction and processing. Mechanical retting, enzymatic processing, and eco-friendly dyeing technologies further reduce the environmental burden associated with natural textile manufacturing. The adoption of cleaner production technologies and green chemistry approaches has enhanced the sustainability profile of natural fiber processing industries. Water consumption is another critical issue in textile sustainability. Conventional textile dyeing and finishing processes consume massive quantities of freshwater and release hazardous chemicals into aquatic ecosystems. Natural fibers processed through sustainable methods can substantially reduce water pollution and chemical toxicity. Organic cotton cultivation, for instance, avoids the use of synthetic pesticides and fertilizers, thereby minimizing soil and water contamination (Textile Exchange, 2022). Natural dyes extracted from plants, fruits, bark, and microorganisms are also increasingly being integrated into sustainable textile systems to reduce chemical pollution. Microplastic pollution has become one of the most alarming consequences of synthetic textile use. During laundering, synthetic garments release microfibers that enter wastewater systems and eventually accumulate in oceans, lakes, and rivers. Browne et al. (2011) reported that synthetic microfibers constitute a major component of marine plastic pollution and are ingested by aquatic organisms, affecting biodiversity and food chains. Natural fibers offer a sustainable solution because cellulosic and protein-based fibers biodegrade more rapidly in aquatic and terrestrial environments and therefore generate significantly lower long-term ecological impacts.

Natural fiber-based clothing also supports circular economy principles by encouraging recycling, composting, reuse, and sustainable consumption patterns. Textile waste generated from natural fibers can be composted or converted into value-added products such as insulation materials, bio-composites, paper, and biodegradable packaging. The circular utilization of textile biomass reduces landfill accumulation and promotes resource efficiency. Sustainable fashion brands worldwide are increasingly integrating circular textile strategies involving recycled cotton, hemp blends, and regenerated cellulosic fibers to achieve environmental sustainability goals. Furthermore, natural fibers contribute positively to rural livelihoods and sustainable agriculture. The cultivation and processing of fibers such as jute, coir, banana fiber, and bamboo create employment opportunities for rural communities and small-scale farmers in developing countries. The promotion of indigenous natural fibers can strengthen local economies while preserving traditional textile heritage and biodiversity. Sustainable textile systems based on agro-residues and underutilized fibers also provide opportunities for waste valorization and income generation.

Recent research has emphasized the importance of life cycle assessment (LCA) in evaluating textile sustainability. Comparative life cycle studies demonstrate that natural fibers generally exhibit lower environmental impacts in terms of energy consumption, greenhouse gas emissions, and waste generation compared to synthetic counterparts (Muthu, 2014). However, the environmental performance of natural fibers also depends on cultivation practices, transportation, chemical processing, and end-of-life management. Therefore, integrated sustainable supply chain

management is essential to maximize the ecological benefits of natural fiber-based clothing.

#### **4. Durability and Performance Characteristics of Natural Fibers**

Durability is one of the most important considerations in sustainable clothing because longer-lasting garments reduce textile waste generation and promote responsible consumption. Natural fibers possess several structural and functional characteristics that contribute to durability, comfort, and wear performance. The durability of textile materials depends on tensile strength, abrasion resistance, elasticity, dimensional stability, moisture management, thermal regulation, and resistance to microbial degradation. Cotton fibers exhibit good tensile strength and softness, making them suitable for daily wear apparel. However, cotton fabrics may shrink and wrinkle easily if not properly treated. Advances in textile finishing technologies such as mercerization, enzyme treatment, and wrinkle-resistant finishes have significantly improved the durability and dimensional stability of cotton garments (Karthik & Rathinamoorthy, 2017). Organic cotton fabrics blended with other natural fibers are increasingly used in sustainable apparel manufacturing. Hemp fiber is regarded as one of the strongest natural textile fibers due to its highly crystalline cellulose structure. Hemp fabrics possess exceptional abrasion resistance, durability, ultraviolet protection, and antimicrobial properties. Historically, hemp was widely used in ropes, sails, and workwear because of its high mechanical strength. Modern textile engineering has improved the softness and flexibility of hemp fabrics, making them suitable for fashion apparel and performance textiles (Pickering et al., 2016). Hemp garments typically have longer service lives

