Review Article

Poly(Lactic Acid) / Polyester Blends:

Review of Current and Future Applications

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Abstract

Poly (lactic acid) (PLA) is a promising polymer with its value and potential due to its sustainability, low carbon footprint, and being a superior bio-based polymer compared to other bioplastics. Since it is also a compostable aliphatic polyester, has been frequently subjected to research.

Researchers have conducted studies on the compatibility of PLA, which is a bio-based, biodegradable, and compostable, renewable polymer, with traditional petrochemical-based polymers, especially polyesters such as polybutylene terephthalate (PBT), and polyethylene terephthalate (PET). It is highly important that applications of PLA/polyester blends will ensure that the materials developed are not only economically and sustainable but also can meet current and future appropriate needs. PLA-based materials have some disadvantages such as slow biodegradation rate, high cost, and low toughness, and to eliminate mentioned drawbacks generally blends are prepared with petroleum-based polymers.

In this review, information about the perspectives with studies for PLA/polyester blends; approaches to the subject, potential application areas, and contributions for the future were given.

Keywords: *PLA, PLA/Polyester Blends, Bio-based Polymers, Petroleum-based Polymers*

1. Introduction

Biodegradable polymers have recently attracted significant interest as a replacement for conventional petroleum-based thermoplastics regarding their effects on the environment because they can be made from various renewable resources and completely decompose via hydrolysis into carbon dioxide and biomass in a short period [1,2]. Lactic acid (LA) or lactide (the cyclic dimer of lactic acid, as an intermediary) are polymerized to produce poly(lactic acid) or polylactide (PLA), respectively [1-4]. PLA is a thermoplastic aliphatic polyester that is produced from non-fossil renewable natural resources by fermentation of polysaccharides or sugar, such as those extracted from corn, potato, cane molasses, sugar beet, etc. This enables the biological cycle to come full circle with PLA biodegradation as well as the photosynthesis process [1,3-5]. The main uses of PLA have historically been confined to medical applications such as implant devices, tissue scaffolds, internal sutures, and others due to the polymer's high cost, limited availability, and low molecular weight [2-4]. High molecular weight PLA has gained a lot of interest as a potential substitute for synthetic polymers in recent years due to new manufacturing techniques that make it possible to produce it affordably [2-6].

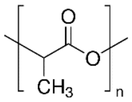
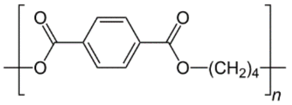
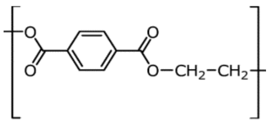
Table 1. List of critical technical keywords for polymer science with their definitions.

Terms	Definition
Biopolymer	Polymers that can degrade naturally. Although polymers are made from biological materials or renewable bioproducts, plastics may or may not be biodegradable.
Bio-based Polymer	The term "bio-based polymer" refers to products that contain at least a fraction of a raw material that is generated sustainably.
Bio-polyester	A microbial polyester known as a bio-polyester is produced by microorganisms from sugar and plant oils, and it degrades naturally in the environment.
Compostability	It is a property of the ability to degrade naturally; any harmful, or noticeable remnants should not leave behind.
Petroleum-Based Polymer	Petroleum-based plastics are synthetic organic polymers made from oil or gas and are widely used in modern civilization in all facets of daily life.
Sustainable Polymer	Materials derived from renewable, recycled, and/or waste carbon sources and their combinations can be recycled, biodegraded, or composted at the end of their life.

This review gathers and summarizes primary data from bioplastics, petroleum-based polymers, PLA blends, and their application areas previously researched, produced, and presented by researchers. Some keywords that are frequently encountered during this study and used while conducting research are used: Bio-based Polymer, Bio-degradable Polymer, Bio-polyester, Compostability, Petroleum-based Polymer, and Sustainable Polymer (Table 1).

The literature reviews are presented in five different sections. The first of these chapters, titled "Bio-based Polymers", describes bio-based plastics, their degradability, environmental effects, and uses. The second section introduces petroleum-based polymers. It gives detailed information about their types and places of use. The third chapter is about what bio-based PLA/polyester blends are. It is explained in how many groups these blends are examined and how there is a distinction. In the fourth chapter and last chapters, the current and future trends of PLA blends, their usage areas, and how they are developing, are evaluated by referring to some published studies. In this review, chemical structures of bio-based PLA and petroleum-based PBT and PET polymers are shown in Table 2.

Table 2. Chemical structures of PLA, PBT, and PET polymers.

Polymers		**Structures of Polymers**
Polylactic Acid (PLA)	$(C_3H_4O_2)_n$	
Polybutylene Terephthalate (PBT)	$(C_{12}H_{12}O_4)_n$	
Polyethylene Terephthalate (PET)	$(C_{10}H_8O_4)_n$	

2. Bio-Based Polymers

Bio-based polymers are materials made from renewable resources. In other words, it is defined as materials whose physical and chemical properties are subject to degradation. They are completely degraded when exposed to microorganisms, carbon dioxide (aerobic) processes, methane (anaerobic processes), and water (aerobic and anaerobic processes). Bio-based polymers make significant contributions by reducing dependency on fossil fuels and, consequently, with positive environmental effects such as reduced carbon dioxide emissions [7].

As a result, there is a worldwide demand to replace petroleum-derived raw materials with renewable resource-based raw materials. They can be natural or synthetic, but due to environmental concerns and the depletion of fossil fuels, intense research is being conducted to develop biodegradable polymers and plastic materials from renewable natural sources such as starch, cellulose, and soy protein. The most important biodegradable polymer derived from renewable resources is polylactic acid. In this review, PLA was selected among the bio-based polymers. The advantages and disadvantages of PLA are shown in Table 3.

