Biopolymers in Textiles

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Given the significant contamination of our ecosystem caused by synthetic fibers involved in the textile industry, biomaterials derived from renewable resources or endowed with biodegradability characteristics have been proposed as a possible green solution for reducing the environmental impact of fabric production. The use of polymers derived from renewable sources (both biodegradable and non-biodegradable) would result in reduced greenhouses emissions (GHG) and fossil fuel consumption (FFC) when compared to common fossil-based, non-biodegradable polymers, the most common polyester (PET), polyamide (PA), polypropylene (PP). Although less biodegradable compared to natural-based fibers (wool, cotton), aliphatic polyester bio-based fibers are biodegraded more quickly compared to PET fibers. Furthermore, the larger moisture vapor transmission of bio-based polymers compared to PET, PA and PP materials, allows greater breathability by corresponding fabrics. Biobased fibers are also endowed with good mechanical resistance and antibacterial properties, low flammability and less smoke generation.

Keywords: Biopolymers ; Textiles ; mechanical properties ; antibacterial properties ; flammability ; breathability ; biodegradability

1. Introduction

Biopolymers can be produced from vegetal or animal-derived polysaccharides (i.e., starch, cellulose, lignin), proteins (i.e., chitosan, collagen) and lipids (i.e., wax, fatty acids), bacterial activities (i.e., polyhydroxyalkanoates (PHA)), the conventional synthesis of bio-derived monomers (i.e., polylactides (PLA) and polyglycolide (PLG)) or synthetic monomers (i.e., polycaprolactone (PCL)s, polyester-amides (PEA), an aliphatic or aromatic co-polyester (poly(butylene succinate-co-butylene adipate (PBSA), polybutylene adipate terephthalate (PBAT)).[1]

Biodegradation consists in the breakage of organic matter by means of microorganisms through two main pathways developed under aerobic (in the presence of oxygen) and anaerobic (in the absence of oxygen) conditions[2]. The final products of aerobic biodegradation are carbon dioxide, water, biomass, and oxidation products of nitrogen and sulfur; whereas, in the case of anaerobic biodegradation, hydrocarbons, methane, carbon dioxide, biomass, and reduction products of nitrogen and sulfur are released [3]

According to ASTM D6400-99 [4], a biodegradable plastic is a degradable plastic in which the degradation results from the action of naturally occurring microorganisms, such as bacteria, fungi, and algae. The ability to be decomposed by microorganisms depends on the chemical structure rather than the origin: petroleum-derived plastics can also be biodegradable [5]. A compostable plastic is a plastic that undergoes degradation through biological processes during composting to yield CO_2, H_2O, inorganic compounds, and biomass at a rate that is consistent with other compostable materials, and leave no visible, distinguishable or toxic residue [4]. Composting is a biological process in which the organic material is decomposed primarily by microorganisms, to produce a soil-like substance, called humus. The composting conditions are affected by environmental factors, such as water or moisture content, temperature, acidity, enzyme specificity; or polymer factors, such as polymer structure and chain flexibility, crystallinity, and molecular weight, as well as copolymer compositions, size, and shape [6].

Plastics can be broadly classified into the four categories: (i) fossil-based and non-biodegradable plastics (polyester (PET), polypropylene (PP); polyethylene (PE); polyamide (PA), thermosets); (ii) fossil-based and biodegradable (PCL, Poly(butylene adipate-co-terephthalate) (PBAT)), (iii) natural-based and non-biodegradable (bio-PP, bio-PE, bio-PET), and (iv) natural-based and biodegradable (PLA, PHA, lignocellulose, starch, proteins) [7] [8] .

Therefore, in light of sustainable green manufacturing, future developing fabrics should be biodegradable. Fabrics made with similar fiber characteristics, but derived from renewable resources, such as bio-PET and bio-PA, could be used as alternatives to current fabrics made with synthetic fibers. However, the debate over the potential pollution induced during

the latter's life cycle remains open, as the latter, not being biodegradable, can equally cause an aggravation of problems already highlighted with the use of fossil-based filaments during the life cycle and at the end of their use [9].