compared to conventional cotton clothing, thereby reducing replacement frequency and environmental impact. Flax fiber, commonly used in linen fabrics, is another highly durable natural fiber. Linen textiles exhibit excellent breathability, moisture absorption, and thermal comfort properties, making them particularly suitable for warm climatic conditions. Linen fibers become stronger when wet and show high resistance to pilling and abrasion. Additionally, flax cultivation has relatively low environmental requirements, enhancing its sustainability profile. Wool fibers possess unique elastic and resilient properties because of their protein-based keratin structure. Wool garments can recover from deformation and maintain their shape over extended periods. Wool also exhibits excellent thermal insulation, flame resistance, and moisture regulation capabilities. The natural crimp structure of wool fibers traps air and enhances insulation efficiency. Merino wool, in particular, has gained popularity in sustainable activewear and outdoor clothing because of its softness, odor resistance, and temperature regulation properties (Russell, 2018). Silk fibers are valued for their luxurious appearance, smooth texture, and high tensile strength. Silk exhibits remarkable durability despite its lightweight structure. Fibroin proteins present in silk contribute to its elasticity and mechanical performance. Recent innovations in silk-based biomaterials and eco-friendly sericulture practices have increased the sustainability potential of silk textiles. Emerging natural fibers such as bamboo, banana fiber, pineapple leaf fiber, nettle fiber, and ramie are also attracting scientific and industrial attention. Bamboo fibers exhibit antibacterial properties and moisture-wicking ability, while pineapple leaf fibers provide excellent tensile strength and lightweight characteristics. Banana



fibers possess high cellulose content and biodegradability, making them suitable for sustainable fashion and technical textile applications. Blending different natural fibers is another important strategy to improve fabric durability and functionality. Cotton-hemp, wool-silk, and bamboo-cotton blends combine the advantages of multiple fibers to produce textiles with enhanced comfort, strength, elasticity, and aesthetic appeal. Nanotechnology and bio-based finishing treatments are further improving the performance characteristics of sustainable textiles by enhancing wrinkle resistance, antimicrobial activity, ultraviolet protection, and water repellency without compromising biodegradability.

### **5. Durability and Performance of Natural Fiber Clothing**

Durability is one of the most essential pillars of sustainable clothing because garments with longer service lives reduce the frequency of replacement, lower resource consumption, decrease textile waste generation, and minimize environmental burdens associated with production and disposal. In sustainable fashion systems, durability is not merely associated with fabric strength but also includes shape retention, resistance to wear and tear, comfort maintenance, aesthetic stability, and functional performance throughout repeated usage cycles. The durability of natural fiber textiles depends upon several interrelated factors including fiber morphology, chemical composition, yarn twist, fabric construction, finishing treatments, dyeing processes, environmental exposure, laundering conditions, and consumer maintenance practices (Kozlowski, 2012).

Natural fibers possess diverse structural characteristics that influence their mechanical and functional properties.

Cellulosic fibers such as cotton, flax, hemp, ramie, bamboo, and jute derive their strength primarily from cellulose microfibrils arranged in highly ordered crystalline structures. Protein-based fibers such as wool and silk exhibit complex molecular structures composed of keratin and fibroin proteins, respectively, which contribute to elasticity, resilience, and thermal performance. The intrinsic structure of these fibers largely determines their tensile strength, abrasion resistance, flexibility, and longevity. Hemp and flax fibers are particularly recognized for their exceptional durability and mechanical strength. Hemp fibers possess high tensile strength due to their elevated cellulose content and low elongation properties. Historically, hemp was widely used in ropes, sails, military fabrics, and industrial textiles because of its remarkable resistance to wear, ultraviolet radiation, and microbial degradation. Modern hemp textiles continue to demonstrate superior abrasion resistance and longevity compared to many conventional textile fibers (Pickering et al., 2016). Hemp garments can withstand repeated washing cycles without significant loss of structural integrity, making them highly suitable for sustainable apparel applications. Furthermore, hemp fabrics exhibit natural antimicrobial properties and excellent moisture management capabilities, which enhance garment hygiene and wearer comfort. Flax fibers, used in linen textiles, are also known for their outstanding durability and comfort characteristics. Linen fabrics exhibit high resistance to friction, pilling, and stretching. Unlike many synthetic textiles that deteriorate over time, linen garments often become softer and more comfortable with repeated washing and use while maintaining structural stability. Flax fibers possess excellent thermal conductivity and breathability, enabling efficient heat

dissipation in warm climates. Additionally, linen fabrics absorb moisture rapidly and dry quickly, contributing to wearer comfort and reduced microbial growth (Muthu, 2014). These characteristics make linen highly desirable in sustainable summer clothing and premium eco-fashion products.