Table 3. The most common advantages, and disadvantages of PLA.

Polymer	**Advantages**	**Disadvantages**
Polylactic Acid (PLA)	%100 Biodegradable. Eco-friendly. Bio-compostable. Good mechanical and physical properties. Gloss and transparency are fine. Non-toxic and safe. Antibacterial and anti-fungal properties. Processing ability. Renewable resources. Blended with petroleum-based polymers. Easy to 3D printing applications.	High cost. A lack of toughness. Low heat resistance. Low melting point. A slow rate of deterioration. Impact resistance and hardness are weak. Permeability to moisture and oxygen is high. Not suitable for high-temperature environments. Not suitable for long-term food storage applications.

The biodegradable linear thermoplastic aliphatic polyester known as PLA is made from lactic acid, which is produced during the fermentation of renewable natural resources like corn, sugar cane, and wheat [8-10]. Because of its environmentally favorable, biocompatibility, and biodegradability characteristics, it has been widely employed in the packaging, disposable products, biomedical, pharmaceutical, and textile industries. Because of their great UV protection, low flammability, and low moisture absorption, PLA fibers can be used in outdoor furniture and sports apparel [11-13]. Because PLA has thermoplastic qualities, it may be processed using common techniques to create fiber, film, and sheets, including extrusion, injection molding, film blowing, thermoforming, and film and fiber applications. The lactic acid used to make PLA is (2-hydroxy propionic acid). Chemical synthesis from petrochemicals or bacterial fermentation of carbohydrates is used to treat lactic acid. L- and D-lactic acid are the two stereoisomers of lactic acid, which is a hydroxyl acid with an asymmetric carbon atom. The direct condensation polymerization method is the least expensive approach to polymerize PLA. Lactic acid is used to make PLA. Due to challenges in getting the water out of the process, low molecular weight PLA with undesirable mechanical traits, such as brittleness, might be produced [10,12]. Without the use of adjuvants or other additions like chain extenders, azeotropic dehydrative condensation of lactic acid yields high molecular weight PLA [14]. Without any chemicals, large chain lengths are possible. The most typical process is called ring-opening polymerization. This technique can be used to create PLA with a high molecular weight and more intricate macromolecular architectures. During this polymerization, lactide is also used as a material in between.

3. Petroleum-Based Polymers

Petroleum-based plastics are artificial or organic polymers derived from natural gas or petroleum and used in a variety of applications. The use of petroleum-based plastic materials in various applications, particularly in the medical, industrial, commercial, and municipal sectors, is increasing, but it also creates a significant environmental problem.

Petroleum-based plastics also can be biodegradable, but due to their high stability, they cannot degrade in a short time. Even biodegradable plastics can last for many years, depending on environmental factors such as temperature, oxygen levels, and ultraviolet (UV) light exposure levels. Additionally, stabilizers and plasticizers are used to improve the properties and effectiveness of petroleum-based plastic materials, and they can leach into the environment during the degradation process. In this review article, Polybutylene terephthalate (PBT) and Polyethylene terephthalate (PET) were selected as petroleum-based polymers.

3.1 Polybutylene Terephthalate (PBT)

Polybutylene terephthalate (PBT) is a semicrystalline engineering thermoplastic that is the commercially second-most important polyester. By 2026, the global PBT market is expected to reach 1.5 million metric tons [15]. PBT is a fast-crystallizing polymer, making it ideal for high-cycle-time extrusion and injection-molding applications [16]. Given its excellent properties, PBT is the preferred material when high strength, good dimensional stability, resistance to various chemicals, and good insulation are required as well as when bearing and wear characteristics play a role in material selection. As a result, PBT can be used to make valves, food processing machinery parts, wheels, and gears. PBT has excellent electrical insulating qualities, including good contact and surface resistance, high dielectric strength, and good tracking current resistance, all of which are stable across a broad temperature and humidity range. For the construction of electrical and electronic equipment, PBT is a dependable and superior material [16]. The advantages and disadvantages of petrochemical PBT are shown in Table 4.

Table 4. The most common advantages, and disadvantages of PBT.

Polymer	**Advantages**	**Disadvantages**
Polybutylene Terephthalate (PBT)	High continuous use temperature up to 150 °C. Very good creep resistance even at higher temperatures. High rigidity. Good friction properties and wear resistance. High dimensional and UV stability. Good weather resistance. Resistant to cracking from environmental stress Low water absorption, Dyeability at low temperatures. Moldability, Resistant to solvents.	Notch impact strength is low. The forming shortening rate is large. Poor resistance to hydrolysis. Susceptible to halogenated hydrocarbon corrosion. Tendency to warp when reinforced with glass fiber. Not resistant to stronger acids and bases. Lower glass transition temperature compared to other high-grade plastics. Poor resistance to hydrolysis.

The condensation polymerization method is used to create polybutylene terephthalate (PBT), a crucial semicrystalline commercial thermoplastic, from 1,4-butanediol (BDO), terephthalic acid (TPA), or dimethyl terephthalate (DMT), in the presence of a polyesterification catalyst [16–18]. Tetraalkyl titanates are the catalysts most frequently employed for PBT polymerization [16,17]. The traditional method for polymerizing PBT involves first transesterifying BDO with DMT to produce the diester, bis (4-hydroxy butyl-terephthalate) (BHBT), or ester oligomers with hydroxy butyl ester end groups [17,19]. Due to the flexible butylene groups that make up part of its molecular structure, PBT crystallizes at a relatively rapid rate, and the melting and crystallization characteristics of the substance are affected by its temperature history. The glass transition temperature (T_g) range for fully crystalline PBT homopolymer is 30 to 50 °C, while the typical melting temperature (T_m) is from 222 to 232 °C. By annealing PBT for a long time, the crystallinity of the material allows for a shift in the glass transition temperature and melting temperature to higher values. Furthermore, annealing can increase the crystallinity of PBT to 60% from its typical range of 35 to 40%. Several melting peaks may appear on the DSC curve for PBT because it often contains crystals of various sizes [16,19,20].

