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COMPARATIVE ASSESSMENT OF PLA, PHA AND NATURAL CELLULOSIC FIBERS IN SUSTAINABLE TEXTILE APPLICATIONS

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Abstract: *The textile industry is under increasing pressure to reduce dependence on petroleum-based fibers and to adopt materials with lower environmental impact. Among the most promising alternatives are polylactic acid (PLA), polyhydroxyalkanoates (PHA), and natural fibers, each offering distinct benefits and limitations for sustainable textile applications. PLA is a bio-based polymer that is relatively easy to process and already used in some textile and nonwoven products, but its biodegradation is often limited to controlled industrial conditions. PHA is a microbial polyester with strong biodegradation potential and high sustainability appeal, yet its commercial adoption remains constrained by high production costs and processing challenges. Natural fibers such as hemp, flax, cotton, and jute are renewable and widely used in textiles, offering comfort, breathability, and established manufacturing routes, although they often require treatment or blending to overcome variability and moisture sensitivity. This short review compares these three material families in terms of origin, biodegradability, processability, mechanical performance, cost, and textile suitability. The analysis shows that no single fiber can satisfy all sustainability and performance requirements. Instead, future sustainable textile systems will likely depend on material selection according to application, blending strategies, and improved end-of-life management.*

Key words: *PLA, PHA, natural fibers, sustainable textiles, biodegradable polymers, bio-based materials*

1. INTRODUCTION

Sustainable textile development has become a major research direction because conventional synthetic fibers are tied to fossil resources and waste problems. Conventional synthetic fibers, which are predominantly derived from petroleum, are associated with substantial greenhouse gas emissions, resource depletion, and persistent waste in the environment [1], [2]. Lifecycle studies indicate that the production of these fibers is energy-intensive and strongly linked to fossil-based supply chains, while their limited biodegradability can result in long-term accumulation in ecosystems [3]. These environmental drawbacks are further accentuated by the global context of energy and raw-material insecurity, including volatility in oil markets and disruptions affecting strategic transport corridors, such as the Strait of Hormuz, nowadays. Such conditions highlight the vulnerability of petroleum-based supply chains and reinforce the need for renewable, bio-based alternatives in textile manufacturing.

Within this context, bio-based polymers and natural cellulosic fibers have received increasing attention as possible substitutes for conventional textile materials. Among them, polylactic acid (PLA), polyhydroxyalkanoates (PHA), and natural fibers such as cotton, flax, hemp, and jute represent three particularly relevant categories for comparative analysis because they differ in technological maturity, biodegradability, cost profile, and textile performance [4, 5]. PLA and PHA are bio-based polyesters with distinct processing and degradation characteristics, while natural fibers are long-established renewable materials that continue to play a central role in sustainable-textile research [4]. The objective of this paper is to compare these three material families in relation to their origin, processing, properties, environmental performance, and textile suitability, and to identify their main advantages and limitations for future sustainable textile systems.

2. MATERIALS AND METHODS

This paper was developed as a short narrative review based on recent literature addressing sustainable fibers for textile applications. The comparison focuses on three material families (PLA, PHA, and natural fibers), selected because they represent distinct but complementary approaches to reducing the fossil-based content of textiles. The review criteria included raw-material origin, fiber-processing routes, mechanical and thermal characteristics, biodegradability, end-of-life considerations, industrial maturity, and representative textile applications.

Sources included review papers, technical overviews, and sector-specific analyses concerning textile processing, biodegradable polymers, and natural-fiber performance along with the use of these materials in apparel, nonwovens, home textiles, and technical textiles. A particular attention was also given to reported constraints linked to cost, moisture sensitivity, hydrolytic degradation, or limited infrastructure for composting and recycling.

The resulting synthesis is qualitative and comparative in nature and is intended to provide an academically grounded overview suitable for a short review article format.

2.1 PLA / PHA, as biodegradable polymers

PLA / PHA are part of the main class of biodegradable polymers [6], as shown in **Fig 1**.