Cotton remains the most extensively used natural fiber in global textile industries because of its softness, comfort, and versatility. However, conventional cotton fabrics may exhibit limitations such as wrinkling, shrinkage, and moderate abrasion resistance. Textile engineering innovations have significantly improved cotton durability through mercerization, resin finishing, enzymatic treatment, and compact spinning technologies. Mercerization enhances cotton fiber strength, dye affinity, and dimensional stability by altering the crystalline structure of cellulose under alkaline treatment. Similarly, compact spinning reduces yarn hairiness and improves fabric strength and smoothness (Karthik & Rathinamoorthy, 2017). Organic cotton textiles blended with stronger natural fibers such as hemp or bamboo are increasingly being used to improve both sustainability and durability. Wool fibers possess unique natural elasticity and resilience because of their crimped protein structure. Wool garments can stretch under tension and recover their original shape after deformation, thereby reducing permanent wrinkling and fabric distortion. This elasticity contributes significantly to garment longevity. Wool also exhibits excellent thermal insulation due to its ability to trap air within fiber crimps. Additionally, wool fibers possess natural flame resistance, ultraviolet protection, and odor resistance properties. Merino wool, characterized by fine fiber diameter and softness, has gained

popularity in sustainable sportswear and performance clothing because it regulates body temperature effectively and resists bacterial growth (Russell, 2018). Wool garments often require less frequent washing, thereby reducing water and energy consumption during their lifecycle. Silk fibers are renowned for their luxurious appearance, luster, smooth texture, and impressive tensile strength. Although lightweight, silk exhibits excellent durability because of its highly organized fibroin protein structure. Silk fabrics possess good elasticity and drape characteristics, making them valuable in premium sustainable fashion. Recent advances in eco-friendly sericulture and silk processing have improved the environmental sustainability of silk textiles. Furthermore, silk biomaterials are increasingly being explored for biomedical and technical textile applications because of their biocompatibility and biodegradability. Emerging natural fibers such as bamboo fiber, banana fiber, pineapple leaf fiber (PALF), nettle fiber, ramie, and coir are gaining scientific and commercial attention due to their promising mechanical and ecological properties. Bamboo textiles exhibit softness, breathability, ultraviolet protection, and antimicrobial characteristics. Banana fibers possess high cellulose content and strong tensile properties suitable for eco-friendly apparel and composites. Pineapple leaf fibers are lightweight yet strong, making them useful in sustainable fashion accessories and innovative textiles. Ramie fibers display excellent strength, luster, and resistance to microbial attack, while coir fibers are increasingly utilized in technical and geotextile applications.

The durability of natural fiber clothing is also significantly influenced by yarn structure and fabric construction. Higher

yarn twist generally increases tensile strength and abrasion resistance, although excessive twisting may reduce softness and flexibility. Fabric construction techniques such as twill weaving, satin weaving, knitted structures, and nonwoven technologies affect dimensional stability, comfort, elasticity, and wear resistance. Dense woven fabrics usually exhibit higher durability than loosely constructed fabrics because of improved fiber interlocking and reduced frictional damage. Textile finishing technologies play a crucial role in enhancing the performance characteristics of natural fiber garments. Enzymatic bio-polishing is widely used to improve fabric smoothness, reduce fuzz formation, and minimize pilling tendencies. Cellulase enzymes selectively remove protruding microfibrils from cotton and other cellulosic fabrics, thereby enhancing appearance retention and softness without causing severe environmental pollution (Hashem et al., 2007). Bio-polishing also improves color brightness and fabric drape. Nanotechnology has emerged as an important innovation in sustainable textile engineering. Nano-finishing treatments improve wrinkle resistance, water repellency, antimicrobial activity, stain resistance, ultraviolet protection, and self-cleaning functionality. Nanoparticles such as titanium dioxide, zinc oxide, and silver nanoparticles are incorporated into textile surfaces to provide multifunctional performance enhancements (Thilagavathi & Kannaian, 2010). Titanium dioxide nanoparticles impart photocatalytic self-cleaning properties, while silver nanoparticles exhibit broad-spectrum antimicrobial effects. Zinc oxide nanoparticles improve ultraviolet protection and antibacterial performance. These advanced treatments enhance garment longevity and reduce maintenance frequency, thereby contributing to