PBT exhibits excellent electrical properties, low creep at elevated temperatures, great dimensional stability, low coefficient of friction, outstanding chemical, grease, oil, and solvent resistance, and good tensile strength due to the presence of its crystalline phase [17,19,21-23]. The mechanical properties of PBT are significantly influenced by the crystallinity level. The resin's solvent resistance and mechanical strength are provided by the crystalline PBT regions. It can be said that the elongation characteristics of a material are provided by the amorphous area. PBT's quick crystallization and low melt strength features make processing simple [16,20].

PBT is a viscoelastic polymer, and its melt has a low viscosity and very fast crystallization, allowing for easier processing when compared to PET. Spinning, extrusion, injection molding, and gas-assisted injection molding can all be used to process PBT resins [16,18]. PBT has good electrical insulating properties (contact and surface resistance) as well as high dielectric strength and tracking current resistance that is stable over a wide temperature and humidity range. As a result, PBT is a dependable and superior building material for electrical and electronic equipment. It is used as an insulator in plugboards, contact strips, and plug connections [16]. Polybutylene terephthalate (PBT) is an important commercial polymer with applications in a variety of industries including automotive parts, electrical, electronic, and textile. It has similar thermal, chemical, and mechanical properties to PET, but slightly better impact strength and PBT crystallizes at a faster rate than PET [16,17].

3.2 Polyethylene Terephthalate (PET)

Engineering grades of PETs, which are part of the polyester polymers family and have high-performance mechanical and electrical qualities, are readily available. PET is a semi-aromatic thermoplastic polyester that is widely used in a variety of industrial applications [19,24,25]. For most of these applications PET as an effective packaging material for food and beverage products, also plays important role in textile fibers, automotive components, and biomedical applications [26,27]. This widespread application is due primarily to its superior mechanical properties, high chemical resistance, good barrier properties against oxygen and water vapor, and thermal stability, as well as its low production cost, processability, and recyclability [28-31]. As a result of such widespread PET use, primarily in soft drink containers, global production exceeded 56 million tons in 2016 and is expected to exceed 70 million tons by 2020 [32]. The advantages and disadvantages of PET are shown in Table 5.

PET is produced in two steps: pre-polymerization and melt polycondensation. Pre-polymerization occurs via two reactions: direct esterification of terephthalic acid (TPA) with ethylene glycol (EG) or transesterification of dimethyl terephthalate (DMT) with ethylene glycol (EG) [19].

PET's thermal properties, which in turn rely on the degree and kind of crystallinity, are a key factor in how processable it is. PET has a low crystallization rate because of the short ethylene chain that separates the aromatic rings. PET samples also frequently display multiple melting endotherms, which depend on the wide temperature range in which crystallization occurs and result in crystals of various sizes and perfections [32,33]. Depending on PET processing and thermal history, PET samples may be in an amorphous, semicrystalline, or completely orientated condition [34,35]. PET has a T_g of 67 °C in the amorphous state, and it is possible to produce amorphous, transparent PET by rapidly cooling from the melt to a temperature below T_g.

Table 5. The most common advantages, and disadvantages of PET.

Polymer	**Advantages**	**Disadvantages**
Polyethylene Terephthalate (PET)	Easily available and inexpensive. Highly resistant to moisture and chemically resistant to organic matter and water. High strength-to-weight ratio. High transparent and shatterproof. Easily recycled. Very strong and lightweight. Easy and efficient to transport.	Lower heat resistance. Resins are susceptible to oxidation. Partially derived from crude oils. PET resins are even susceptible to oxidation. Non-biodegradable.

Semi-crystalline PET, which has a T_g of 81°C in the semi-crystalline state, can be created by heating solid amorphous PET over T_g. While PET's fully annealed melting point is 280 °C, its melting temperature ranges from 250 to 265 °C. The final polymer's processability and thermal characteristics are significantly influenced by the degree of crystallinity and shape [34]. The molecular weight of the polymer may have an important bearing on the crystallinity of PET. Low-molecular-weight grades could provide more crystallinity because, in contrast to greater molecular weights, they make it easier for the chain to align. Combinations of crystallinity and molecular weight can have an impact on the final mechanical characteristics [19,23,33,36,37]. It has a range of high tensile strengths and flexural modulus between 55 and 75 MPa and 2412-3102 MPa respectively. It is also nearly impermeable to most of gases and liquids, and its properties could be further enhanced by increasing crystallinity. Moreover, it shows resistance to being dissolved by ordinary solvents. The low melt strength and slow rate of crystallization of PET, which is primarily brought on by the presence of ethylene units in its structure, make processing it is challenging [38,39]. The most widely used PET has a narrow molecular weight distribution, comparatively low molecular weight, and weak melt strength and viscosity by nature. For applications like foaming or extrusion blow molding, these properties are not appropriate. By raising the molecular weight and expanding the molecular weight distribution, it will be feasible to improve the attributes of PET, such as die swell, melt strength, and melt flow index [23,37]. Since diverse applications call for different features, PET can be produced through modification such as chain extension, grafting, branching, blending, controlled cross-linking, or controlled degradation [23].

