Polylactic Acid (PLA)

Applications

Anju Paul, K. Sreedevi, Sreekala S. Sharma, and V. N. Anjana

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Abstract

Polylactic acid (PLA) is an excellent biopolymer that can be synthesized from renewable resources. It is a thermoplastic polyester generated from starch, rice, and corn. The features of PLA such as renewable origin, easiness in composite formation, simplicity in processing, and recyclability make it an exceptional polymer in many commercial applications. Its biodegradability, biocompatibility, and bioabsorbability extend its interest in biomedicine. These properties also make PLA stand out as a good choice when environmental pollution is concerned. These features assist the material in substituting conventional polymers in many fields of applications. The mechanical, thermal, and rheological

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A. Paul (✉) · K. Sreedevi · S. S. Sharma · V. N. Anjana
Department of Chemistry, Sree Sankara Vidyapeetom College, Valayanchirangara, Kerala, India

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properties of PLA create contributions to medical, food packaging, textile, and many other industries. Blending PLA with other biopolymers results in value-added composites that have features better than neat PLA. The chapter focuses on various properties of PLA and the latest developments in its applications in different fields.

Keywords

Polylactic acid · Biopolymers · Renewable resources · Biomedical applications · Green packaging · Textile applications · Automotive applications

Introduction

Traditional fossil-based plastics like polyvinyl chloride, polyethylene terephthalate, and polyethylene which have become an ubiquitous part of our daily lives are nonbiodegradable and persist in the environment for a long period of time, adding to the exponentially increasing carbon footprint (Agrawal 2010; Malinconico et al. 2018; Zheng and Suh 2019). The increasing demand for energy and decline of petroleum-based resources has forced researchers to look for bio-based, greener, sustainable, and more economic alternatives. Bio-based polymers are the front-runners in replacing petroleum-based ones which are marred by their severe economic, health, and environmental impacts (Chen and Yan 2020; Pellis et al. 2021; Sousa and Silvestre 2022).

Biopolymers are derived from natural resources. They are either biosynthesized entirely by living organisms or chemically synthesized from biological materials. A majority of the biopolymers can be degraded into nontoxic small molecules like water and carbon dioxide with the aid of microorganisms, making them an environment-friendly material (Aaliya et al. 2021; Baranwal et al. 2022; MacGregor 2003). Currently, bioplastics represent only a small-scale market compared with conventional plastics. However, the global market for bio-based polymers is expected to undergo significant growth in the coming years as a result of the increasing demand for greener materials and stringent regulatory policies on the use of nondegradable synthetic polymers (Masutani and Kimura 2017; Rodríguez et al. 2020; Song et al. 2018).

Among the biopolymers, PLA is touted to be the most promising and economically viable polymer and has received extensive attention from researchers in the past few decades. Attractive properties including biodegradability, biocompatibility, nontoxicity, thermoplasticity, high strength, high modulus, and good processability has made this polymer an ideal candidate in many areas of applications like biomedical devices, food packaging, disposable household items, and agricultural films (Ahmed and Varshney 2011; Lasprilla et al. 2012; Jandas et al. 2013a; Calcagnile et al. 2019; Liu et al. 2020a; Knoch et al. 2020; Boey et al. 2021). Innovations and developments in processing techniques of high molecular weight polymers have led to the large-scale industrial production of PLA, which has brought down its cost to a great extent (Kühnert et al. 2018). An abundance of literature is available on the synthesis, properties, and applications of PLA. This chapter aims to present these results in a concise manner, with main focus on the applications of PLA in diverse fields.

Synthesis of Polylactic Acid

Poly(lactic acid) or polylactide (PLA) is a linear aliphatic thermoplastic polyester of lactic acid, which can be easily obtained by fermentation of renewable carbohydrate resources. Glucose, sucrose, lactose, maltose, and starch are the commonly utilized carbohydrates in lactic acid fermentation and are produced from feedstocks such as beet sugar, molasses, whey, and barley malt. Microbial fermentation is a frequently employed approach for the preparation of lactic acid. Fermentation temperatures vary, depending on the microorganisms utilized, but are normally between 30 and 60 °C with a pH of 5.0–6.5 (Masutani and Kimura 2018; Montané et al. 2020; Pretula et al. 2016).

The monomer, lactic acid, exists in two optically active configurations, D-lactic acid and L-lactic acid. Hence, PLA has several configurational isomers in which the D- and L-lactic acid units are present in different ratios and different sequences. Poly(L-lactic acid) (PLLA) and poly(D-lactic acid) (PDLA) are enantiomeric polymers that solely include L- and D-units, respectively, whereas poly(DL-lactic acid) (PDLLA) is a racemic polymer that contains a random sequence of both enantiomeric units (Fig. 1). Different grades of PLA with a wide range of properties can be prepared by varying the ratio of the D- and L-isomers (Avérous 2008; Chan et al. 2018; Dorgan et al. 2000; Gupta et al. 2007; Rivero et al. 2017).

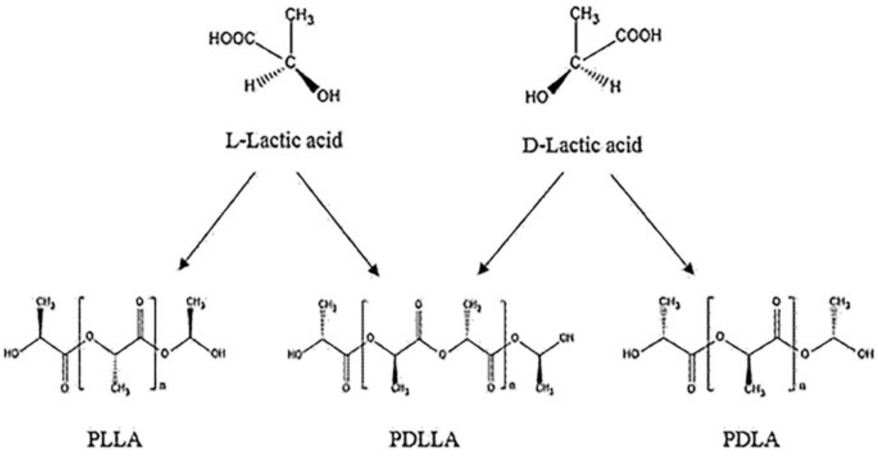

Fig. 1 Stereoisomeric forms of lactic acid and poly(lactic acid) – poly(L-lactic acid) (PLLA), poly(D-, L-lactic acid) (PDLLA), and poly(D-lactic acid) (PDLA). (Reproduced from Rivero et al. 2017. Copyright © 2017 with permission from Elsevier)