sustainability objectives. Blending natural fibers with other natural or regenerated fibers is another important strategy for improving durability and performance. Cotton-hemp blends combine the softness of cotton with the strength and antimicrobial properties of hemp. Bamboo-cotton blends enhance moisture management and fabric smoothness, while wool-silk blends provide luxurious texture, elasticity, and thermal regulation. Blended textiles optimize the desirable characteristics of multiple fibers and expand the functional possibilities of sustainable clothing. Maintenance and consumer care practices also greatly influence garment durability. Proper laundering techniques, moderate washing temperatures, eco-friendly detergents, air drying, and careful storage can significantly extend the lifespan of natural fiber garments. Excessive mechanical agitation, harsh chemicals, and high-temperature drying can weaken fibers and accelerate fabric deterioration. Consumer education regarding sustainable clothing care is therefore essential for maximizing textile longevity and reducing environmental impacts. Recent research has emphasized that durable clothing is central to sustainable consumption and circular fashion systems. Longer-lasting garments reduce the demand for raw materials, manufacturing energy, transportation, packaging, and waste disposal. Consequently, improving the durability and functional performance of natural fiber textiles contributes directly to environmental conservation, resource efficiency, and sustainable development goals.

## 6. Sustainable Processing Technologies in Natural Fiber Textiles

Sustainable textile processing technologies are essential for minimizing the

environmental impacts associated with natural fiber clothing production. Although natural fibers themselves are biodegradable and renewable, conventional textile manufacturing processes often involve excessive consumption of water, chemicals, and energy. Textile wet processing industries are among the largest contributors to industrial water pollution because dyeing, bleaching, scouring, and finishing operations generate chemically contaminated wastewater containing dyes, salts, surfactants, heavy metals, and toxic auxiliaries (Niinimäki et al., 2020). Therefore, the development and adoption of sustainable processing technologies have become crucial for environmentally responsible textile production. Natural dyeing represents one of the oldest and most eco-friendly coloration methods in textile history. Natural dyes are derived from renewable biological and mineral resources including plants, flowers, leaves, bark, roots, fruits, insects, algae, and microorganisms. Unlike synthetic dyes, many natural dyes are biodegradable and exhibit lower toxicity toward aquatic ecosystems. Common plant-derived natural dyes include turmeric for yellow coloration, indigo for blue shades, madder root for red tones, henna for orange-brown hues, pomegranate peel for yellow-green shades, and onion skin for golden-brown coloration (Samanta & Agarwal, 2009). These dyes often possess additional functional properties such as antimicrobial, antioxidant, and ultraviolet protective effects.

The increasing demand for eco-friendly textiles has revived scientific interest in natural dyeing technologies. However, natural dyes historically faced limitations such as poor color fastness, limited shade reproducibility, and lower stability compared to synthetic dyes. Recent

advances in mordanting techniques, bio-mordants, and fixation technologies have significantly improved natural dye performance. Bio-mordants derived from tannins, alum, plant extracts, and biomolecules reduce dependence on toxic heavy metal mordants traditionally used in dye fixation. Enzymatic pretreatments and plasma technologies further improve dye uptake efficiency and color durability. Enzyme-based textile processing has emerged as a major sustainable innovation in modern textile industries. Enzymes are biological catalysts capable of accelerating chemical reactions under mild operating conditions. Unlike conventional chemical treatments that require harsh chemicals and high temperatures, enzymatic processes operate efficiently at moderate temperatures and neutral pH conditions, thereby reducing energy consumption and environmental pollution (Hashem et al., 2007). Cellulases are widely used in biopolishing and denim finishing, amylases in desizing operations, proteases in wool processing, and pectinases in bioscouring treatments. Bioscouring is an eco-friendly alternative to conventional alkaline scouring processes used for removing impurities from natural fibers. Traditional scouring methods consume large quantities of caustic chemicals and generate highly alkaline wastewater. In contrast, bioscouring utilizes pectinase enzymes to selectively remove pectin substances and impurities under milder conditions, thereby reducing fiber damage and environmental impacts. Similarly, enzymatic bleaching technologies using laccases and peroxidases reduce the need for chlorine-based bleaching agents. Water conservation is another major objective in sustainable textile processing. Conventional dyeing operations require enormous quantities of freshwater, contributing to water scarcity and pollution. Waterless dyeing