4. Bio-Based PLA/Polyester Blends

The purest bio-based polymers are typically expensive and underwhelming. But, if the bioplastics, which contain both fossil and renewable carbon, can be synergistically adjusted for creating the blends, higher performance can be reached. Hence, these cannot be used as-is, and it is necessary to achieve a balance between performance and cost while blending the polymers because combining thermodynamics does not help the blending process and is not a simple task. One of the promising approaches for attaining durability is by formulating PLA blends or synthesizing PLA/polyester blends because of the distinctive properties and cost competitiveness of PLA. Hence, work needs to be done to fabricate PLA-based blends. However, preparing a good miscible blend or composite of PLA with other polymers is a challenging task that should not hamper the toughness of the PLA. Also, the environmentally beneficial properties of the synthetic PLA blend must be considered. Hence, choosing the right antecedents is crucial and demands careful consideration when PLA is modified [40,41].

Many petroleum-based plastics, including PBT and PET, can be replaced by PLA compounds over time for a variety of engineering uses. Aside from issues with energy and the environment, this trend is fueled by lower prices for commercial PLAs, initiatives to make up for or circumvent PLA's flaws, and the introduction of PLA-based goods with superior functionality and desirable attributes. But in order to create PLA-based blends with better performance, fewer defects, reduced cost, and desirable multifunctional properties, extensive study is needed [55,56].

There are generally two classes of polymer blends containing PLA; blends with other degradable/renewable resource polymers and blends with non-degradable polymers. In this section, some notable PLA-based blend findings that have been reported are explained. PLA/polyester blends are divided into two parts: PLA/PBT and PLA/PET blends. The schematic representation of PLA/Polyester Blends prepared to understand in more detail is shown in Figure 1.

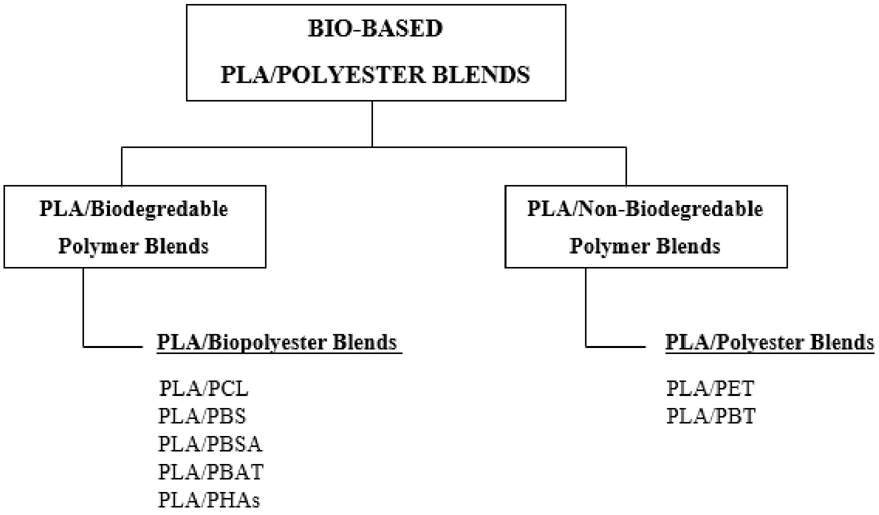


Figure 1. Schematic representation of Bio-Based PLA/Polyester Blends.

4.1. PLA/PBT Blends

Butylene terephthalate, or PBT, a commonly used polyester, crystallizes quickly and has a high melting point for crystals (higher than the PLA melting temperature). Hence, when utilizing PBT spherulites, PLA might function as a crystal-nucleating agent. Although having high compatibility, blends of PLA and PBT are believed to be immiscible due to interactions between their functional groups.

This leads to good phase adhesion and dispersion. Kim et al. examined the crystallization behavior when PLA/PBT was produced using reactive extrusion and para phenylene diisocyanate (PPDI) as a chain extender. PLA crystallized more readily when PBT was present, although PBT had the reverse effect on PLA [42-44]. When PLA, PBT, and PPDI were blended, the PLA crystallization rate was increased while PPDI lowered the crystallinity of the PLA and PBT phases separately. The increased interfacial adhesion between PLA and PBT caused by PPDI slowed down the pace of PLA breakdown. Samthong and colleagues also looked at how PBT droplet size and shape affected the morphology and porosity structure of the biaxially stretched PLA blend films [45,46].

Stretched films containing PBT droplets displayed ellipsoidal microvoids because of the interfacial debonding, and the void size matched that of the PBT droplets. They claimed that the PBT droplet size had no bearing on the void content of the stretched films. Since the dispersed quick crystallizing phase may act as a nucleating agent for PLA, boosting its crystallization kinetics, blends of PLA and highly crystalline polyesters, notably PBT, have also been extensively studied [47,48]. In physical blended phase-separated systems, an extra compatibilizer is required to enhance interfacial adhesion and compatibility between different phases [49]. This is true even though it is simple and affordable to blend two or more polymers to create desired combinations of characteristics. However, it was found from the previous literature study that prolonged two-step polymerization at high reaction temperature results in thermal degradation of poly (L-lactic acid) (PLLA) and production of copolymers with random distribution throughout the copolymer chain. Only the copolymers studied by Olewnik et al. and having an equimolar terephthalate/lactate ratio showed some block copolymer features [50]. Furthermore, copolymers consisting primarily of PBT and PLLA (PLA-b-PBT-b-PLA) with a relatively defined blocky structure were produced by ring-opening polymerizing LA with bis-(4-hydroxyethyl) terephthalate (BHBT) in solution [45]. Even though the final product had an average molecular weight (M_n) of just a few, with a maximum value of 81.1 g/mol, the strategy was successful in encouraging the organization into a blocky structure. The latter method has shown potential for producing polymers with distinctive properties [46,51,52].

