A COMPREHENSIVE REVIEW OF BIODEGRADABLE AND SUSTAINABLE POLYMERS FOR TEXTILE APPLICATIONS

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Abstract: *The textile sector is one of the biggest users of petroleum-derived synthetic polymers, such as acrylic, polyester, and nylon, which are resistant to deterioration. Biodegradable and sustainable substitutes made from renewable feedstocks or designed to be recyclable have received more attention lately. With an emphasis on natural biopolymers like cellulose, chitosan, and proteins; bio-based synthetic polymers like PLA, PHA, and PEF; blends; and nanocomposites, this review provides a thorough summary of recent developments in totally biodegradable and sustainable textile polymers. Future directions that involve improved recycling technologies, 3D printing using bio-based fibers, and smart biodegradable polymers have also been highlighted. To sum up, biodegradable polymers have the potential to significantly change the future of textiles in terms of sustainability and circularity. This analysis highlights recent advances and unresolved issues in the context of circularity while integrating natural, bio-based, and recycled polymer techniques in textiles in an exceptional manner.*

Keywords: Textile polymers, biodegradable fibers, sustainable textiles, bio-based polymers, polymer recycling.

SVEOBUHVATNI PREGLED BIORAZGRADIVIH I ODRŽIVIH POLIMERA ZA PRIMENU U TEKSTILU

Apstrakt: *Tekstilni sektor je jedan od najvećih korisnika sintetičkih polimera izvedenih iz nafte, kao što su akril, poliester i najlon, koji su otporni na razgradnju. U poslednje vreme sve više pažnje posvećuje se biorazgradivim i održivim zamenskim materijalima dobijenim iz obnovljivih sirovina ili dizajniranim da budu reciklabilni. Sa fokusom na prirodne biopolimere poput celuloze, hitozana i proteina; bio-bazirane sintetičke polimere poput PLA, PHA i PEF; mešavine; i nanokompozite, ovaj pregled pruža sveobuhvatan sažetak najnovijih dostignuća u potpunosti biorazgradivih i održivih tekstilnih polimera. Sprovedena je detaljna analiza glavnih izazova povezanih sa troškovima, mehaničkim performansama i prihvatanjem od strane potrošača. Istaknuti su i budući pravci koji uključuju unapređene tehnologije reciklaže, 3D štampanje pomoću bio-baziranih vlakana i pametne biorazgradive polimere. Ukratko, biorazgradivi polimeri imaju potencijal da značajno promene budućnost tekstila u pogledu održivosti i cirkularnosti. Ova analiza na izuzetan način ističe najnovija dostignuća i nerazrešena pitanja u kontekstu cirkularnosti, integrišući prirodne, bio-bazirane i reciklirane polimerne pristupe u tekstilnoj industriji.*

Ključne reči: tekstilni polimeri, biorazgradiva vlakna, održivi tekstili, bio-bazirani polimeri, reciklaža polimera.

1. INTRODUCTION

This industry is one of the largest industries globally, covering the needs for fabrics and fibers in apparel, interior textiles, personal healthcare, and technical textile applications. However, it is also one of the most resource-intensive and polluting sectors in terms of water consumption, chemicals used, and the generation of waste. As stated by UNEP, the textile sector contributes nearly 10% to global carbon emissions and produces millions of tons of solid waste every year [1]. The reason for all this environmental concern is the widespread use of petrochemical-based polymers like polyester (PET), nylon (polyamide), and acrylics dominating the fiber market due to their low cost, durability, and versatile properties [2]. These synthetic fibers are indispensable, but they are non-biodegradable and contribute to microplastic releases into terrestrial and aquatic ecosystems, thus forming urgent sustainability challenges [3-4].The paradigm of textile research and industrial innovation has shifted in recent years in favor of sustainable polymer substitutes. These comprise bio-based synthetic polymers (like polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and polyethylene furanoate (PEF), as well as natural polymers (like cellulose, chitosan, silk, and keratin) and polymer blends and composites intended to improve biodegradability, performance, and recyclability [5]. Additionally, developments in mechanical and chemical fiber recycling technologies are making it possible to recover and repurpose polymeric fibers, which is consistent with the ideas of the circular economy [6].