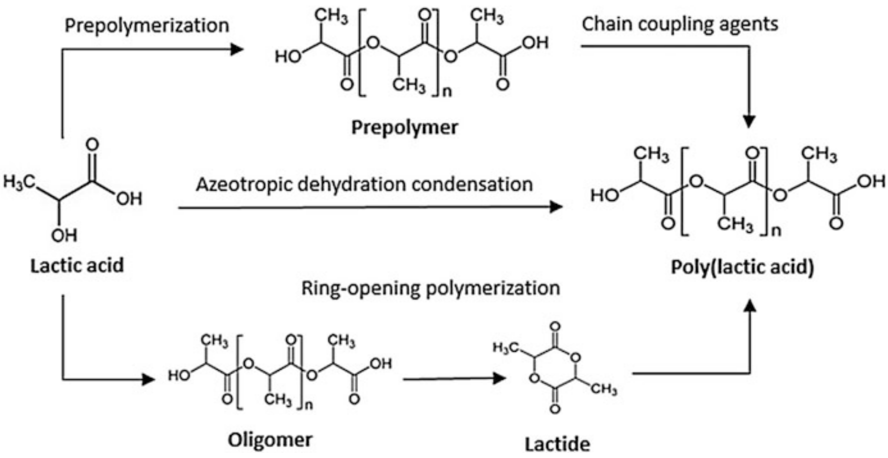

Fig. 2 Synthesis of poly(lactic acid). (Reproduced from Rivero et al. 2017. Copyright © 2017 with permission from Elsevier)

PLA was first synthesized by Theophile-Jules Pelouze in 1845 by condensation of lactic acid (Blukis 1992). Later, Wallace Hume Carothers et al. devised a technique for polymerizing lactide to generate PLA in 1932, which DuPont patented in 1954 (Carothers et al. 1932; Lunt 1998). PLA is currently approved for use in food and medical applications by the US Food and Drug Administration (FDA) and European regulatory authorities (Li et al. 2020; Singhvi et al. 2019).

PLAs can be synthesized by three different routes, viz., direct condensation polymerization, azeotropic dehydration condensation, and ring-opening polymerization (ROP) of lactide, as shown in Fig. 2 (Li et al. 2020; Masutani and Kimura 2018; Rivero et al. 2017).

Direct polycondensation of lactic acid is a two-step process in which first lactic acid undergoes self-esterification through a reversible step-growth mechanism to form low molecular weight oligomers (or prepolymers), which in a second step will form higher molecular weight polymers with the aid of chain-coupling agents (Balla et al. 2021; Masutani and Kimura 2014). Both these steps are reversible and require the removal of water, which is formed as a side-product, to shift the chemical equilibrium in the forward direction. The water removal which is a crucial step in this reaction becomes difficult with increase in the molecular weight and hence viscosity of the polymer. Hence, this method is more suitable for the preparation of low molecular weight PLA (Montané et al. 2020; Ren 2011; Södergård and Stolt 2010).

Azeotropic dehydration condensation is a modification of the direct polycondensation method wherein an azeotropic solution is used to increase the efficiency of water removal. This method was patented by Mitsui Toatsu Chemicals in 1994. In this method an organic solvent with a high boiling point is used as the azeotropic solvent which forces the removal of water and shifts the equilibrium in the direction of esterification. This is a single step process in which the equilibrium between the monomer and polymer can be tuned by choosing appropriate organic solvent. PLA with comparatively high molecular weight can be synthesized by this method. The solvent selected in this method plays a key role in the polymerization conditions and properties of the final PLA product (Montané et al. 2020; Sabu et al. 2014; Södergård and Stolt 2010).

Ring-opening polymerization of cyclic lactide diesters is the most popular method used for the preparation of high molecular weight PLA on an industrial scale. As mentioned before this method was first reported in 1932 by W. H. Carothers. In this technique lactic acid is converted into low molecular weight prepolymer by condensation reaction, which in turn is converted into its cyclic dimer or lactide by controlled de-polymerization. The lactide after purification is allowed to undergo ring-opening polymerization to yield PLA with controlled molecular weight (Carothers et al. 1932; Montané et al. 2020; Södergård and Stolt 2010; Thongchul 2013). Different catalysts based on Al, Zn, Sn, Mg, Ca, Fe, Ti, Sm, Y, Lu, and Zr have been used for ring-opening polymerization, of which stannous octoate is the most extensively studied one because of its high catalytic efficiency (Ghalia and Dahman 2017; Jiménez et al. 2014; Stefaniak and Masek 2021; Toshikj et al. 2020). Ring-opening polymerization of the lactide can take place through three different mechanisms: cationic, anionic, and coordination insertion mechanism. The type of mechanism followed depends on the catalyst used (Masutani and Kimura 2014; Mehta et al. 2005; Stefaniak and Masek 2021). Complete discussion on the different ring-opening polymerization mechanisms is beyond the scope of this chapter and can be found in various reviews and books dedicated to synthesis of PLA (Masutani and Kimura 2018; Mehta et al. 2005; Södergård and Stolt 2010; Yao and Yang 2009).

Properties of Polylactic Acids

Thermal Properties

The degree of crystallinity determines many of the properties of PLA (Gaweł and Kuciel 2020; Jiménez et al. 2014). PLA is a semicrystalline polymer with a glass transition temperature (T_g) of around 50 °C–80 °C and a melting temperature (Tm) of about 130 °C–180 °C (Ren 2011; Vouyiouka and Papaspyrides 2012). Different structural characteristics, such as molecular weights and composition (percentage of stereoisomers), could influence PLA's thermal performance (J Ahmed et al. 2009; Hamad et al. 2015). The impact of molecular weights and composition (L/D ratio) on the thermal characteristics of PLA polymers was studied by Dorgan et al. (Dorgan et al. 2000). They showed that the T_g value of PLAs varied with the number average molecular weight according to the Flory-Fox equation:

$$T_g = T^{\infty} - \frac{K}{M} \qquad (1)$$

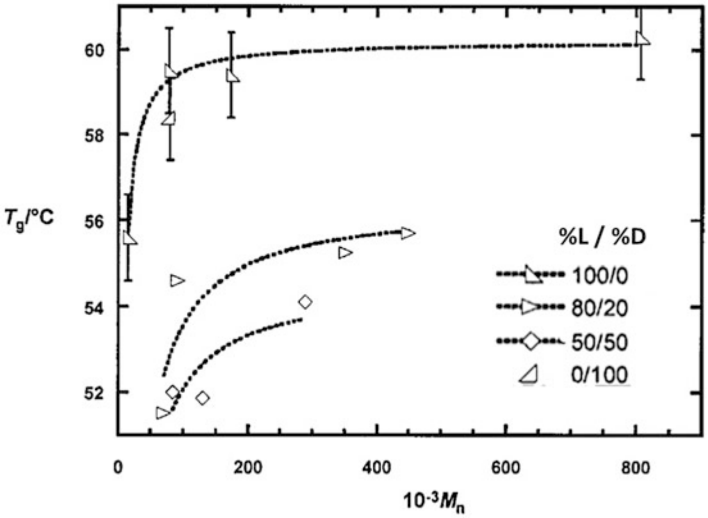

Fig. 3 Glass transition temperature of PLAs with different L/D ratios as a function of number-average molecular weights (M_n). (Reproduced from Dorgan et al. 1999. Copyright © 2005 with permission from AIP Publishing)

where T^{∞} is the glass transition temperature at infinite molecular weight, M is the molecular weight, and K is a constant and is related to the free volume of the end groups for the polymer chains. Figure 3 shows the variation of glass transition temperature with change in composition and number-average molecular weight of PLA.