The two requirements that must be met to apply this method in the production of copolymers are the immiscibility of the polymer pair and the presence of groups that can react during melt blending [53]. Both conditions have been satisfied in their system. PBT and PLA cannot be combined, and high temperatures in a polyester-polyester blend can cause three separate chemical reactions, including alcoholysis, acidolysis, and ester exchange [47,49]. As a result of these chemical reactions, block or random copolymers are produced. Chain structure can be impacted by several factors, including reaction temperature, catalyst amount, and blending time. In the current work, the morphologies that resulted from the manufacturing of two PBT/PLA systems' physical blends and reactive blends have been compared.

The biodegradable polymer polylactic acid (PLA), which can also be employed in industrial settings, is produced by fermenting renewable materials. PLA's brittleness at room temperature limits its applicability. To overcome this drawback, researchers created PLA blends with PBT (Polybutylene Terephthalate). Hence, it aims to give new raw materials to numerous sectors, including textile, automotive, and electrical products, by creating materials that are biodegradable, ecologically benign, and have improved performance attributes.

In our work, PLA/PBT blends containing 5%, 10%, and 15% PBT by weight were extruded in a twin screw extruder with maleic anhydride grafted ethylene/butyl acrylate (EBA-g-MAH) and glycidyl methyl methacrylate (GMA) as compatibilizers and chain extender. PLA/PBT blends without compatibilizers were also prepared for comparison studies. Melt Flow Index (MFI) and Rotational Rheometer measurements were used to investigate the flow, viscoelastic properties, and rheological properties of the prepared samples. Mechanical and impact resistance properties are determined in accordance with applicable standards. Mold shrinkage, density, and hardness values of the blends were also determined. PBT samples were heated to 240°C for 15 minutes, while PLA samples were heated to 260°C for 15 minutes. Moreover, it was shown that PLA/PBT combinations with 5% PBT had increased mechanical and notched izod impact strengths. Results of the notched izod impact test reveal that adding the compatibilizer PLA/PBT combination increases the impact resistance by 16%. The EBA-g-MAH compatibilizers' interface compatibility is responsible for the blends' noticeable improvement in notched izod impact strength. The EBA-g-MAH adapters' interface compatibility is what led to the blends' notched izod impact strength significantly increasing [55,56].

4.2. PLA/PET Blends

PET is a significant engineering thermoplastic used in commerce that has strong thermal and mechanical characteristics as well as low permeability and chemical resistance. Girija et al. examined the thermal and mechanical properties of blends of PLA and PET [57]. The integration of PET improved the thermal stability of PLA, but PET's impact and tensile strengths and elongation at break were reduced because of the increased stiffness of PLA. Chen et al. have thoroughly investigated the crystallization behavior of PLA/PET blends created using solution casting [58]. The blends of PLA and PET were discovered to be miscible over the whole composition range. As the quantity of either crystalline or amorphous PLAs increased, the PET's crystallinity dropped. The PLA crystallinity, however, was only reduced when the PET crystallized. Moreover, Fu et al. and Huerta et al. validated the miscibility of PLA/PET blends across the board of blend content [59,60]. Despite the results of all this research, Li et al. showed that cold crystallized electrospun PLA/PET (70/30 and 50/50) blends were immiscible and had two unique glass transition temperatures [61]. They verified that during electrospinning, cold crystallization, and blends of 70/30 and 50/50 PET/PLA, phase separation occurred. The crystallization of both PLA and PET was hampered in these immiscible blends. The ability to combine the two polymers is restricted by the considerable gap between the melting temperature of PLA (160–180 °C) and the processing temperature of PET (260–300 °C) [35,66,67]. Torres-Huerta et al. investigated how miscible PET/PLA blends were. Weak interactions in the blends point to electrostatic contact and hydrogen bridges between the constituents [60].

McLauchlin et al. investigated the impact of adding PLA (0.5–20%) to PET [67]. The investigation was done to see how the mechanical and thermal behavior of PLA in recycled PET (rPET) process streams would be affected. The polymers were co-processed in an injection molding machine over a brief (4s) residence time. To improve the compatibility of the two polymers, no additive was utilized in the procedure. The addition of more than 2% of PLA to PET resulted in a significant loss in mechanical strength. The larger and more numerous PLA tiny beads were blamed for the behavior.

Using epoxide compatibilizers, You et al. made PLA/PET blends compatible. As a chain extender and toughening agent, respectively, EBA-GMA and SA-GMA were employed. The epoxy group on EBA-GMA interacted with the carboxylic and hydroxyl groups of PLA [66]. Furthermore, SA-GMA (Joncryl) reduced the rate of PLA thermal degradation in the blend. The epoxide reaction stopped PLA from degrading. Two compatibilizers were added, but it was found that this did not appreciably improve the characteristics. EBA-GMA, on the other hand, produced micelles and had little adherence to the PLA phase. Just SA-GMA was added, and it concurrently served as a chain extender and compatibilizer. The impact strength increased by 292% because of the toughening agent's inclusion, however, the modulus dropped to 25%. Moreover, McLauchlin et al. demonstrated the immiscibility of PLA/PET blends with a maximum of 20 wt.% PLA in injection molding tests [61]. The addition of PLA considerably decreased the impact and tensile strength of the blends. With a maximum PLA content of 7.5 wt.%, partial miscibility of PLA/PET blends was reported using single-screw extrusion [62,63].