The exploration of textile polymers in the context of sustainability is highly interdisciplinary, spanning polymer chemistry, textile engineering, environmental science, and consumer studies. Natural polymers like cellulose and chitosan offer biodegradability and bio-functionality, while synthetic bio-based polymers such as PLA and PHA present scalable solutions but face challenges in cost, mechanical strength, and processing [7]. Hybrid materials, polymer blends, and nanocomposites are emerging as strategies to combine the advantages of multiple materials, potentially achieving both high performance and ecocompatibility [8].

A systematic review of textile polymers for sustainable fibers is both necessary and timely, given the speed at which innovation is occurring and the pressing need to shift to sustainable practices. Prior research has focused on specific polymer classes or discrete sustainability issues, but a thorough synthesis encompassing polymer classes, fiber applications, and recycling techniques is still lacking [9]. This review aims to:

1. Examine the environmental constraints of traditional textile polymers based on petrochemicals.
2. Examine the latest developments in synthetic and natural polymers used in textiles.
3. Talk about the way nanotechnology, composites, and polymer blends can improve fiber performance.
4. Assess the possibilities for combining the circular economy with the existing textile recycling technologies.
5. Identify key challenges and future research directions for achieving sustainability in textile polymer applications.

This paper aims to be a reference for scholars, industry participants, and policymakers working toward a sustainable textile future by offering a comprehensive overview of the current state of research.

2. MATERIALS AND METHODS

This review was conducted by systematically analyzing scientific literature published between January 2020 and August 2025 on biodegradable and sustainable polymers in textile applications. The following steps were taken:

2.1. Database Search

- Major scientific databases including *Scopus, Web of Science, Science Direct, Springer Link, and Google Scholar* were searched.
- Keywords used: *"biodegradable textile polymer," "bio-based fibers," "sustainable textiles," "polymer recycling textiles," "PLA fiber," "PHA fiber," "textile circular economy."*

2.2. Inclusion and Exclusion Criteria

Inclusion: Peer-reviewed journal articles, conference proceedings, review papers, and book chapters in English focusing on textile polymers, biodegradability, recycling, or sustainability.

Publications unrelated to textiles (such as general plastics), studies conducted prior to 2020 unless they are foundational, non-English sources, and non-peer-reviewed articles are excluded.

2.3. Screening and Selection

More than 420 early publications were found. 156 articles underwent a thorough review following title/abstract screening and duplicate removal. Lastly, 47 important papers were selected for inclusion based on their quality and relevance.

2.4 Organization of Review

The results were organized into several major themes:

- Environmental concerns and conventional textile polymers.
- Natural polymers that break down naturally.
- Synthetic bio-based polymers, polymer blends, and nanocomposites.
- Circular economy and recycling strategies.
- Obstacles and potential paths.

This methodical approach guarantees a thorough and objective synthesis of the most recent developments in biodegradable and sustainable textile polymers.

3. TRADITIONAL TEXTILE POLYMERS AND ENVIRONMENTAL ISSUES

3.1. PET, or polyester

The most popular synthetic fiber is polyester, which is prized for its great strength, ability to resist wrinkles, and affordability [9].

PET, on the other hand, comes from fossil fuels and is very resistant to biodegradation. PET textiles may endure for centuries in natural settings, according to studies [10]. One of the main sources of secondary microplastics in aquatic environments is microfibers shed during laundry [11].

3.2. Polyamide (Nylon)

Sportswear, hosiery, and industrial textiles can all benefit from nylon's exceptional elasticity and abrasion resistance [12]. Nitrous oxide, a greenhouse gas with almost 300 times the potential for global warming as CO_2, is produced during its production, though [13]. Environmental issues are made worse by nylon's durability and microplastic shedding.

3.3 Acrylic Fibers

Acrylic fibers are frequently used in knitwear and upholstery because they are similar to wool in terms of softness and thermal insulation [14]. Acrylonitrile, a hazardous monomer categorized as a probable human carcinogen, is used in their extremely energy-intensive production [15]. In marine environments, acrylic microfibers are also one of the most commonly found plastics [16].

3.4 Environmental Impact

Synthetic fibers' combined environmental issues include:

- A high carbon footprint due to their petrochemical origins.
- The ongoing buildup of waste in landfills.
- The contamination of aquatic systems by microplastics.
- Hazardous byproducts from production.

Research on biodegradable natural and bio-based synthetic substitutes has accelerated as a result of these worries.