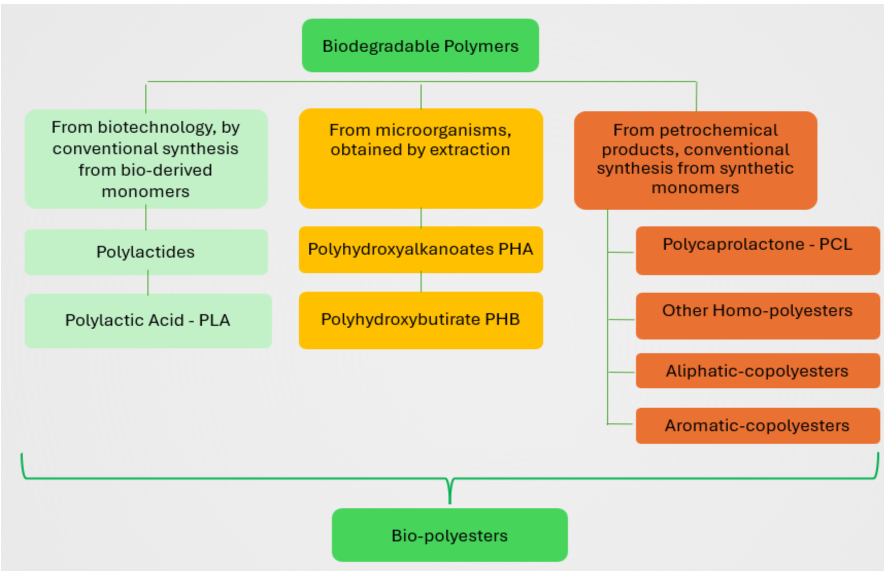

***Fig. 1**: Main biodegradable polymers*

Bio-based polymers could be obtained from microbial production, such as PHA, or by producing bio-based monomers through fermentation and conventional chemistry followed by polymerization, such as PLA. There are also polymers that are prepared from petrochemical products (synthetic monomers, such as polycaprolactone, PCL). [6 Averous, 2012]

2.2 PLA for textiles

PLA is a bio-based and biodegradable polymer produced from renewable plant-based feedstocks, such as corn starch or sugar cane, which makes it a prominent alternative to petroleum-based polyesters, used in the textile industry [4]. The raw material used in the synthesis of PLA is the high purity monomer, lactide [4]. Chemical formula is stated in **Fig. 2** [6].

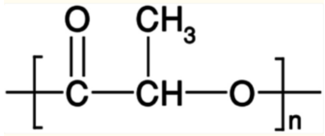

Fig. 2*: The chemical structure of PLA [6]*

The PLA family includes poly(l-lactide) (PLLA), poly(d-lactide) (PDLA), poly(dl-lactide) (PDLLA), poly(meso-lactide), and copolymers obtained from the monomers [4]. Based on the stereochemistry of the polymer structure, PLA can be semicrystalline or amorphous, which provides the PLA fibers with specific properties, as increased durability, while the purity of lactic acid stereo-copolymers affects the physical properties of PLA, depending on the applied production process [4]. PLA fibers are typically produced via melt spinning, either as continuous filaments or as staple fibers, and can be integrated into conventional spinning, knitting, and weaving lines without major process changes [7]. This relative process compatibility has supported its introduction into apparel blends, home-textile products, and disposable or semi-durable nonwoven articles. **Fig. 3** shows PLA short fibers and filaments produced by Shenzen Esun Industrial Group.

Fig. 3*: PLA short fibers and filaments [8]*

With respect to performance, PLA fibers exhibit useful tensile strength, acceptable dimensional stability, low pilling tendency, and a smooth, soft handle surface which enhances comfort in next-to-skin products such as sportswear, underwear, and children's clothing [9]. PLA also offers moderate moisture-wicking and reasonable breathability, which can be further improved by texturing, fiber cross-section design, or blending with cellulosic fibers [10]. However, several limitations remain significant. PLA exhibits lower thermal resistance than polyethylene terephthalate (PET), with a relatively low glass-transition temperature and susceptibility to deformation during high-temperature processing, finishing, or ironing [9,10]. In addition, PLA is sensitive to hydrolytic degradation under conditions of moisture, elevated temperature, or alkaline treatment, which can constrain dyeing and wet processing.

From an environmental point of view, PLA is frequently described as biodegradable and industrially compostable, although its effective degradation generally depends on controlled conditions rather than unmanaged natural environments [9].

In summary, PLA is a technologically mature and relatively versatile bio-based fiber that can be processed with conventional textile machinery and offers advantages in renewability and compostability. However, its thermal sensitivity, hydrolytic degradation, and dependence on industrial end-of-life infrastructure imply that its deployment should be carefully aligned with specific textile applications and value-chain capabilities.