Jiang et al. examined blends including PLA-g-MA as a compatibilizer and 20% PET glycol-modified (PETG) and 80% PLA by weight [64]. They also claimed that the blends had an immiscible, droplet-like shape. They demonstrated that the use of 3 wt.% PLA-g-MA greatly decreased the interfacial tension between PLA and PET using rheological data and emulsion models, such as the Palierne model. By maintaining the tensile strength and modulus, the droplet size was decreased, and the size distribution was improved. The addition of PLA (up to wt. 5%) had a detrimental effect on the rheological characteristics of PET made from recycled bottles [63,65].

In our study, PLA/PET blends containing 5%, 10%, and 15% PET by weight, maleic anhydride grafted ethylene/butyl acrylate (EBA-g-MAH), and glycidyl methyl methacrylate (GMA) were used as compatibilizers. The prepared PLA/PBT blends were extruded in a twin screw extruder. Granules of PLA/PET blends made in a twin screw extruder were injected into molds as test samples, and samples for the thesis analysis were created. The rheological, physical, mechanical, and thermal properties of PLA/PET blends made in various ratios were evaluated. These blends were made without a compatibilizer, with a compatibilizer, and without a chain extender. While the izod value of PLA/PET blend containing 15% PET prepared without compatibilizer or chain extender is 2.69 kJ/m^2 increased to 5.49 kJ/m^2 when a chain extender is used. Thus, it is thought that PLA can be used more easily and successfully instead of using PLA alone in applications requiring low viscosity such as PLA/PET blends, injection molding, and 3D printing [55,56].

5. Current Status of PLA/Polyester Blends

Polymers have been employed more and more over the past 100 years to the point that they are now common place and indispensable due to their advantages of being lightweight, affordable, easily processed, and durable. Yet, it is anticipated that by 2050, there will be 850 million tons of plastic trash produced year because of the continued manufacture of plastics made from petroleum and an unprecedented waste management catastrophe [68]. According to estimates, there are already more than 150 million tons of plastic trash floating on the ocean's surface [70]. Because of the use of fossil fuels, this linear economy causes the reckless depletion of natural resources and the release of greenhouse gases. Hence, environmentally friendly, durable, and sustainable products need to be produced without sacrificing performance to achieve a sustainable circular economy. So, it is necessary to engineer products with decreased fossil carbon, which include both conventional and bio-based plastics, to partially reduce reliance on petroleum resources, ameliorate climate change, and minimize the carbon footprint of the materials [70,71].

As the synthesized material will have low fossil carbon and low CO_2 emission and may be recycled or burned for energy production at the end of its life, the durable bio-based product will maintain the materials in use, promoting low carbon and circular economy. As a result, the products should be more durable and suitable for high-performance applications. The addition of renewable carbon to reduce the amount of fossil carbon in products shouldn't adversely influence the products' qualities, performance, or aging. Also, objects made of PLA can be recycled chemically. Chemical recycling is a depolymerization method that makes use of chemicals, typically solvents or acids [71].

As a consequence, efforts are being made to combat the problem of an increased carbon footprint in the atmosphere by substituting even a small portion of conventional (petroleum-based and nonbiodegradable) plastics, such as poly(ethylene terephthalate) (PET), polyethylene (PE), polypropylene (PP), and polystyrene (PS), with bio-based plastics like starch, cellulose, polyhydroxyalkanoates (PHAs), and polylactic acid (PLA) [68,69]. PLA has no material carbon footprint and produces fewer CO_2 emissions when compared to plastics made from fossil fuels. Other processing methods for modified PLA include extrusion, injection molding, casting, thermoforming, compounding, 3D printing, and fiber spinning. Moreover, the bio-based carbon from PLA can be added to long-lasting products. The characteristics of PLA must therefore be improved for a greater variety of high-performance applications.

Researchers have begun designing products to allow for the coexistence of fossil or non-renewable and renewable carbon. Yet, there is still more to be done to make bio-based products durable and with improved qualities for high-performance applications.

Together with the mechanical characteristics, research advancements were addressed and contrasted, particularly regarding thermal, electrical, and electromagnetic radiation shielding, viscoelastic, and creep. Nevertheless, PLA-based blends and composites with synthetic plastics, glass, carbon, natural, and biocarbon fibers have not been covered elsewhere. Furthermore, the impacts of additives, potential uses for durable PLA blends and composites, their major difficulties, and the outlook for the future have not been covered. The focus of this review is to discuss recent research efforts into the development of PLA/polyester-based blends to achieve properties with the potential for durable use, such as engineering plastics .

The focus of this discussion is on PLA-based blends with synthetic, nonbiodegradable additives and at least one non-biodegradable filler (in the case of composites), which demonstrated a notable improvement in thermal and mechanical properties for long-lasting applications. Based on the methods and approaches used to address the materials' constraints, the extensive literature on the subject is carefully arranged. There has been a discussion of the most recent developments in PLA-based blends and composites, as well as the major difficulties in customizing the blends and composites. It is also highlighted how synthetic durable PLA-based goods are used in a variety of industries, including textiles, electronics, housing, and the automobile industry.

5.1. PLA/Polyester Blends for Automotive

Specifically, as interior components and engine-behind gears, PLA finds use in the engineering of automotive sector elements. The product is well known for reducing carbon footprints and offering several advantages, including better impact and UV resistance, high gloss, and dimensional stability. The majority of conventional thermoplastics, such as polycarbonate (PC), poly (ethylene terephthalate) (PET), acrylonitrile butadiene styrene (ABS), poly(butylene terephthalate) (PBT), and polyamide (PA), which are typically used in automotive engine compartments and interiors, can be perfectly replaced by PLA thanks to all the features listed above [73]. Automotive interiors are just one of the many uses for PLA bio-fiber composites, which are used all over the world. The simplest and most environmentally friendly ingredients to increase the mechanical and thermal properties of PLA are fibers or fillers. Plant fiber is extensively used in the Mercedes-Benz E-class. These biopolymers made from fibers are utilized to create a range of vehicle parts, including dashboards, door panels, package trays, headliners, and some interior parts [72]. The use of nanofillers and suitable processing methods seems to offer a way to enhance the performance of PLA composites. In the automobile industry, thermal stability and high moisture absorption behavior are two important restrictions that are solved by graphene-reinforced PLA nanocomposites

[75]. To obtain better characteristics, more PLA composites were reinforced with different fibers.