technologies such as supercritical carbon dioxide (SC-CO<sub>2</sub>) dyeing have emerged as revolutionary alternatives. In this process, carbon dioxide under supercritical conditions acts as a solvent for dye penetration into fibers, eliminating the need for water entirely. SC-CO<sub>2</sub> dyeing also enables efficient dye recovery and recycling, thereby minimizing waste generation and chemical discharge. Digital textile printing technologies have further enhanced sustainability by reducing dye wastage, water consumption, and energy use. Unlike traditional screen printing methods that require large volumes of dye pastes and water for cleaning, digital printing precisely deposits colorants onto fabrics through computer-controlled systems. This technology improves design flexibility, reduces inventory waste, and supports customized sustainable fashion production. Nanotechnology has significantly expanded the functional capabilities of natural fiber textiles. Nano-finishes containing silver nanoparticles, titanium dioxide nanoparticles, silica nanoparticles, and zinc oxide nanoparticles impart advanced properties such as antimicrobial activity, ultraviolet protection, flame retardancy, self-cleaning effects, and stain resistance (Thilagavathi & Kannaian, 2010). Such multifunctional finishes improve garment durability and reduce maintenance frequency, thereby lowering water and detergent consumption during laundering.

Green chemistry approaches are increasingly being integrated into sustainable textile manufacturing. Green chemistry emphasizes the use of safer chemicals, renewable feedstocks, biodegradable auxiliaries, and energy-efficient processes. Bio-based softeners, eco-friendly surfactants, biodegradable detergents, and non-toxic finishing agents

are replacing hazardous synthetic chemicals in modern textile industries. Closed-loop production systems that recycle water, chemicals, and heat energy further enhance sustainability and resource efficiency. Life cycle assessment studies have shown that sustainable textile processing technologies can substantially reduce environmental impacts related to greenhouse gas emissions, eutrophication, toxicity, and water depletion (Muthu, 2014). Nevertheless, large-scale industrial adoption of sustainable technologies requires economic feasibility, infrastructure development, regulatory support, and consumer awareness.

## 7. Circular Economy and Sustainable Fashion

The concept of circular economy has emerged as a transformative approach for achieving sustainability in the fashion and textile sector. Unlike the traditional linear economic model based on “take, make, use, and dispose,” the circular economy emphasizes resource efficiency, waste minimization, recycling, repair, reuse, and regeneration throughout the product lifecycle. Circular fashion systems aim to maintain the value of materials and products for as long as possible while minimizing environmental degradation and resource depletion (Ellen MacArthur Foundation, 2017). The global fashion industry currently operates predominantly under a linear production model characterized by rapid production cycles, excessive consumption, and enormous waste generation. The rise of fast fashion has intensified these challenges by encouraging consumers to purchase inexpensive, low-quality garments with short usage lifespans. Millions of tons of textile waste are generated annually worldwide, much of which ends up in landfills or incineration facilities, causing



significant environmental pollution (Niinimäki et al., 2020). Synthetic garments contribute additionally to microplastic pollution because they release plastic fibers during washing and degradation. Natural fibers are highly compatible with circular economy principles because of their renewable origin, biodegradability, recyclability, and lower ecological persistence. At the end of their useful life, garments made from cotton, hemp, flax, wool, silk, and other biodegradable fibers can decompose naturally under composting conditions, thereby returning nutrients to the ecosystem. This biodegradability contrasts sharply with petroleum-based synthetic textiles that persist in the environment for several centuries. Recycling and upcycling are central components of circular textile systems. Mechanical recycling involves shredding and re-spinning textile waste into new yarns and fabrics, whereas chemical recycling breaks down fibers into molecular components for regeneration into new materials. Recycled cotton and regenerated cellulose fibers are increasingly used in sustainable apparel manufacturing. Upcycling converts discarded garments and textile scraps into higher-value fashion products, accessories, home furnishings, and industrial materials, thereby extending product life and reducing waste generation. Fiber regeneration technologies have further strengthened circular fashion systems. Regenerated cellulosic fibers such as lyocell, modal, and viscose are produced from wood pulp and textile waste using relatively sustainable chemical processes. Lyocell production, in particular, employs closed-loop solvent recovery systems that minimize environmental pollution. These regenerated fibers combine the comfort and biodegradability of natural fibers with improved strength and uniformity.