Nevertheless, the step forward in reducing the environmental impact during the production of fibers from renewable sources cannot be neglected. The lack of biodegradability could not be considered an issue as durable bio-plastics have identical performance compared to petroleum-based ones, and could be directly applied in existing recycling systems. Furthermore, during the production of durable bio-plastics, although these are still more expensive, a large reduction in greenhouse gas (GHG) imprint emission is obtained compared to petro-equivalents [10]. Life-cycle assessments (LCAs) for bio-PE and PLA bioplastics were compared to those of two fossil-derived plastics, high-density polyethylene (HDPE) and low-density polyethylene (LDPE), in terms of greenhouse emissions (GHG) and fossil fuel consumption (FFC). The results demonstrated the benefits of bio-based plastic pathways over fossil-based pathways by showing GHG equal to −1.0 and 1.7 kg CO_2e per kg for bio-PE and PLA with no biodegradation, compared with 2.6 and 2.9 kg CO_2 e per kg for LDPE and HDPE; and FFC equal to 29 and 46 MJ per kg of bio-PE and PLA, compared with 73 and 79 MJ per kg of LDPE and HDPE. However, despite the benefits of biogenic carbon uptake, at the end-of-life, PLA emissions were increased from 16% to 163%, passing from composting to landfill because less CH_4 was emitted in the composting gas [11].

2. Properties of Bio-Based Fibers and Fabrics

Choosing an appropriate fiber among various renewable fibers derived from biomass necessitates an awareness of sustainability based on the product's GHG imprint and the energy requirements of its production and distribution. The selection of material should be based on the product's value chain, previous use in clothing, and comparable physical parameters with the most commonly used synthetic fibers derived from PET (terylene, dacron, etc.).[9]

2.1 Biodegradability

Once discarded in the environment, PLA is hydrolyzed into low-molecular-weight oligomers, and then converted into CO_2 and H_2O by microorganisms present in the environment [12]. However, microorganisms able to degrade PLA are not widespread in the soil, making PLA biodegradation less feasible than that of other polyesters, such as polyhydroxybutyrates (PHB), PCL, and polybutylene succinate (PBS) [13].

Cotton fibers are mostly made of cellulose, which is biodegraded by microorganisms that secrete enzymes called cellulases. Cellulases catalyze the hydrolysis and oxidation of the cellulose molecular chain into cellobiose units, which then degrade into glucose and glucose derivatives, both of which are non-hazardous to the environment [14]. The biodegradation of cotton fabric is affected by textile finishing (silicone softener, durable press, water repellent, and a blue reactive dye). The rate of degradability of textile microfibers during laundering decreased with durable press- and water-repellant finishing treatment. The presence of crosslinking (durable press) and hydrophobicity (water repellent) on the surface slows down the initial adsorption of enzymes excreted by microorganisms in the inoculum. Therefore, the use of manufacturing techniques such as derivatization, blending, and coating to improve bio-based material performance in practical applications affects the environmental impact of the final product [15]. Experimental evidence of the aquatic biodegradation of cotton, rayon, and polyester-based fabrics has demonstrated that during, laundering cellulose-based fabrics releases more microfibers (0.2–4 mg/g fabric) than synthetic textiles (0.1–1 mg/g fabric). However, cotton and rayon fibers degraded in aquatic conditions faster than polyester fibers, which, by contrast, persisted in the environment for a long time [16].

The biodegradation of wool (natural keratin fiber), cotton (a natural cellulose fiber), and fiber of PLA was evaluated at 35 °C for 42 days to determine the time-dependent changes in weight loss, strength loss, and morphology under natural soil and aqueous medium conditions. The results made it possible to determine that the degradation rates in natural soil were higher than in aqueous medium, listed in the following order: cotton > wool > PLA fiber. This led to the conclusion that natural fibers degrade more easily than man-made biodegradable PLA fibers [17].

Based on a study by Egan and Salmon [2], the percentage biodegradation of textile fibers in various environments can be summarized as follows: (i) cotton fibers are biodegradable in soil (180 days) and anerobic conditions (30 days), and semi-biodegradable in compost (45 days); (ii) PLA-based fibers are biodegradable in compost (45 days), semi-biodegradable under anerobic conditions (30 days) and seawater (90 days), and completely non-biodegradable in soil (180 days); (iii) PET fibers are never biodegradable.

2.2 Mechanical Performance

Polylactide acid (PLA) is one of the most promising biopolymers in textiles, since it possesses similar characteristics to synthetic fibers, with superior biodegradability compared to other biopolymers. It is soft to the touch, features a silky sheen, and offers good durability. However, the breaking strength of pure PLA was very low, making it necessary to set specific parameters for the production and processing of PLA fibers [18], or for blending it with other polymers [19].