5.2 PLA/Polyester Blends for Textile

The most promising biodegradable fiber made from renewable resources is PLA, which is being touted as a potential replacement for traditional PET fibers in the textile industry. While some of the qualities of PLA fibers are similar to those of PET fibers, others are different. The gap between synthetic and natural fibers is filled by PLA, which combines environmental benefits with high textile performance. However, unlike PET, PLA is susceptible to thermal deterioration and exhibits low hydrolytic resistance to high alkalis. When making and processing PLA fiber or fabrics, this may have an impact on parameter setting and method choice. Pharmaceutical and medical applications, as well as eco-friendly films and fibers for packaging, apparel, and home goods, are just a few of the many possibilities for PLA fibers [76,77].

5.3 PLA/Polyester Blends for Electronic Devices

PLA is also widely used in the electronic industry due to its distinct properties [40]. Electronic devices and personal electronic products (TVs, smartphones, wires, cables, gaming systems, and portable computing) appear to be the fastest-growing segments of the electronics industry. China is the world's largest producer of electronics, owing to domestic demand as well as the exportation of electronic products to other countries. The use of renewable PLA materials in the manufacture of electronic products can result in energy savings in small electronic applications and energy storage, as well as a reduction in the depletion of limited material resources [78].

5.4 PLA/Polyester Blends for 3D Printing

Polylactic acid (PLA) is the most widely used raw material in many fields as it is biodegradable and environmentally friendly in extrusion-based three-dimensional (3D) printing (molten deposition modeling, FDM approach), but its use is limited due to some of its properties. Disadvantages such as mechanical weakness, water solubility ratio. FDM is a simpler and more cost-effective fabrication process compared to other 3D printing techniques [3,4]. Unfortunately, the FDM approach has shortcomings, such as the mechanical weakness of FDM parts compared to parts produced by traditional injection and compression molding methods. In order to improve the properties of 3D printed PLA parts obtained by FDM method, it is the most useful technique to be prepared with PLA blends with appropriate additives. PLA/polyester blends, which have been newly developed in the last decade, find wide use in both academic and industrial environments [79, 80]. The application of new PLA blends using FDM-based 3D printing technology is increasing in the fields of biomedicine, tissue engineering, human bone repair, antibacterial, conductivity, electromagnetic, sensor, battery, automotive, aerospace, four-dimensional (4D) printing, smart textiles. It is a significant challenge to maintain equal or better mechanical resistance, durability, and comfort than plain textile substrates when using direct deposition of polymeric materials onto textiles via 3D printing. In the study, nonconductive PLA and conductive PLA-carbon composite filaments were 3D printed onto white PET woven fabrics [68,79]. It was discovered that the deposition process affects the tensile properties of the printed textile due to the lower flexibility and diffusion of the printed polymer track through the PET fabric, resulting in a weak adhesion at the polymer/textile interface. Furthermore, the temperature of the printing platform and the fabric properties influenced the tensile and deformation properties of the 3D printed PLA on PET textiles. The addition of conductive fillers to PLA did not affect the tensile properties of the extruded polymeric materials [80]. The same group attempted to optimize the adhesion of 3D printed PLA onto PET-woven fabrics using textile properties in another study [80]. Thermal conductivity, surface roughness, and mean pore size of uncoated PET-woven fabrics were measured using "hot disk," profilometer, and capillary flow porosimetry methods. The same properties were discovered following the 3D printing process. The higher roughness coefficient, mean pore size, and lower thermal conductivity of the PET-woven textiles were found to improve polymer/fabric adhesion properties. However, after washing, the adhesion strength was reduced by half. The rougher and more porous textile structures outlasted the others. The surface topography properties of the PET fabrics, which determined the results, explained these findings [73,79,80].

The use of biocompatible and biodegradable biomaterials is now seen to play an active role in every field of technology. Biodegradable PLA is a type of polymer that is starting to replace some traditional plastics. PLA/polyester blends can be formed with petroleum-derived polymers such as PBT, PET, and the performance properties of PLA can be increased. Using eco-friendly components to replace PLA is an eco-friendly method and can also be used to lower the cost of PLA products if a low-cost blend is used. Due to the differences in the properties of the PLA itself and the blended material, the qualities of the blend-modified PLA/polyester blends often increase significantly and can be used in a variety of applications [42,43,44].

As a result, when the application areas of PLA are examined, it is seen that the use of biocompatible and biodegradable biomaterials now plays an active role in all areas of technology. Due to the differences in the properties of the PLA itself and the blended material, the qualities of PLA blends modified by blending often increase significantly, and PLA/polyester blends can be used in a variety of applications.

The application areas for PET, PBT, and PLA polymers are presented in Table 6.

Table 6. The application areas for PLA, PBT, and PET polymers.