Repairability and garment longevity are also important principles of sustainable fashion. Durable clothing designed for long-term use reduces the frequency of replacement and lowers cumulative environmental impacts. Sustainable fashion brands increasingly emphasize timeless designs, modular garments, repair services, and take-back programs to encourage responsible consumption patterns. Consumer awareness and environmentally conscious purchasing behavior are major driving forces behind the growth of sustainable fashion markets. Modern consumers are increasingly concerned about environmental pollution, climate change, labor rights, and ethical manufacturing practices. Eco-labels, sustainability certifications, and transparent supply chains influence purchasing decisions by providing information regarding environmental and social performance. Certifications such as Global Organic Textile Standard (GOTS), OEKO-TEX, Fair Trade, and Better Cotton Initiative promote environmentally responsible and socially ethical textile production systems. Digital technologies are also contributing to circular fashion innovation. Artificial intelligence, blockchain, and digital product passports enhance supply chain transparency, inventory optimization, traceability, and recycling efficiency. Rental fashion, resale platforms, and second-hand clothing markets are gaining popularity as alternative consumption models that reduce resource use and extend garment life cycles. Despite substantial progress, several challenges remain in implementing circular economy practices within the textile sector. These include technological limitations in fiber recycling, high costs of sustainable materials, lack of recycling infrastructure, consumer resistance, and inadequate policy frameworks. Blended fabrics containing

both natural and synthetic fibers are particularly difficult to recycle because fiber separation processes remain technologically complex and expensive. Nevertheless, the transition toward circular fashion systems is essential for achieving global sustainability goals. Governments, industries, researchers, and consumers must collaborate to promote sustainable production practices, eco-design principles, waste reduction strategies, and environmentally responsible consumption behaviors. Natural fiber-based clothing has enormous potential to support circular economy models and create a more sustainable, resilient, and ethical textile future.

## 8. Challenges and Future Prospects

Although natural fibers offer substantial environmental, social, and economic advantages, several scientific, technological, and commercial challenges continue to limit their widespread adoption in modern textile industries. The dominance of synthetic fibers in global textile markets is largely attributed to their low production cost, uniform quality, high scalability, easy processability, and versatile performance characteristics. In contrast, natural fibers often exhibit variability in physical and mechanical properties because their quality is strongly influenced by climatic conditions, soil fertility, agricultural practices, harvesting methods, retting procedures, and storage conditions (Kozlowski, 2012). Such inconsistency creates difficulties in achieving standardized textile production and maintaining uniform fabric quality in industrial-scale manufacturing systems. One of the major limitations associated with natural fibers is variability in fiber dimensions, fineness, color, cellulose content, and tensile strength. Unlike synthetic fibers that can be engineered with

highly controlled specifications, natural fibers are biological materials subject to seasonal and environmental fluctuations. Variations in rainfall, temperature, humidity, and soil nutrients significantly affect fiber growth and quality. For instance, cotton fiber length and strength may vary according to cultivation region and irrigation practices, while flax and hemp fibers are highly influenced by retting techniques and harvesting stages. This variability complicates spinning, weaving, dyeing, and finishing operations and may reduce industrial processing efficiency.

Another significant challenge is the relatively high processing cost of certain natural fibers compared to petroleum-based synthetic fibers. Fiber extraction, retting, degumming, cleaning, and softening processes often require specialized technologies and labor-intensive operations. Fibers such as hemp, banana fiber, pineapple leaf fiber, and ramie require extensive mechanical or chemical treatments before they become suitable for textile manufacturing. Conventional retting processes may also generate unpleasant odors and wastewater pollution if not properly managed (Muthu, 2014). Consequently, the commercialization of several promising natural fibers remains economically constrained despite their environmental benefits. Wrinkling and dimensional instability are additional concerns associated with many natural fiber textiles, particularly cotton and linen fabrics. Cellulosic fibers tend to crease easily because hydrogen bonds within cellulose molecules rearrange under pressure and moisture exposure. Shrinkage during laundering is another common problem that affects garment fit and consumer satisfaction. Textile scientists have developed wrinkle-resistant and shrink-resistant finishes to address these

limitations; however, some conventional chemical treatments may compromise biodegradability or involve hazardous substances such as formaldehyde-based resins. Therefore, the development of environmentally safe and biodegradable finishing agents remains an important research priority.