A comparison of the mechanical, thermal, and surface properties, as well as the anti-bacterial behavior, of five different types of synthetic multi-filament yarn and the corresponding knitted fabrics was presented in the work of Huang et al. [20]. Three bio-based materials (PLA/PHBV, PLA, Cupro) and two petroleum-based materials (PET, PA6) were considered. The final results made it possible to attest that the bursting strength, extension, and recovery of jersey-knitted fabrics from PLA/PHBV yarns satisfy industrial requirements. For these fabrics, a bursting strength of 375.8 kPa was measured, which was higher than that of PLA fabrics, similar to that of PA 6, and significantly lower than PET fabrics. Dyed PLA/PHBV knitted fabrics displayed the worst abrasion resistance (2250 rubs) compared with other fabric samples (the highest: PET fabrics with abrasion resistance > 50 000 rubs), promising tearing property, and good air permeability, as well as excellent antibacterial performance against staphylococcus aureus, klebsiella pneumoniae, and candida albicans.

2.3 Breathability and Comfort

Polylactide acid has a higher natural hydrophilicity than most other thermoplastic polymers, including polypropylene, nylon, and PET, because water molecules can enter in PLA macromolecules through polar oxygen linkages [21]. Although PLA fibers are not as wettable as cotton, the improved wettability characteristics of these fibers determine a larger moisture vapor transmission compared to PET or nylon fiber-based fabrics. This aspect allows the greater “breathability” of garments such as shirts, dresses, underwear, and shoes composed of PLA-based fibers when these fibers are used in place of fibers such as PET or nylon [21].

2.4 Antibacterial Properties

Resistance against microbial attack is one of the important aspects of the textile industry. A good contact area and the absorption of moisture are the two main causes of microbial growth, which leads to unpleasant odors, dermal infections, allergic reactions, and fabric deterioration. Thus, the incorporation of antimicrobial agents on textile products capable of overcoming these issues is critical [22]. Endowed with strong antimicrobial activity and excellent biocompatible and biodegradable properties, PHBV can be represented as a potential candidate for replacing petroleum-derived polymers [23]. Unfortunately, the mechanical strength, water sorption and diffusion, and electrical and/or thermal properties are all lacking, necessitating its use in conjunction with other polymers [23]. Chitin and chitosan are highly versatile biomaterials that have gained widespread attention due to their unique properties, such as nontoxicity, biocompatibility, biodegradability, low allergenicity, biological activity, low cost, and so on [24]. One of the most common applications of chitosan in the textile industry is as an antimicrobial agent, given its ability to provide protection against allergies and infectious diseases, as well as moisture retention and wound-healing capabilities[25]. Because of the presence of reactive amino and hydroxyl groups along the backbone, chitosan has some intriguing properties for use in textile dyeing and finishing. However, low water solubility at neutral pH and poor durability on textile surfaces limit the widespread use of chitosan[26]. Experiments have been conducted on the use of crosslinking and graft polymerization to chemically modify chitosan to produce water-soluble bioactive derivatives [27].

2.5 Flammability

A comparison of the flammability properties of PLA and PET fibers showed low flammability and less smoke generation than PET[28]. However, the high flammability of PLA is well known, which can result in the production of toxic gases during combustion in vitiated atmospheres [29]. As a result, PLA’s flame-retardant properties have become an issue, limiting the scope of its applications [30]. Although most systems have not yet been commercialized, phosphorus-based PLA formulations have proven to be quite effective at increasing the flame-retardant features of corresponding PLA-based materials [29]. In this regard, intumescent formulations mainly composed of acid and carbon sources was analyzed in the work of Cayla[31]. Lignin from wood waste was selected as the carbon source, and added in different PLA-based preparations, to ammonium polyphosphate (AP) by melt extrusion, and then hot-pressed into sheets. The spinnability, thermal behavior, and flame retardancy of the developed PLA formulations containing lignin and/or ammonium polyphosphate were explored. Results confirmed that not all the formulations were spinnable and endowed with an increase in thermal flame-retardant properties. Depending on the concentration, the presence of ammonium polyphosphate in blends may not only degrade the macromolecular PLA chains, but also change interactions between all of the compounds.

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