Several studies have shown that the crystallinity of PLA is determined by its optical purity. Differential scanning calorimetry is the most common method used for determining the crystallinity of PLA. The equation used for calculating the crystallinity C[%] of the polymer is given below:

$$C[\%] = \frac{\Delta H_m}{\Delta H_m^0} \tag{2}$$

where ΔH_m is the enthalpy of fusion of the studied sample and ΔH_m^0 is the enthalpy for 100% crystalline PLA samples, assuming that no cold crystallization takes place during the heating run. Otherwise, the cold-crystallization enthalpy should be subtracted from the melting enthalpy (Müller et al. 2015). Depending on the molecular weight and amount of L-, D-, or meso-lactide in the main chain, the polylactides can be either amorphous or semicrystalline at room temperature. PLA resins with a higher concentration of D-lactic acid show a lower tendency to crystallize (Hamad et al. 2015). Figure 4 DSC curves PLA films with different D-lactide contents. PLA film with 1.4% D-lactic acid exhibited the lowest cold crystallization temperature at 104.1 °C with a sharp and narrow exothermic peak. The films showed a lower tendency to crystallize on increasing the D-lactic acid

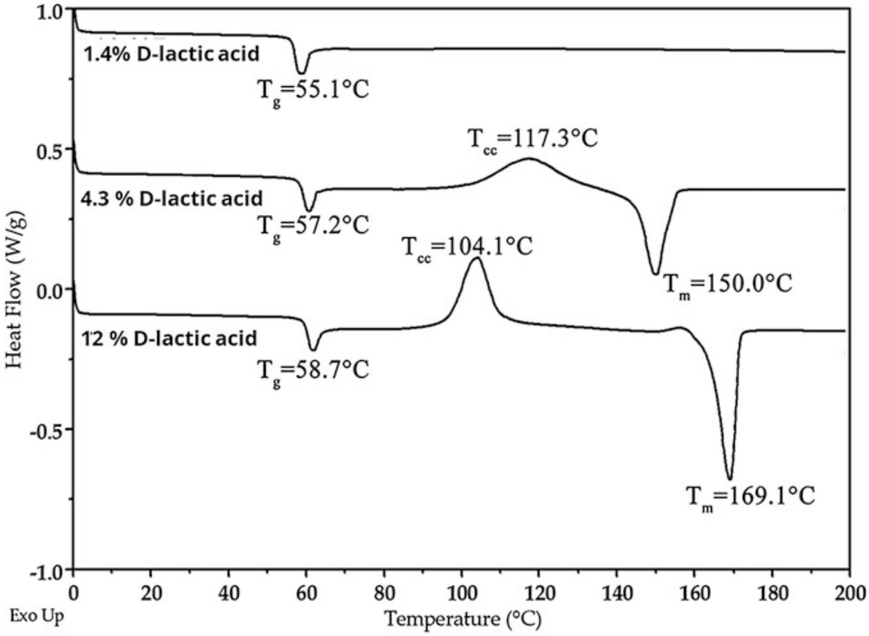

Fig. 4 DSC curves of the PLA films with different D-lactic acid contents. (Reproduced from Pölöskei et al. 2020)

content to 4.3% which is represented by a wide cold crystallization exothermic peak at 117.3 °C. PLA films with the highest D-lactic acid content (12%) did not show any tendency to crystallize (Pölöskei et al. 2020).

High molecular weight, on the other hand, can reduce the crystallization rate and thus the degree of crystallinity (Casalini et al. 2019; Jiménez et al. 2014; Müller et al. 2015). A decrease in percentage of L-lactic acid and increase in percentage of the D-isomer are observed to decrease the crystallinity of the polymer. The relationship between the T^{∞} and the concentration of D-lactide (X_D) can be given by the following equation (Saeidlou et al. 2012):

$$T^{\infty} = \frac{13.36 + 1371.68\,X_D}{0.22 + 24.3X_D + 0.42X_D^2} \tag{3}$$

Rheological Properties

The rheological properties of PLA and its blends and composites have been investigated extensively by different characterization techniques (Fang and Hanna 1999; Hamad et al. 2010, 2011, 2012; Huneault and Li 2007). Dorgan and co-workers investigated Schulz-Blaschke and Mark-Houwink constants for dilute PLA with 0–20% D-lactic acid and different chain lengths in solvents like chloroform, tetrahydrofuran, and a mixture of acetonitrile and dichloromethane. Their findings showed that the relative percentage of the optical co-monomers in the PLA chain did not impact the fundamental rheological parameters. The viscosity of branched PLA was higher than that of linear PLA in the Newtonian range, which implies that PLA behaves as a linear polymer with random coil conformation in the tested solvents (Dorgan et al. 2000). Chile et al. studied PLA with controlled stereochemical configuration and concluded that only the isotactic chain of PLA developed higher viscosity than the other types of configurations (Chile et al. 2016). Kim et al. revealed that branched and starlike structures decreased the intrinsic viscosity of PLA compared with the linear polymer chain of equivalent molecular weight (Kim et al. 2004). The dependence of hydrodynamic radius on molecular weights in solvents like tetrahydrofuran has been investigated extensively by various authors. The values obtained were characteristic for random coil polymers in good solvent (Othman et al. 2011, 2012).