Polymer	**Applications**
Polylactic Acid (PLA)	It is used in architectural scale models that appeal to the eye because it has a brighter appearance. It is used as a medical implant in the form of screws, plates, pins, rods, and mesh, as it turns into harmless lactic acid in the body over time. It is suitable for producing sachets, compost bags, food packaging, and disposable tableware. Due to its biocompatibility and biodegradability, PLA is used as a polymeric scaffold for drug delivery purposes.
Polybutylene Terephthalate (PBT)	It is used in electrical and electronic parts. For example, connectors, sockets, coils, low voltage switch assemblies, lamp fixations, automotive ignition system parts, electrical system components, eensors. They are most commonly used in body exterior and safety applications, including automotive airbag covers and containers, brake and fuel line clips, cable liners and power distribution boxes. It has been used in electrical electronics applications, connectors, switches, and heavy-duty enclosures as well as telephone line junction enclosures.
Polyethylene Terephthalate (PET)	Used for refillable water bottles. Its high mechanical strength makes it ideal for use in tape applications. Its chemical inertness along with other physical properties make it particularly suitable for food packaging applications. Packaging applications include rigid cosmetic jars, microwaveable containers, clear films, etc. takes place. PET monofilament is mainly used in knitting fabric production, for example; used in greenhouses in agricultural applications.

6. Prospects for the Future of PLA/Polyester Blends

The creation of long-lasting biopolymer blends and composites is significantly influenced by the presence of bio-based components. The use of renewable resources and sustainable sourcing is becoming increasingly common in many important industries and company activities. To establish a good balance between product performance and environmental friendliness, green chemistry, sustainability, and engineering principles are being incorporated into R&D. In-depth study has been put into creating PLA blends and bio-composites with suitable shape and crystallinity for long-lasting applications. Yet, developing practical and affordable manufacturing procedures for the mass manufacture of such materials has proven to be rather difficult. It has been suggested that improving matrix crystallization is a successful method for producing PLA blends that are heat resistant. While preserving or improving the toughening efficiency, thermal annealing and nucleating agent induced matrix crystallization might both greatly improve the blends' heat resistance. However, an increase in matrix crystallinity alone cannot ensure an improvement in toughness since the plastic deformation of the PLA matrix requires a proper shape. The most crucial determining parameters for toughening PLA are discovered to be optimal elastomer content, particle size, and interparticle distance.

The economic potential of PLA to build a sustainable environment is now being explored by researchers and polymer materials engineers, however, there are still numerous obstacles and drawbacks to be overcome. PLA must overcome technical and economic obstacles if it is to compete shortly with polymers made from petroleum. Due to the difficult process of getting lactic acid and the polymerization procedure used to create PLA, PLA is now quite expensive on the market. The last ten years have seen the development of a biodegradable impact modifier due to limited toughness (also known as impact strength). Another difficulty is being able to recognize and apply process additives, such as compatibilizers and plasticizers, in a way that is consistent with the idea of sustainable materials, especially PLA blends made from renewable resources. Natural fibers must, nevertheless, adhere to several performance standards, including predicted degradability (as necessary to biodegrade and not before). Other significant obstacles to overcome include brittleness, flame retardancy, and resistance to moisture absorption. The future quest to build the material of the future should be held by the development of PLA/polyester blends. Yet, due to the dearth of practical applications, PLA blends' adoption has been rather gradual. Notwithstanding the setback, the features of these PLA blends thus far demonstrate that the promise of a dream material for the 21st century can be realized. Consequently, more investigation is needed to fully comprehend the interactions and mechanisms involved in the PLA blends system's formulation, structure, property connection, and hardening.

To create bio-based durable products with sustainability, a small carbon footprint, and cost competitiveness, PLA is proving its value and promise above alternative bioplastics. Future developments are necessary to prove that the created materials will not only be economically sustainable but will also be obtained, produced, used, and recycled in a way that will meet the demands of both the present and future generations. Material scientists have used a variety of techniques to create PLA-based blends and composites that are durable when combined with the right additives. The viewpoint on the topic and the studies that were done have given knowledge on the techniques, strategies, and comprehension of the topic. For applications that need durability, it is necessary to regulate the interdependence between the crystallinity, molecular weight, and mechanical properties of PLA. Since toughness is typically attained at the expense of stiffness and strength, a novel technique must be created to concurrently improve both unique qualities, namely, strength and toughness. Impact modifiers, nucleating agents, and compatibilizers are crucial in decreasing the technological hurdle to achieving durable PLA for intended applications, according to research on improving PLA durability. Super mechanical characteristics, which lead to lasting PLA, require improved interfacial adhesion between components. The phase structure and interface adhesion are the two innate variables that have an impact on the tensile strength of blends. A wide range of high-performance applications in the automotive, biomedical, electrical appliance, textile, and housing industries are now possible thanks to robust PLA-based composites. The solution to the problems with adapting PLA for different commercial purposes is the development of durable PLA blends. The market has a huge potential for growth for bioplastics made from PLA that can be used for long-lasting applications. So, it is necessary to investigate simple yet highly effective strategies to achieve circularity and sustainability.

As a result, awareness and interest in the sustainable use of available resources is increasing due to its global importance. Polylactic acid (PLA) is a biopolymer, and the increasing trend in the number of publications on PLA staining over the last decade indicates increasing interest in this research area. The increasing popularity of PLA can not only be attributed to its eco-friendly nature but also to its other desirable physical, mechanical and functional characteristics.Given the limited worldwide production and higher prices, PLA is very less likely to grab a notable share out of the conventional polyester fiber market in the foreseeable future. However, it will surely continue to enjoy its place in the niche market because of its ecological and functional advantages over the conventional polyester. Considering the limited production and higher prices around the world, PLA's PLA/polyester blends will certainly continue to take its place in the niche market in the industrial market due to its ecological and functional advantages over conventional polyester in the foreseeable future.

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