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# Innovations and Challenges in Biodegradable Textile Materials: A Review of PLA, PHA and Natural Fibers in Sustainable Fashion

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**Abstract** The textile industry is a major contributor of environmental degradation. Biodegradable textiles made from biopolymers such as Polylactic Acid (PLA), Polyhydroxyalkanoates (PHA) and natural fibers like hemp, bamboo and organic cotton provide sustainable alternatives. This review explores recent advancements in biodegradable textiles specifically focusing on improvements in biodegradability. While these materials offer environmental benefits, challenges such as high production costs, performance limitations and lack of specialized recycling infrastructure slow down their widespread adoption. The review highlights innovations in biopolymer blends, sustainable fiber production and eco-friendly dyeing techniques. It also addresses barriers to implementation including the need for better biodegradability in various environments and investment in recycling systems. Recommendations for future research include enhancing material properties, developing cost-effective biopolymers and integrating biodegradable textiles into circular economy models to promote sustainability in the textile industry.

**Keywords** Biodegradable textiles, Polylactic acid, PLA, Polyhydroxyalkanoates, PHA, Sustainable fashion

## 1. Introduction

The textile sector makes a major contribution to environmental degradation causing over 10% of worldwide carbon emissions and produces nearly 92 million tons of trash annually and a significant percentage that ends up in landfills [1]. Traditional synthetic fibers like polyester and nylon sourced from non-renewable petroleum resources are non-biodegradable and increase enduring issues with the environment such as microplastic contamination and resource depletion [2]. This circumstance has led to the demand for sustainable and biodegradable alternatives within the textile sector.

Biodegradable textiles which made from natural fibers or bio-based polymers have become known for an attractive option. These materials are engineered to degrade naturally under particular environmental conditions with minimizing their longevity in environments and reducing the environmental impacts of textile waste [6]. Recent improvements have concentrated on improving the mechanical characteristics, biodegradability and scalability of biodegradable textiles and making them feasible substitutes for typical synthetic fibers [7].

This literature review aims to bring together the latest advances in biodegradable textile materials specially focusing developments in biopolymers such as Polylactic Acid (PLA) and Polyhydroxyalkanoates (PHA) along with natural fibers including hemp, bamboo and organic cotton. The objective of this review is analysis of recent advancements in the development and application of biodegradable textile materials along with identifying key challenges and limitations associated with the use of biodegradable textiles. Also the possible recommendations for future research and development discussed to improve the performance and adoption of biodegradable textiles.

## 2. Background Study of Biodegradable Textiles

Textile industry create a huge impact for its use of synthetic fibers and resource intensive manufacturing processes. In 2022 polyester was a common synthetic fiber which accounted for more than 54% of global fiber production [8]. These non-renewable degradation-resistant fibers contribute to ongoing environmental contamination and the buildup of microplastics in ecosystems [2].

Biodegradable textiles have come about as an important area of development for dealing with these environmental concerns and they are designed to decompose naturally under

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particular conditions which reduce their ability to persist in the environment. Recent advancements in biopolymers including PLA and PHA alongside natural fibers provide a sustainable alternative for traditional synthetic fibers and reduce the environmental impact of textile manufacturing [7].

### 2.1. Essential Materials in Biodegradable Textiles

Polylactic Acid (PLA) is an extensively studied biopolymer made from renewable resources such as corn starch and sugarcane. Despite its biodegradability and excellent mechanical qualities its fragility and poor heat resistance have limited its utilization in high-performance textiles [6]. Recent improvements have concentrated on integrating PLA with other biodegradable polymers and natural fibers to improve its performance and extend its applications in textiles. However, Polyhydroxyalkanoates (PHA) form a category of biopolymers synthesized from microbial fermentation of sugar and lipids. These entirely biodegradable materials can be transformed into fibers and films which making them appropriate for many textile applications. Research indicates that the degradability of PHAs is more rapid in soil and marine environments compared to traditional plastics [3]. Natural fibers such as hemp, bamboo and organic cotton serve as sustainable alternatives to synthetic fibers because of their biodegradability and diminished environmental impact on water and energy usage in their production stage. Advancements in growing and processing techniques have considerably increased the environmental impact of these fibers becoming them more competitive with synthetic alternatives [7].