To understand the processability and flow during melt processes, study of the viscoelastic behavior as a function of temperature is useful. Due to the low thermal stability of PLA during rheological measurements, PLA often fails to comply with the time-temperature superposition principle. Palade et al. developed a method, now often employed, using tris(nonyl phenyl)phosphite (TNPP) as a stabilizer to suppress thermal hydrolysis of PLA. PLA exhibited Newtonian behavior at the low shear rates ($<10\ s^{-1}$), whereas it exhibited shear thinning at the high shear rates ($>10\ s^{-1}$) (Palade et al. 2001). Numerous studies have described the rheological behavior of PLA and indicated that PLA obeyed the power law over a certain range of shear rates and temperatures in the same way as other polymers. The tacticity of the macromolecules had some impact on the melt rheology, where isotactic PLA had a higher zero-shear viscosity and syndiotactic PLA had a lower zero shear viscosity than heterotactic PLA (Hamad et al. 2014; Saeidlou et al. 2012; Shin et al. 2010; Wang et al. 2011). The increase in melt viscosity can be achieved by stereocomplex technology. The connection between stereocomplexed domains could be varied from chain entanglement to direct molecular bridging by changing the content of stereocomplex (from 10 to 23%) (Ma et al. 2015).

Mechanical Properties

PLA has better mechanical properties, especially tensile elastic modulus and tensile and flexural strength, in comparison with conventional polymers like polystyrene or polyethylene. However, they have a low elongation at break and impact strength which limits their applications in areas requiring deformation at a higher stress (Farah et al. 2016; Hamad et al. 2015; Sanivada et al. 2020).

Mechanical properties of PLAs can be improved by plasticization, copolymerization, or blending with other biodegradable polymers (Cheng et al. 2009; Liu and Zhang 2011; Zou et al. 2021). It has been observed that the mechanical properties of PLA are to a great extend dependent on their molecular weight, stereochemistry, and crystallinity. Semicrystalline PLAs are shown to exhibit better mechanical properties in comparison with their amorphous counterparts. Semicrystalline PLA has a tensile strength of ~50–70 MPa, a tensile modulus of 3–4 GPa, a 2–10% elongation at break, a flexural strength of 90–100 MPa, and a flexural modulus of 4–5 GPa (Farah et al. 2016; Ilyas et al. 2022; Perego and Cella 2010). Many researchers have looked into the relationship between PLA mechanical characteristics and its molecular weight. A 20% increase in tensile strength was observed by Engelberg and Kohn on increasing the Mw of the polymer from 107 to 550 Kg/mol (Engelberg and Kohn 1991). The variation in mechanical properties relative to molecular weight becomes less pronounced at higher molecular weight. PDLLA and amorphous PLLA exhibited different tensile and flexural properties in a selected range of molecular weights, which can be attributed to the stereochemical makeup of the polymer backbone. Hence, by manipulating the molecular weight, stereochemistry, and crystallinity of PLA, one can tune the mechanical properties of PLAs from soft elastic materials to stiff, high-strength materials (Farah et al. 2016; Hamad et al. 2015; Perego and Cella 2010).

Biodegradation

Degradation of polymers generally occurs by scission of their main or side chains. This can be induced by hydrolysis, enzyme action, photolysis, oxidation, or thermal activation (Madhavan Nampoothiri et al. 2010; Zaaba and Jaafar 2020). Polymers containing hydrolytically unstable linkages like esters, anhydrides, or amides will undergo biodegradation (Saad and Suter 2001). PLAs contain ester linkages in their backbone and can undergo biodegradation. PLA biodegradation occurs in two stages: first hydrolysis of the ester bonds and then enzymatic breakdown of lower molecular weight fragments (lactic acid or water and carbon dioxide). The rate of hydrolytic breakdown is mostly determined by temperature, pH, and humidity (Rudnik 2013; Siakeng et al. 2019; da Silva et al. 2018; Tokiwa and Calabia 2006). Degradation of PLAs under natural conditions has not been successful. Soil burial tests of PLLA showed that they were not degraded even after three years (Calabia et al. 2010). A study by Tsuji and co-workers showed that blended films of PLLA and poly (e-caprolactone) had better biodegradability than the neat polymer itself (Tsuji et al. 1998). Several investigations have shown that biodegradability of PLAs can be improved by mixing them with natural materials like cellulose and starch (Cheung et al. 2010; Kalita et al. 2021; Wan Ishak et al. 2020; Yu et al. 2020). Brdlik et al. demonstrated the improvement in biodegradability of PLA on incorporating natural-based plasticizers like acetyl tributyl citrate (ATBC), $CaCO_3$, and lignin-coated cellulose nanocrystals (L-CNC) into the polymer. Figure 5 shows SEM images of the surfaces of neat PLA film and PLA films with different additives after processing and after three months of biodegradation (Brdlík et al. 2021). The surface of the neat PLA films was relatively smooth, with a small number of cavities. PLA films with plasticizer, on the other hand, had a rough surface with many eroded pinholes which is an indication of higher biodegradation rates of these films compared to a pure PLA film.

The slow degradation rate of PLA under natural conditions is due to the low population of microorganisms capable of degrading PLA in the environment