2.3 PHAs for textiles

Polyhydroxyalkanoates (PHAs) are a class of intracellular biopolymers synthesized by various bacteria, where they serve as carbon and energy storage in the form of granules [11]. These biopolymers are produced through fermentation of renewable carbon resources, including sugars, plant oils, and agricultural residues [12]. Structurally, PHAs consist of hydroxyalkanoate (HA) monomer units arranged into polymer chains formed during bacterial fermentation [12]. Chemical structure is presented in **Fig. 4.**

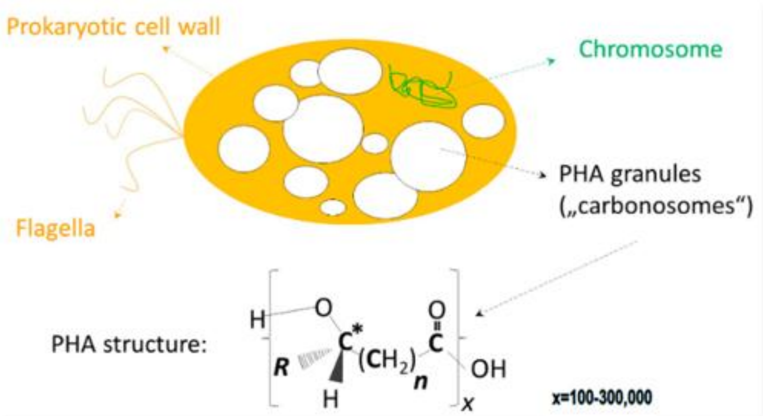

Fig. 4: *The chemical structure of PHA [11]*

PHAs can be converted into textile fibers mainly through melt spinning or solution-based techniques (such as wet, dry, or electrospinning), often with modifications like copolymerization or blending to improve processability and mechanical performance [11]. Melt spinning is the closest to conventional synthetic fiber production. The PHA (e.g., PHB or PHBV) is melted and extruded through spinnerets, then drawn to orient the polymer chains [13]. PHA's principal attraction in the textile sector lies in their biodegradability profile, since PHA materials have been reported to degrade in soil, water, marine environments, and industrial composting systems under suitable conditions [12]. This characteristic provides a substantial conceptual advantage for textile products designed within circular-economy or low-persistence in ecosystems. Depending on formulation, PHA materials can exhibit behavior ranging from relatively rigid to more elastomeric, which creates opportunities for diverse textile uses, including biodegradable wipes, agricultural textiles, selected medical or hygiene materials, protective layers, and niche fashion products where biodegradability is prioritized [14]. **Fig. 5** presents variants of staple PHA fibers, in paralell with fillaments.

***Fig. 5**: The chemical structure of PHA [15,16]*

PHAs are often blended with other polymers (PLA, PCL) to improve spinnability, flexibility, and durability. This is currently one of the most practical approaches for textile applications [14]. PHA fibers are reported to be lightweight, mechanically robust, and breathable, with good comfort properties for clothing and personal protective applications.

Despite these advantages, PHA fibers still face significant challenges. Production costs are higher than those of conventional synthetics due to complex fermentation and downstream processing requirements, and industrial scale PHA manufacturing remains limited globally [4]. Thermal and mechanical behavior can be less predictable than that of PLA or PET, and long term performance under repeated washing and mechanical stress has not yet been extensively documented in open literature [4].

2.4 Natural cellulosic fibers in textiles

Natural fibers, such as cotton, flax, hemp, jute, are widely regarded as sustainable alternatives to synthetic fibers because they are derived from renewable biological sources and are generally biodegradable at end of life. These fibers are typically extracted from plant stems, seeds, bast layers, and can be processed into yarns and fabrics using well established spinning, weaving, and knitting technologies. Natural fibers are valued for their low thermal conductivity and good thermal insulation, which makes them suitable for protective clothing and other purpose-related textiles.

The specific properties of natural fibers vary substantially according to botanical origin, cultivation conditions, harvesting method, and subsequent treatment [17]. Bast fibers such as flax and hemp can offer relatively high stiffness and strength, whereas cotton is typically associated with softness and wear comfort. Natural fibers also present hydrophilic behavior and significant moisture regain, which can improve thermophysiological comfort but may also result in dimensional instability or property changes under humid conditions [17].

On the other hand, natural fibers display several limitations that affect their widespread deployment as unique components in high performance textiles. Variability in fiber diameter, length, and strength between batches can complicate quality control and fabric consistency. Sensitivity to moisture and biological degradation, especially in humid environments, can reduce durability unless fibers are chemically treated.