Despite significant advancements in the production of biodegradable textiles certain obstacles remain. Higher production costs compared to traditional synthetic fibers, limitations in mechanical properties and inadequate recycling infrastructure create significant barriers to their wider implementation [4]. In addition, established procedures for assessing the biodegradability and environmental performance of these materials under various circumstances have limitations [10]. This review aims to fill these gaps by combining recent progress while providing a thorough analysis of the present condition of biodegradable textiles.

## 3. Methodology

A targeted literature review was conducted utilizing Scopus and Web of Science databases to identify relevant studies published between 2012 and 2024. The search terms use "biodegradable textiles", "sustainable textiles", "Polylactic Acid", "Polyhydroxyalkanoates", "natural fibers", "innovations", "advancements" and "developments." Only open-access articles, reviews and conference papers were included to ensure the accessibility of the findings. The results from the Scopus database ended up with 11 publications while Web of Science have 1 publication after applying the inclusion and exclusion criteria. Articles not available in English or studies not providing empirical data related to the purpose of this review excluded for this paper.

For the data analysis process, all the data were systematically extracted from the selected studies, gathered information on the type of biodegradable textile material, specific advancements reported, methods used for synthesis and characterization and potential applications. The quality of the studies was assessed on the basis of their relevance to the research question, methodological rigor and contribution to the field of biodegradable textiles. The collected data were categorized based on the type of material (PLA, PHA and natural fibers) and type of advancement (mechanical property enhancements, cost reduction strategies and improved biodegradability). Article that doesn’t fit with this category excluded from this study.Thematic analysis conducted to identify common trends and emerging themes in the development and application of biodegradable textiles.

## 4. Findings

### 4.1. Biodegradable Textiles in Environmental Engineering

An extensive analysis of biodegradable textiles utilized in environmental engineering, emphasizing natural fiber-based geotextiles such as jute, flax, and coconut fiber [7]. These materials were evaluated for their biodegradability and performance in applications such as erosion control and soil stabilization [7]. This study emphasizes the necessity of chemical and mechanical treatments to improve the durability of materials vulnerable to degradation from moisture and microbiological activity. These findings highlight the potential of biodegradable geotextiles to diminish environmental impact while preserving functioning across diverse applications.

### 4.2. Enhancement of Yarn Characteristics

Researcher examine the enhancement of yarn characteristics by the amalgamation of flax and cotton fibers utilizing response surface methodology [11]. The research determined that a 70:30 ratio of flax to cotton is ideal for improving mechanical qualities, including tensile strength and flexibility [11]. Study illustrates the potential of hybrid yarns that merge the ecological advantages of natural fibers with enhanced performance attributes, rendering them appropriate for many textile applications [11]. This method could markedly diminish dependence on synthetic fibers while preserving the requisite characteristics of textiles.

### 4.3. Sustainable Production of Natural Fibers

Investigation on the generation of natural fibers via an agroforestry methodology that amalgamates agriculture and forestry operations to promote sustainability [13]. Utilizing agroforestry systems for the cultivation of fibers, including hemp and bamboo can markedly reduce the environmental impact of fiber production [13]. This approach enhances biodiversity, augments soil health, and serves as a sustainable source of raw materials for the textile sector. These techniques correspond with the tenets of the circular economy and enhance a more sustainable textile production framework.

### 4.4. Advancements in Dyeing Techniques

Researchers propose a sustainable dyeing method for PLA that does not require hydrolysis and use a non-aqueous medium [12]. This novel technique decreases water use and mitigates the possibility of hydrolytic degradation, a prevalent problem in conventional dyeing methods for PLA. This work demonstrates that this method can yield brilliant and persistent colors on PLA fabrics while preserving the biodegradability and mechanical qualities of the polymer. This development tackles a significant issue in the manufacturing of biodegradable textiles: improving both ecological and functional efficacy.

### 4.5. Potential of Regenerated Protein Fibers in a Circular Economy

Another study examined the possibilities of regenerated protein fibers including those sourced from waste silk and wool, in the context of a circular economy [14]. This study emphasizes that reintegrating waste materials into the production cycle can markedly diminish the environmental impact of textile manufacturing [14]. Regenerated protein fibers serve as a sustainable substitute for traditional materials and facilitate the repurposing of textile waste, so advancing the objectives of a circular economy by reducing waste and conserving resources [14].