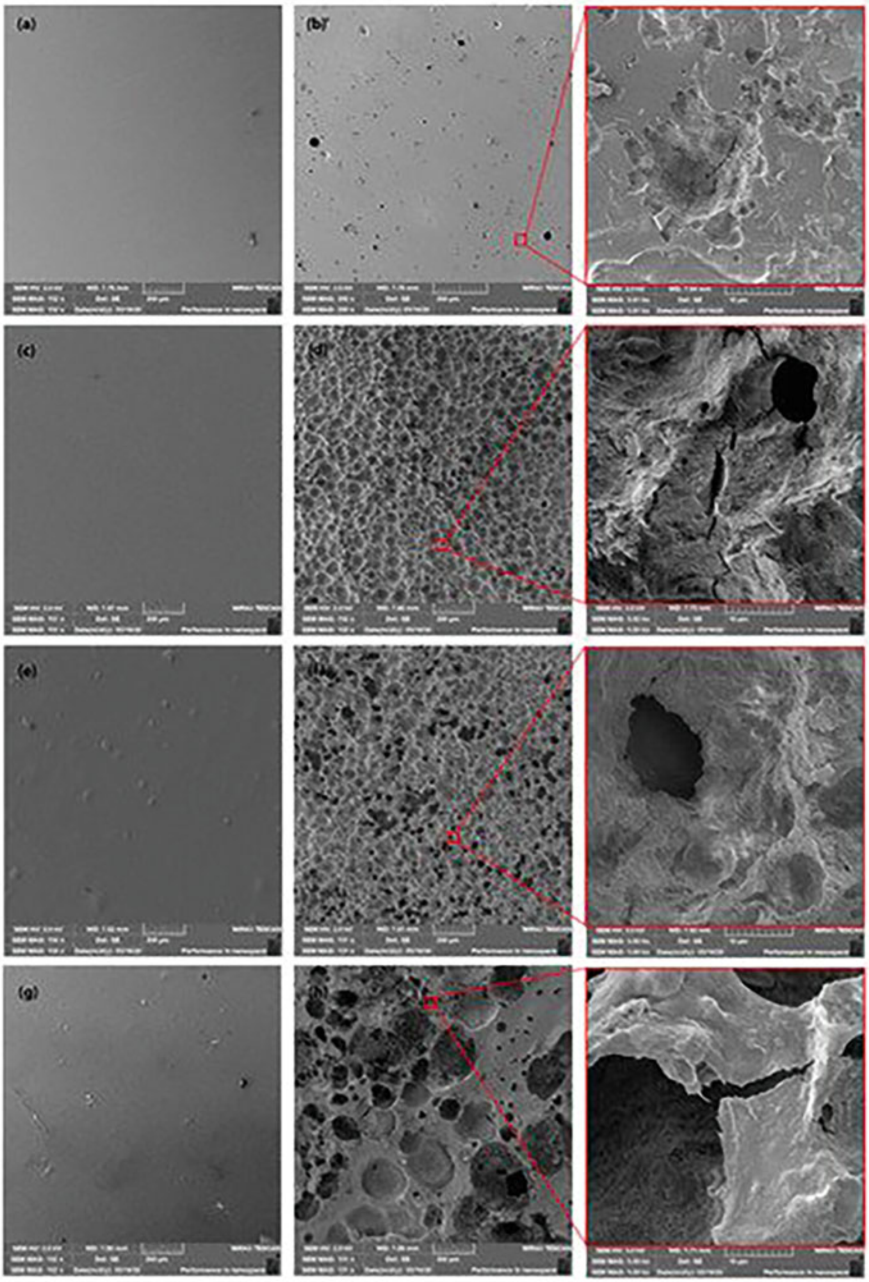

Fig. 5 SEM images of (**a**) neat PLA film after processing, (**b**) neat PLA film after biodegradation, (**c**) PLA/ATBC film after processing, (**d**) PLA/ATBC film after biodegradation, (**e**) PLA/ATBC/L-CNC film after processing, (**f**) PLA/ATBC/L-CNC film after biodegradation, (**g**) PLA/ATBC/$CaCO_3$ film after processing, and (**h**) PLA/ATBC/$CaCO_3$ film after biodegradation. (Reproduced from Brdlík et al. 2021)

(Tokiwa and Calabia 2006). Nevertheless, degradation of PLAs can be achieved by different microorganisms under controlled conditions. PLAs degrade within a period of a few weeks to months in a compost, where the temperature and humidity are high (Calabia et al. 2010; Ho et al. 1999; Satti et al. 2018). *Amycolatopsis*, *Lentzea*, *Kibdelosporangium*, and *Saccharothrix* are some of the microorganisms which are capable of degrading PLAs (Jarerat et al. 2002; Sukkhum 2011). Several enzymes, including pronase, esterases, and bromelain, have been used to study their effect on PLLA degradation rate. Among these, proteinase K which is isolated from *T. album* Limber has been shown to significantly accelerate the degradation rate of PLLA (Lee et al. 2014; Sukkhum 2011; Tokiwa et al. 2009; Williams 1981). Degradation studies of PLA are of particular interest due to their applicability in the medical field to make drug delivery vehicles, implants, or surgical sutures (Baranwal et al. 2022; Calabia et al. 2010; Saad and Suter 2001).

Applications of PLA

PLA is called the "polymer of the twenty-first century" owing to its multifunctional properties. As discussed in the previous sections of this chapter, PLA is a bio-based polymer derived from renewable resources like corn, sugar cane, rice, wheat, and other starch-rich products. The FDA has approved PLA for direct contact with biological fluids. PLA on degradation gives lactic acid which is naturally present in our body and hence is compatible. Biocompatibility and bioresorbability are two qualities of PLAs which have made them popular in the healthcare sector to make active packaging materials, tissue engineering scaffolds, drug delivery vehicles, medical implants, and medical instruments. PLA is also in demand in other industrial sectors like automotive, textile, and agriculture due to its relatively low production cost and commercial availability compared to other biopolymers. PLAs can be used to prepare breathable, lightweight, recyclable fabrics. Moreover, PLA fibers have good UV resistance, inherent biological resistance, and good anti-flame property. It is the only bio-based biodegradable polymer which can be melt-spun into strong textile fibers on a large scale (Yang et al. 2020). They also have gained interest in the packaging industry to make compostable eco-friendly packaging materials. PLA exists in a glassy state at room temperature which prevents the movement of large molecules through the polymer matrix. Hence, PLA materials are excellent barriers to aroma, flavor, or other large molecules. Thus, PLA packaging can protect the product inside from extrinsic elements like moisture, unwanted odors, and other contaminants. It also prevents the odor or flavor molecules of the product to escape the package, thereby keeping the product fresh (Whiteman et al. 2001). PLA-based products have several advantages such as good thermomechanical properties, durability, corrosion resistance, lightweight, ease of processability using existing techniques (injection molding, extrusion), and relatively low cost. As a result, PLA plastics are becoming more appealing for long-lasting applications such as electrical, electronic, and automotive products, as well as mechanical components that require high-performance materials with low environmental impact.

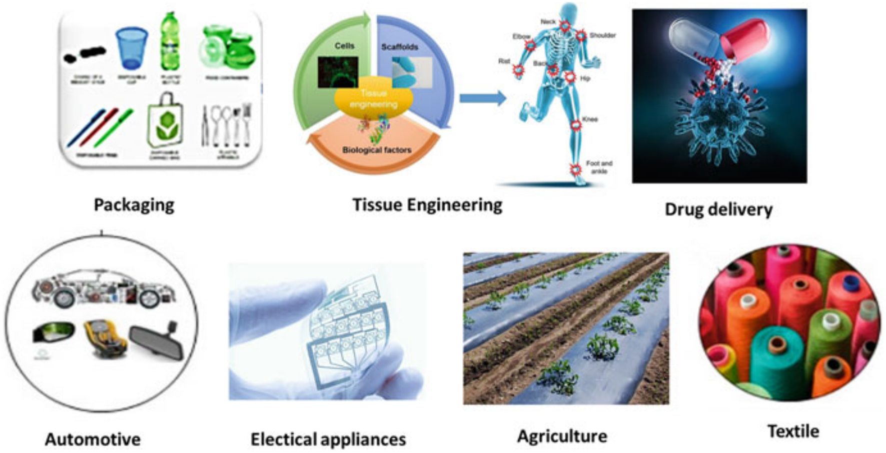

Fig. 6 Various applications of PLA

In many research works, PLA is blended with other biopolymers or composites to attain the desired features. It can be formulated to be both rigid and flexible to suit different applications. Both physical and chemical features of PLAs may be further enhanced by surface modification. The following sections cover the applications in tissue engineering, drug delivery, and so on. Figure 6 gives the various applications of PLA.