4. NATURAL TEXTILE BIODEGRADABLE POLYMERS

4.1. Fibers created from cellulose

The most common natural polymer, cellulose, is essential to innovative sustainable textiles. Fibers made from regenerated cellulose, including modal, lyocell, and viscose, are extensively marketed [17]. Lyocell production is thought to be less damaging to the environment than viscose because it uses a closed-loop process with non-toxic Nmethylmorpholine N-oxide (NMMO) [18]. Fiber strength, breathability, and biodegradability have all been further improved by advancements in nanocellulose incorporation [19].

4.2. Derivatives of chitosan

Derived from the chitin found in crustacean shells, chitosan is antimicrobial, biodegradable, and biocompatible [20]. Chitosan is frequently used as a functional coating for cotton, polyester, and blends, offering antimicrobial and moisture-management qualities, even though it is not usually spun into bulk fibers [21]. Chitosan-based nanocomposites for protective and medical textiles have been the subject of recent studies [22].

4.3 Fibers Based on Proteins

For sustainable textiles, research has been done on silk fibroin, keratin (found in wool or feathers), and casein (found in milk). These protein-based polymers have special functional qualities like biocompatibility and biodegradability [23]. For example, biomedical textiles may use regenerated keratin fibers, although scalability and cost are still obstacles [24].

Here, Table 1 presents a summary of natural biodegradable polymers for textile applications.

Table 1: Summary of Natural Biodegradable Polymers for Textile Applications

Polymer	Source	Key Properties	Applications	Limitations
Cellulose	Cotton, wood pulp	High strength, breathable, biodegradable	Apparel, technical textiles	Moisture sensitive, processing complexity
Chitosan	Crustacean shells	Antimicrobial, film-forming	Coatings, wound dressings	Cost, limited fiber spinning
Silk fibroin	Silk cocoons	Biocompatible, biodegradable	Biomedical textiles, luxury apparel	Expensive, limited scalability

5. BIO-BASED SYNTHETIC POLYMERS

5.1. Polylactic acid (PLA)

PLA is synthesized from renewable resources such as corn starch and sugarcane. PLA fibers are biodegradable under industrial composting conditions and exhibit good strength, low flammability, and moisture management [25]. Limitations include relatively low thermal stability and brittleness [26]. Research on PLA nanocomposites with cellulose nanocrystals and clays has improved mechanical properties and processability [27].

5.2. PHAs, or polyhydroxyalkanoates

Microbial polyesters known as PHAs break down in soil and marine environments, among other natural settings [28]. High production costs and processing challenges impede their potential for biomedical textiles [29]. To cut costs and improve performance, PHA blends with PLA or natural fibers are being investigated [30].

5.3. Furanoate of polyethylene (PEF)

PEF is a bio-based polyester made from biomass-derived 2,5-furandicarboxylic acid (FDCA). Compared to PET, PEF has better barrier qualities, is recyclable, and has a lower carbon footprint [31]. PEF is regarded as a promising substitute for traditional PET in clothing and packaging, despite its ongoing development [32].

The whole thing about bio-based synthetic polymers (sources to uses) is summarized in Table 2.

6. BLENDS OF POLYMERS AND NANOCOMPOSITES

Performance and sustainability are balanced by combining synthetic and biodegradable polymers. Blends of PLA and PET, for instance, increase processability and flexibility while lessening their negative effects on the environment [33]. Blends of PLA and chitosan also show improved antimicrobial qualities [34].

Tensile strength, flame retardancy, and barrier qualities are greatly improved by nanocomposite techniques that include clay nanoparticles, graphene oxide, or cellulose nanocrystals [35]. For filtration and biomedical applications, PLA and chitosan nanocomposites electrospun nanofiber mats are being investigated [36].

7. STRATEGIES FOR RECYCLING AND THE CIRCULAR ECONOMY

7.1. Recycling by mechanical means

PET textiles are frequently recycled mechanically, although fiber deterioration results in lower quality

Table 2: Bio-Based synthetic polymers in textiles.

Polymer	Source	Key Properties	Applications	Limitations
PLA	Corn, sugarcane	Biodegradable, good tensile strength	Apparel, nonwovens	Low thermal stability, brittle
PHA	Microbial fermentation	Biodegradable in soil/water	Medical textiles, packaging	High production cost
PEF	Biomass (FDCA)	Recyclable, barrier properties	Apparel, packaging	Industrial scale still limited

and fewer uses [37]. Due to material incompatibilities, recycling blended textiles remains very challenging.