Moisture sensitivity is another challenge affecting the durability and maintenance of natural fiber clothing. Most natural fibers possess hydrophilic characteristics because of their cellulose or protein composition, enabling them to absorb moisture from the environment. Although moisture absorption improves comfort and breathability, excessive moisture retention may reduce dimensional stability, increase drying time, and promote microbial growth under humid conditions. Fungal and bacterial attack can weaken fibers, produce unpleasant odors, and reduce garment lifespan. Wool fibers are particularly vulnerable to moth damage, while cotton fabrics stored under damp conditions may develop mildew and discoloration. Natural fibers are also generally less resistant to ultraviolet radiation, prolonged weather exposure, and certain chemicals compared to synthetic fibers. Sunlight exposure may cause fiber degradation, color fading, and reduction in mechanical strength over time. Furthermore, repeated laundering and friction can gradually weaken natural fibers and alter fabric appearance. Research efforts are therefore increasingly focused on improving ultraviolet protection, antimicrobial activity, and abrasion resistance through sustainable textile engineering approaches. Competition from synthetic fibers presents another major obstacle to the expansion of natural fiber markets. Synthetic fibers such as polyester dominate global textile production because of their affordability, easy maintenance,

high durability, and mass production efficiency. Polyester alone accounts for more than half of total global fiber consumption (Textile Exchange, 2022). Additionally, established industrial infrastructure and supply chains favor synthetic textile manufacturing. Transitioning toward sustainable natural fiber systems therefore requires substantial investment in research, infrastructure development, farmer support programs, and industrial modernization. Despite these challenges, continuous advancements in textile science, biotechnology, nanotechnology, and materials engineering are significantly improving the performance and commercial viability of natural fiber-based textiles. Fiber modification technologies such as plasma treatment, enzymatic treatment, acetylation, graft copolymerization, and nanocoating are being used to enhance strength, wrinkle resistance, water repellency, dye affinity, and antimicrobial properties without compromising biodegradability (Thilagavathi & Kannaian, 2010). Nano-finishing technologies involving titanium dioxide, zinc oxide, silica, and silver nanoparticles have demonstrated promising results in enhancing fabric functionality and longevity. Biotechnology is playing an increasingly important role in sustainable textile innovation. Enzyme-assisted fiber extraction and processing technologies provide environmentally safer alternatives to harsh chemical treatments. Genetically improved fiber crops with enhanced yield, strength, pest resistance, and reduced water requirements are also being developed through advanced agricultural biotechnology. Bio-based polymers and regenerated cellulose fibers are further expanding opportunities for biodegradable and high-performance sustainable textiles. Smart textile technologies represent

another promising area for future development. Researchers are exploring the integration of sensors, conductive coatings, phase-change materials, and nanofibers into natural fiber fabrics to create multifunctional textiles capable of monitoring temperature, moisture, movement, and health parameters. Sustainable smart textiles based on biodegradable natural fibers could revolutionize wearable technology while minimizing electronic waste and environmental pollution.

Future research should focus on developing high-performance biodegradable textiles that combine sustainability with advanced functional properties. Innovative research areas include bio-composites, hybrid natural fiber blends, recyclable textile structures, low-impact dyeing systems, and closed-loop textile recycling technologies. Greater emphasis should also be placed on sustainable cultivation methods such as organic farming, regenerative agriculture, precision irrigation, and agroecological fiber production systems. These approaches can reduce pesticide use, conserve biodiversity, improve soil health, and lower greenhouse gas emissions associated with textile raw material production. The adoption of eco-friendly processing technologies is equally essential for improving the sustainability of natural fiber textiles. Water-efficient dyeing systems, enzyme-based treatments, green solvents, biodegradable auxiliaries, and renewable energy integration can substantially reduce environmental impacts during textile manufacturing. Life cycle assessment (LCA) and environmental footprint analysis will continue to play crucial roles in evaluating the sustainability performance of textile products and guiding policy decisions. Government policies and international sustainability frameworks are