Biomedical Industry

Biomedical industry demands biocompatible materials for numerous applications. Nowadays, traditional biocompatible materials are substituted by biopolymers in many fields. In addition to biocompatibility, biodegradability of these biopolymers is also a significant feature that attracts researchers to use them in biomedical devices. PLA is an important polymer possessing these properties. Degradation of these biopolymers results in nontoxic products that can be easily eliminated from the body by means of usual cellular functions (Uzun et al. 2015). Bioabsorbability of PLA is also highly advantageous when used in fixation devices as dissolvable suture meshes. It can overcome many of the limitations of metallic implants. During bone implants and scaffoldings, a second surgery can be avoided by the usage of bioabsorbable polymer such as PLA as the implant material. A gradual recovery by the regeneration of the tissues is possible along with the degradation of the device.

Tissue Engineering

Tissue engineering is an interdisciplinary field that finds a solution to organ failure and tissue loss. It aims at restoring injured tissues, thereby improving their functions. Earlier, metals have been used as implants and in regenerative medicine. But the usage of metals is limited due to their lack of biodegradability. These metals are nowadays replaced with biopolymers, which offer better biodegradability and biocompatibility.

Cell proliferation and growth demand temporary support known as a scaffold or template. When cell growth and regeneration happen, the scaffold slowly degrades along with the development of the new tissue. Current research suggests that biomaterials are an important choice to act as scaffolds. Easy processing, cell adhesion, porosity, biocompatibility, and biodegradability are the major characteristics for a biomaterial to act as an excellent scaffold. Such scaffolds should never induce any inflammatory or cytotoxic responses in the body (Monnier et al. 2018). Also, degradation products should be easily metabolized and removed from the body. The mechanical properties of the scaffold should be similar to those of the restored tissue. Biomimetic structures can be successfully fabricated by 3D printing. It is a promising technology through which bone regeneration can be achieved. Synthetic polymers have been widely chosen for 3D printing owing to their excellent mechanical properties and easiness in fabrication. In the case of the synthetic polymer PLA, ductility and toughness may be enhanced by copolymerization and the formation of nanocomposites. Many research works have been proposed to generate scaffolds for bone tissue engineering by the copolymerization of PLA with hydroxy apatite, polyethylene glycol, and so on. Such copolymerization enhances the mechanical properties, which is highly beneficial in the case of tissue regeneration. Along with good mechanical properties, bioactivity is also essential in generating new tissues. It can be achieved by surface modification of the polymer by proteins or peptides, DNA molecules, and so on. As a result, cell adhesion and proliferation can also be enhanced. In a recent work, bone-regenerating 3D scaffolds were prepared from PLA and gelatin with mucic acid. It was found that the physicochemical properties were improved compared to the neat synthetic polymer. The viability of mouse mesenchymal stem cells remained unaffected when seeded onto this PLA/gelatin/mucic acid scaffold. This proved that the 3D printed PLA scaffolds coated with gelatin and mucic acid have potential applications in bone tissue engineering (Velioglu et al. 2019).

3D printing is a brilliant methodology to fabricate macro- and microporous structures from polymers, metals, and ceramics. Among 3D printing techniques, fused deposition modeling is a prominent one for fabricating scaffolds. Bone tissue engineering is a complicated process since many factors such as pore size, shape, mechanical properties, biocompatibility, and biodegradability are taken into consideration during regeneration. Fused deposition modeling is utilized to develop PLA scaffolds containing polydopamine and collagen I. In the synthetic method, PLA scaffolds are dipped in dopamine solution followed by the conjugation of polydopamine. When polydopamine is coated, it assisted in the coupling of collagen onto the PLA scaffolds. High cell density on the scaffold controlled the level of F-actin cytoskeleton and vinculin adhesive plaques (Teixeira et al. 2019). A similar work was done by Ritz et al. by developing PLA scaffolds loaded with collagen I and stromal-derived factor-1 by means of fused deposition modeling. It produced both disc-like and cage-like scaffolds, and they could promote endothelial cell growth. The results prove that these scaffolds have potential applications in bone tissue engineering (Ritz et al. 2017). The same synthetic method was used by Oladapo et al. to prepare the PLA/hydroxyapatite composite. These scaffolds possess a cylindrical shape that mimics the architecture and structure of the bone. Also, the ability of bone regeneration and bioactivity can be enhanced by the incorporation of hydroxyapatite in PLA (Oladapo et al. 2019). In another work, phenylenediamine functionalized carbon dots were composited with silk fibroin and PLA to obtain bioactive scaffolds. A uniform distribution of carbon dots was obtained, which improved mechanical, physical, and chemical properties. These nanofibrous porous scaffolds displayed an improvement in young modulus and good efficiency in implantation. These prepared scaffolds were implanted into rat cardiomyocytes, and the cell viability was significantly improved when made into a composite with carbon dots. This proves its potential to act as well organized scaffolds for cardiac tissue engineering (Yan et al. 2020).

Scaffolds prepared from nanofibers of PLA have been widely used in regenerative medicine. The high surface area, ability to mimic living cell architecture, and tunable mechanical properties of these scaffolds offer a design apt for tissue regeneration in the body. PLA is often opted for tissue regeneration since it has good thermal processability (Farah et al. 2016). But the brittleness of PLA is an important drawback to be considered. Modification of PLA may be performed to improve chemical inertness, hydrophilicity, degradation rate, and toughness. PLA nanofibers act as potential scaffolds for nervous, cutaneous, cardiovascular, and musculoskeletal tissue engineering. The most significant factor in the construction of scaffolds is cell adhesion. To improve mechanical properties and cell adhesion, scaffolds have been fabricated by different methods such as melt mixing, leaching, electrospinning, and so on. Blending with different polymers and composite formation also modify the properties. For bone tissue engineering, 3D printing is considered as a recent procedure to develop a porous scaffold (Roseti et al. 2017). Such scaffolds could provide strong osteoinduction activity and fast vascularization. In bone tissue engineering, it is very essential that the engineered bone must integrate completely with the native bone and surrounding environment. The lack of such integration may lead to many complications in physiological functioning. Implantation of such a biomaterial may not be able to achieve the expected result of tissue regeneration and immune response. An excellent result was observed when PLA was blended with hydroxyapatite. In this case, each component in the blend affects the features of the other components (Bae et al. 2011).