7.2. Recycling of chemicals

Polymers are broken down into monomers for reuse by chemical recycling techniques like enzymatic depolymerization, glycolysis, and methanolysis [38]. Under mild conditions, enzyme-based depolymerization has demonstrated encouraging results, especially when employing PET hydrolases [39].

7.3. Textiles and the circular economy

Fiber-to-fiber recycling and closed-loop manufacturing are encouraged by circular systems. Closed-loop PET recycling initiatives have been piloted by companies such as Adidas and H&M [40]. Reliance on virgin fossil-based materials and textile waste could be further decreased by incorporating biodegradable polymers into circular economy frameworks [41]. Table 3 shows various strategies for recycling synthetic polymers.

Despite enormous advancements, issues still exist:

Performance trade-offs: Compared to PET or nylon, biodegradable fibers frequently have lower tensile strength and thermal stability.

Processing constraints: Conventional polymers are best served by the current infrastructure for spinning and finishing [42]. Expensive: Compared to polymers derived from fossil fuels, PLA, PHAs, and PEF continue to be more costly.

Consumer acceptance: Knowledge of and willingness to pay for sustainable alternatives are necessary for market penetration [43].

This figure [1] shows the flow of textile polymer circular economy in some simple words which helps to understand the whole flowchart of production to be reused.

Table 3: Recycling strategies for synthetic textile polymers (2020–2025)

Polymer	Method	Efficiency	Applications	Limitations
PET	Mechanical	Moderate	Apparel	Fiber degradation
PET	Chemical (glycolysis)	High	Fiber/filament	Requires solvents
PET	Enzymatic	High	Textile-to-textile	Enzyme cost, scale-up
Nylon	Chemical	Moderate	Apparel	Nitrogen oxides by-products

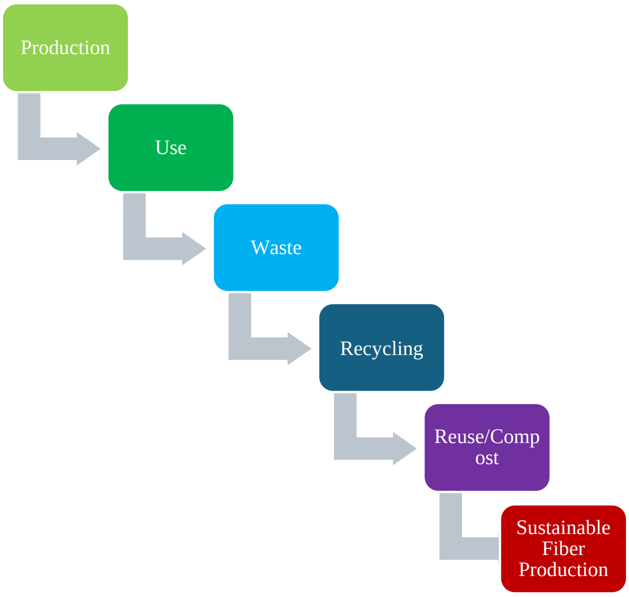

Figure 1: Conceptual flowchart of textile polymer circular economy.

8. FUTURE PATHS

Among the top research goals are:

- Smart biodegradable polymers that combine biodegradability with stimuli-responsive properties (drug release, conductivity, and sensing) [44].
- Green processing technologies that reduce the need for dangerous chemicals for dyeing and finishing [45].
- Efficient depolymerization of textile polymers through bio-catalytic recycling employing enzymes that have been engineered.
- Customized, waste-free textile production using 3D printing and biopolymers [46].
- Incentives and policies to encourage the widespread use of sustainable fibers [47].

Future research should concentrate on digital manufacturing techniques like 3D printing with biopolymers, enzyme-assisted recycling, and intelligent biodegradable polymers.

9. CONCLUSION

Sustainable and biodegradable polymers offer an innovative approach to lessen the textile industry's environmental impact. Developments in bio-based synthetics, blends, natural biopolymers, and recycling techniques show great promise for replacing traditional fibers derived from petroleum. Cost, durability, and scalability issues are still major obstacles, though. Achieving a circular and sustainable textile economy will require interdisciplinary innovation, supportive legislation, and consumer involvement. The Sustainable Development Goals (SDGs 12: Responsible Consumption and Production and 13: Climate Action) of the UN are directly aided by these developments.

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