expected to play a critical role in accelerating the transition toward environmentally sustainable textile systems. Policies promoting organic farming, renewable resources, waste reduction, carbon neutrality, and circular economy practices can encourage industries to adopt sustainable fiber alternatives. Financial incentives, subsidies, eco-labeling systems, green certifications, and stricter environmental regulations may further stimulate investment in sustainable textile production and innovation. Consumer awareness and responsible purchasing behavior are also becoming increasingly influential in shaping the future of sustainable fashion. Modern consumers are showing growing interest in ethical sourcing, biodegradable materials, eco-friendly brands, and transparent supply chains. Social media campaigns, sustainability education, and environmental advocacy movements are encouraging individuals to adopt slow fashion principles and reduce excessive clothing consumption. Educational institutions, researchers, industries, and policymakers must collaborate to promote awareness regarding the environmental consequences of fast fashion and the benefits of natural fiber-based sustainable clothing. In the coming decades, natural fibers are expected to play an increasingly important role in achieving global sustainability goals, reducing environmental pollution, and promoting circular textile economies. The integration of scientific innovation, sustainable agriculture, eco-friendly processing technologies, and responsible consumer behavior can transform the textile industry into a more resilient, ethical, and environmentally sustainable sector capable of meeting future societal and ecological needs.



## 9. Conclusion

The growing environmental crisis associated with the global textile and fashion industry has created an urgent need for sustainable alternatives to conventional synthetic textiles. Excessive resource consumption, greenhouse gas emissions, chemical pollution, microplastic contamination, and enormous textile waste generation have made the textile sector one of the most environmentally challenging industries worldwide. In this context, natural fibers have emerged as highly promising materials for the development of eco-friendly, biodegradable, durable, and sustainable clothing systems. This review highlights that natural fibers such as cotton, hemp, flax, jute, bamboo, banana fiber, pineapple leaf fiber, wool, and silk possess several environmental and functional advantages over synthetic fibers. Their renewable origin, biodegradability, breathability, moisture regulation capacity, comfort properties, and lower ecological persistence make them highly suitable for sustainable textile applications. In addition to reducing dependence on fossil fuel-based materials, natural fibers contribute to circular economy principles by supporting recycling, composting, reuse, and waste minimization strategies. Furthermore, the cultivation and processing of natural fibers can generate rural employment opportunities, strengthen local economies, and promote sustainable agricultural systems. The paper also demonstrates that advancements in textile science and engineering have significantly improved the durability, performance, and commercial viability of natural fiber clothing. Innovations such as enzymatic processing, bio-polishing, nano-finishings, sustainable dyeing, water-efficient technologies, and green chemistry approaches have enhanced fabric strength,

wrinkle resistance, antimicrobial properties, ultraviolet protection, and overall garment longevity while reducing environmental impacts. Blended natural fiber textiles and regenerated cellulosic materials further expand the possibilities for sustainable apparel and technical textile applications. Despite these advantages, several challenges continue to hinder the large-scale adoption of natural fibers in modern textile industries. Variability in fiber quality, moisture sensitivity, wrinkling, microbial degradation, limited large-scale processing infrastructure, and relatively higher production costs remain important constraints. Additionally, the dominance of low-cost synthetic fibers and fast fashion business models continues to pose significant obstacles to sustainable textile transitions. Nevertheless, ongoing research in biotechnology, nanotechnology, smart textiles, and eco-friendly fiber modification technologies offers promising opportunities to overcome these limitations and improve the performance of natural fiber-based fabrics. The future of sustainable fashion depends upon the collective efforts of researchers, industries, governments, policymakers, and consumers. Greater investment in sustainable agriculture, renewable materials, green processing technologies, circular economy infrastructure, and environmental awareness programs is essential for accelerating the transition toward eco-friendly textile systems. Government regulations, eco-labeling initiatives, carbon reduction strategies, and responsible consumer behavior will play critical roles in promoting sustainable fashion practices globally. In conclusion, natural fibers represent a scientifically viable and environmentally responsible solution for reducing the ecological footprint of the textile industry. Their integration into modern fashion systems



can contribute significantly to climate change mitigation, resource conservation, waste reduction, and sustainable economic development. The continued advancement of sustainable textile technologies and circular fashion models will help establish a more resilient, ethical, and environmentally sustainable future for the global apparel industry.

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