Mechanical properties, porosity, biodegradability, and bioactivity influence the quality of a scaffold. PLA/calcium phosphate composites have been prepared to integrate into host tissues, and it was seen that these porous scaffolds can be successfully utilized for the proliferation of osteoblasts. This modified scaffold could bring about a better cell adhesion as the pure PLA offers a poor adhesion to the cells. In addition, porosity also improved to 97% from 93%. These composites established superior mechanical properties when compared with the pure PLA scaffold. Hassanajili et al. proposed an indirect 3D printing to fabricate bone scaffolds using PLA/PCL/HA composite. The porosity of the scaffold was found to be 77%, and the mechanical properties were comparable with the normal tissue. The in vitro studies on the osteoblast cells found that the excellent cell adhesion, as well as cell proliferation of the scaffold, makes it a potential candidate for bone tissue engineering (Hassanajili et al. 2019). Figure 7 shows the demonstration of PLA/PCL/HA scaffold for osteoblast cells.

In a recent work, the electrospinning technique was used to prepare zeolite-hydroxyapatite blended PLA/PCL nanofibers for dental tissue engineering. Ring-opening method was used for PLA/PCL polymerization, and zeolite and hydroxyapatite were prepared via hydrothermal synthesis. Cell viability was tested by the MTT assay, and it was seen that blended nanofibers act as potential scaffolds for dental tissue regeneration (Mohandesnezhad et al. 2020). Figure 8 demonstrates the electrospinning method for the preparation of nanofibers from zeolite-nHA blended PCL/PLA for dental tissue engineering.

Table 1 shows various PLA scaffolds for tissue engineering. The aim of tissue engineering is to develop scaffolds for the regeneration of damaged tissues. Recent studies prove that nanofibers are well suited to form porous structures that can provide mechanical support as well as mimic the normal tissue. PLA is a synthetic polyester, and its degradation rate can be altered by changing the structure, porosity, molecular weight, viscosity, and crystallinity. PLA and its blends and composites have been widely studied for various types of tissue engineering.

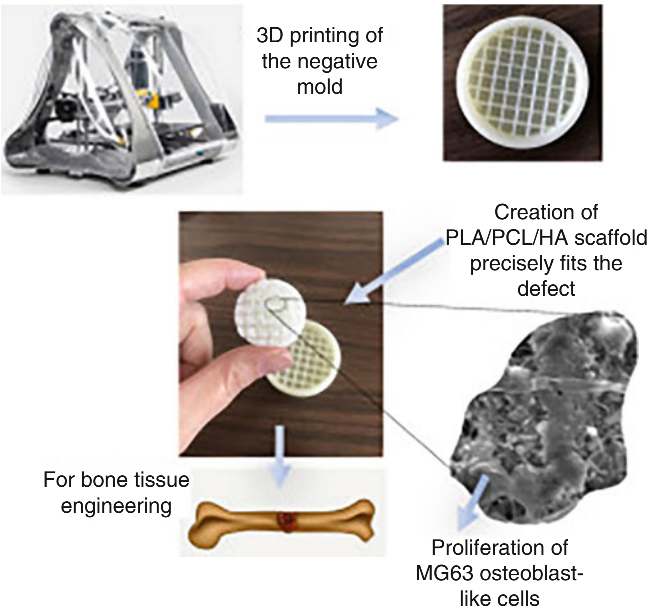

Fig. 7 PLA/PCL/HA scaffold for osteoblast cells. (Reprinted with permission from Hassanajili et al. 2019)

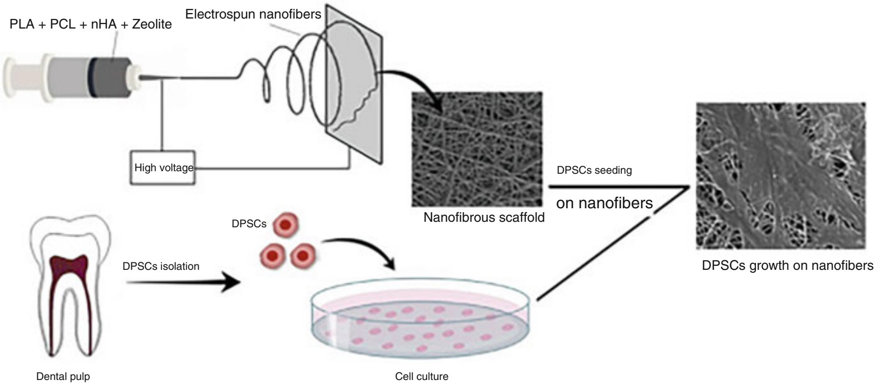

Fig. 8 Zeolite-nHA blended PCL/PLA nanofibers for dental tissue engineering. (Reprinted with permission from Mohandesnezhad et al. 2020)

Table 1 Different PLA scaffolds for tissue engineering

Sl. no.	PLA scaffold	Type	Application	References
1	PLA/PCL	Dental	Proliferation of human dental stem cells	Mohandesnezhad et al. (2020)
2	PLA/HA nanocomposite	Musculoskeletal	Better ceramic-polymer interactions	Z. Fang and Feng (2014)
3	PLA/silk fibroin	Nervous	Neuronal cell differentiation, neurite extension	Tian et al. (2015)
4	PLA/gelatin	Cardiovascular	In vitro culture with endothelial cells and muscle cells	Shalumon et al. (2015)
5	PLA (mineralized)/ strontium	Bone	Promoting bone defect repair	Han et al. (2019)
6	Electrospun PLA	Cutaneous	In vitro test on human dermal keratinocytes and fibroblasts; in vivo implant mouse skin model	Mohiti-Asli et al. (2017)
7	PLA scaffold	Bone	Osteosarcoma cell proliferation	Gregor et al. (2017)
8	PLA scaffold	Dermal	Biocompatibility on human dermal fibroblasts	Karabay et al. (2019)
9	PLA/ hydroxyapatite	Bone	Proliferation and differentiation of osteoblastic cells	Carfì Pavia et al. (2018)
10	PLA/ hydroxyapatite/ lignocellulose/ bioactive glass	Bone	In vitro biomineralization studies	Mao et al. (2018)

Drug Delivery

The efficiency of a drug is mainly assessed by the responses given by the body after its administration. Bioactive carriers are usually chosen as drug delivery system, and PLA is a good choice owing to its features. Degradation rate is also a determining factor in the case of drug delivery systems. The desired effect can be obtained by altering the degradation rate. For a constant, timely, and continuous release of the drug, the rate of breakdown of the drug carrier plays a prominent role. In some cases, this drug release should be prolonged for a sustainable drug release. Such a drug release assists in providing sufficient time so that the expected result may be obtained. Also, in some cases, targeted drug delivery at some specific sites is essential for the better action.