### 4.6. Impact of Woolenization on Jute Yarn Quality

A study performed on the woolenization procedure to enhance the quality of jute yarn [15]. Woolenization entails mechanical processing to improve the softness and resilience of coarse jute fibers [15]. This study revealed that woolenization enhances the mechanical properties of jute yarn, including flexibility and tensile strength, rendering it a more viable alternative for diverse textile applications typically dominated by synthetic fibers [15]. This approach can enhance the application of jute in clothing and home textiles, consequently fostering the utilization of biodegradable and sustainable resources.

### 4.7. Biodegradability and Ecological Consequences

The analysed articles together highlight the enhanced environmental efficacy of biodegradable textiles in comparison to conventional synthetic fibers. Biodegradable textiles, including PLA, PHA, and natural fibers, demonstrate a diminished carbon footprint and a lesser impact on microplastic contamination. Biodegradable geotextiles and natural fiber-based materials offer efficient erosion control while decomposing naturally without producing toxic residues [7]. Innovations like the sustainable dyeing procedure for PLA illustrate the capacity to mitigate the environmental impact of textile manufacturing [12].

## 5. Challenges of Biodegradable Textiles

### 5.1. Cost and Performance Limitations

Price is a major barrier to the adoption of biodegradable textiles. Most biodegradable polymers, such as PLA and PHA, have very expensive raw material requirements and are also costly to process. PLA production for example, may be up to 50% more than the production cost of polyester and hence cannot be economically well-matched in price-sensitive applications [4]. One of the ways in which this could be done would be to improve mechanical properties in naturally biodegradable textiles for future research, so that their competitiveness against synthetic textiles is improved.

### 5.2. Need for Specialized Infrastructure

The wide usage and dissemination of biodegradable textiles require specific composting and recycling infrastructure. Existing waste management systems are not appropriately tuned for the handling of biodegradable textiles, which diminishes their overall environmental impact. For instance, PLA is able to degrade under industrial composting conditions; it may not necessarily degrade properly in landfills or under home compost conditions [10]. Successful integration of the wastes is also possible only through investment in appropriate waste management infrastructure capable of processing biodegradable textiles.

### 5.3. Research and Innovation in Biodegradability

Further research needs to be done in developing the biodegradability of the materials for different environmental conditions. The possibility of developing a polymer that can easily deteriorate in natural environments, in soil or under marine conditions, would notably increase the use of biodegradable textiles. Another promising area still involves the degradation-enhancing property of some bio-based additives, including enzymes and microorganisms [4].

## 6. Future Directions

Biopolymer research must be extended by finding substitute feedstocks, such as agricultural or industrial waste to replace the very costly raw materials which needed for the production of biopolymers. Mechanical properties should be improved by chemical modification. Nanofillers or reinforcements can be used to improve the strength, flexibility and environmental degradation resistance of the biodegradable matrices, making them increasingly suitable for a wider range of textile applications [5]. Besides developing various international standards for certification that would reliably assess the environmental performance of biodegradable textiles under diverse conditions, these standards provide clarity to consumers and other industry stakeholders on how to select environmentally friendly textile products and will further help in building consumer confidence in biodegradable textiles. Future research should also focus on the potential of biodegradable textiles to be incorporated into circular economy systems closed-loop practices where materials are recycled or composted at the end of their lifecycle to regenerate resources. This could also involve the design of new recycling technologies with high separation and recovery rates for biodegradable materials mixed with other textile waste streams [9]. Enacting change throughout the industry will require collaboration among policymakers, industry representatives and researchers to create an enabling regulatory environment that will help make sustainable textile production a reality [10].

## 7. Conclusions

Biodegradable textiles would appear to offer an alternative solution to most environmental challenges presented by conventional textiles. Plenty of improvement has been observed in developing materials like PLA and PHA. Natural fibers, such as hemp and bamboo, are still among the good options for sustainable textile manufacturing. It is evident that the environmental impact of these materials is higher, and thus many advantages may be drawn from them by providing lower carbon footprints and more sustainable disposal methods. Yet, there are a number of challenges to be overcome: higher prices compared to conventional ones, partial performance limitations, and missing specialized infrastructure for waste management are major barriers that stand in the way of further growth. Future research should be directed at improving the performance and economies of biodegradable materials, improving their biodegradability in various environmental conditions, and building the ancillary infrastructure to take care of their disposal. Supportive policies and regulations will also be required to hedge the fashion industry in a more sustainable direction.

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