3. RESULTS AND DISCUSSIONS

3.1 Comparative assessment

PLA, PHA, and natural cellulosic fibers each occupy a distinct niche in the landscape of sustainable textile materials, and their relative strengths and weaknesses become clearer when examined side by side. From a production and process perspective, PLA is the most mature among the bio based options, with fibers that can be integrated into standard spinning, knitting, and weaving lines without major modifications. PLA's mechanical properties are broadly comparable to those of conventional polyester, yet its lower thermal stability and susceptibility to hydrolytic degradation limit its suitability for high temperature processing and long term durability under moisture stress. In contrast, PHA offers superior biodegradability in a wider range of environments, including soil, water, and marine settings, which makes it attractive for circular economy oriented textiles, but its production cost structure and scale-up challenges restrict its current deployment to niche, high value products.

Natural fibers, such as cotton, flax, hemp, and jute, provide a renewable and biodegradable base material with well established comfort and thermal insulation properties, and they can be processed on existing textile equipment with minimal capital investment. However, their mechanical performance and quality can vary with cultivation conditions and post harvest treatments, and many require additional processing to improve moisture resistance, strength, and dyeing behavior. In practical terms, PLA is particularly suitable for blends, disposable textiles, and technical nonwovens where end of life management can be controlled, while PHA is currently better positioned for niche biodegradable products and specialized applications where environmental degradation is a primary design objective.

3.2 Stuctured comparison

Fig. 6 offers a structured comparison which includes the main characteristics of PLA, PHA, and natural fibers in terms of origin, biodegradability, processability, mechanical performance, and typical textile applications.

Criteria	PLA	PHA	Natural fibers
Origin	Renewable plant-based feedstocks	Microbial production	Plant or agricultural sources
Biodegradability	Biodegradable, often under industrial composting conditions	Strong biodegradability, including broader environmental settings	Biodegradable, well accepted as renewable
Processing	Good compatibility with textile existing processes	More difficult, less mature industrially	Highly established in textile manufacturing
Mechanical performance	Usefull strength, but limited heat resistance	Variable; depends on formulation and processing	Recommended for multiple uses, properties vary by fiber type
Comfort	Can work well in blends and nonwoven products	Less common in curent apparel use	Strong advantage in comfort and breathability
Cost and scale	More commercially mature than PHA	High costs and scale-up barriers	Widely available, especially for mature crops
Best-fit uses	Blends, disposable textiles, nonwovens	Niche sustainable textiles, specialty uses	Apparel, home textiles, blends, technical uses

Fig. 6*: A structured comparison of PLA, PHA and natural cellulosic fibers*

The structured summary highlights the trade-offs between these three material families:

PLA's relatively high industrial maturity and processability, PHA's strong biodegradability but limited economic and technological readiness, and the comfort and renewal potential of natural fibers balanced against their variability and moisture-sensitivity. By presenting these attributes side by side, the table supports the discussion of appropriate fiber selection for different types of sustainable textile products.

4. CONCLUSIONS

This review has highlighted that PLA, PHA and natural fibers each contribute in different ways to the development of sustainable textile systems. PLA represents a relatively mature bio based polymer with good processability and mechanical properties comparable to conventional polyester, making it suitable for apparel blends, disposable textiles, and technical nonwovens, when paired with controlled end of life strategies, such as industrial composting or collection based recycling. PHA, although less economically viable at present, offers enhanced biodegradability under diverse environmental conditions and is particularly promising for niche, high value textiles, where biodegradability is a primary design criterion. Natural cellulosic fibers, including cotton, flax, hemp, jute, and others, remain the most versatile option for apparel, because they combine renewability, biodegradability, comfort, and industrial familiarity, even if they require optimization for performance, consistency and durability.

Taken together, these materials suggest that the most effective solution toward more sustainable textiles lies not in choosing a single "best" fiber, but in strategically combining complementary materials. Blends and hybrid structures that integrate PLA or PHA with natural fibers can balance performance, comfort, and environmental footprint while reducing dependence on fossil based resources.

In the light of the authors'contribution to the literature, the comparison table offers a concise, structured overview that synthesizes key properties and application profiles of PLA, PHA, and natural fibers, reinforcing the paper's argument that no single fiber type is universally optimal for application-driven material selection in sustainable textile design.

Future textile systems are likely to depend on hybrid material combinations, improved fiber engineering, better composting and recycling infrastructure, and more rigorous lifecycle assessment, in order to balance environmental objectives with real manufacturing and consumer requirements.

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