Polymeric nanofibers are widely used for many biomedical purposes among which the encapsulation of antitumor drugs for drug delivery applications covers a major area. Polymers possessing stimuli-responsive abilities and biocompatibility are well suited for this purpose. PLA is an excellent material because of its good biodegradability and dissolution in the extracellular environment. The FDA (US Food and Drug Administration) has approved the usage of PLA as a biomaterial (Liu et al. 2020b). PLA scaffolds possess nanofibers of variable pore diameter, which permits the delivery of different types of drugs. A controlled drug release is also possible by this characteristic nature (Martin et al. 2019).

Electrospinning is a widely accepted technique to obtain nanofibers from polymeric materials. Electrospinning always produces fine fibers with a large surface area, which assists in improving the properties. It can be used to produce nanofibers with a high surface-area-to-volume ratio which supports efficient drug delivery. Before loading the drug into the polymeric material, dissolution should be tested. Drug can be dissolved directly, if both the polymer and drug are soluble in the same solvent. Otherwise, another solvent is used for solubilizing the drug. Drug-releasing mechanism proceeds via desorption of drug from the surface of nanofiber. Nanofiber diameter, morphology, and porosity are the different parameters regulating the drug-release kinetics (Fig. 9).

The design of nanofiber-assisted drug release systems depends on both the nature of the drug and the purpose of drug delivery. Such a delivery mechanism can be either by immobilization on the nanofiber surface or through encapsulation. Figure 10 depicts these two mechanisms of drug delivery. The quantity of drug release depends on various factors such as the interaction between the drug and the carrier, nanofiber diameter, and the drug content (Cheng et al. 2018). In a recent study, polylactic acid-hydroxyapatite-doxycycline nanofibers obtained via electrospinning have been used as the drug carrier. Drug-releasing abilities were tested in phosphate buffer solution and simulated body fluid. In vitro drug release analysis and its kinetics confirmed that 3 and 7% of the drug-loaded samples obtained via physical adsorption are acceptable systems for prolonged release of drugs (Farkas et al. 2022).

It is significant to note the physicochemical processes that affect the drug release rate and steps in the release mechanism before developing a drug carrier. The various ways of drug release may happen while passage through the polymer, water-filled pores, or by dissolving in the encapsulated polymer. In the case of PLA, water-filled pores are the most convenient way. Various mechanisms

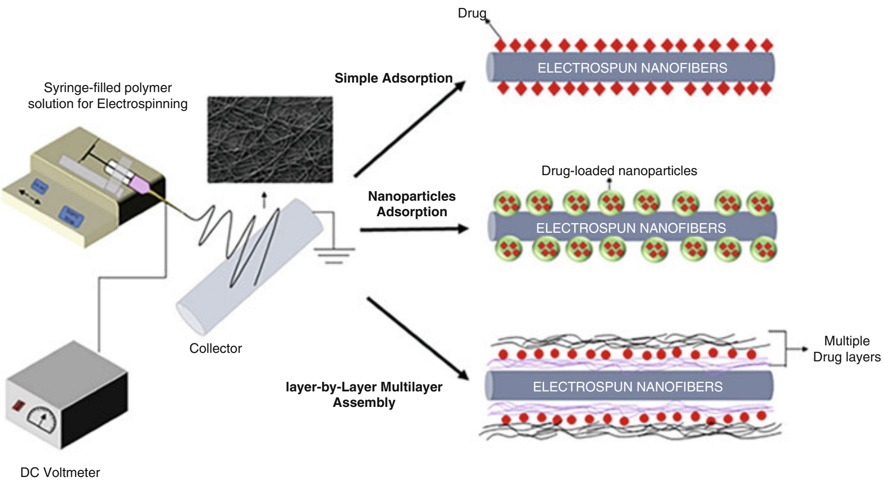

Fig. 9 Electrospun nanofibers for drug delivery. (Reprinted with permission from Stack et al. 2018)

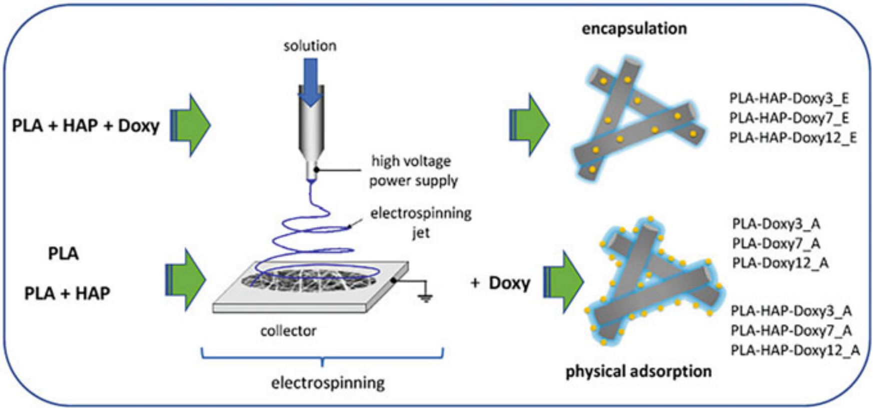

Fig. 10 Two different routes of drug loading. (Reprinted with permission from Farkas et al. 2022)

involved are diffusion from the surface and diffusion of particles at the time of degradation of the polymer, through swelling of matrix. These mechanisms are depicted in Fig. 11.

Packaging

Plastics have been considered as the chief source of packaging material for decades, and synthetic plastics are heavily consumed by the packaging industry. But these packaging materials leave a bulk amount of waste which pollutes the environment,

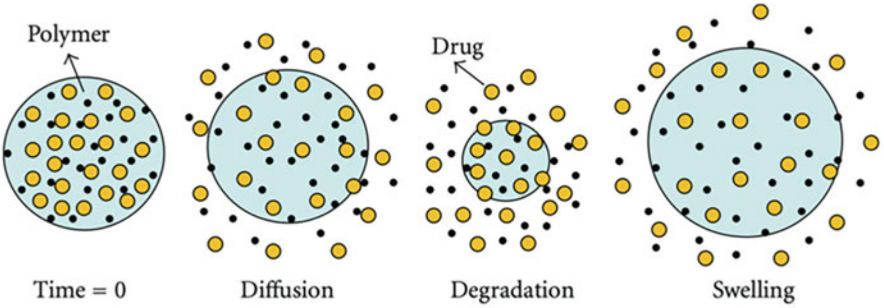

Fig. 11 Mechanisms of drug release. (Reprinted with permission from Vlachopoulos et al. 2022)

and now it’s a real threat to the existence of life. So, it is a necessity to replace conventional plastics with biodegradable materials that can function as packing materials. Biopolymers are a good choice of green materials which can serve the purpose. Among these biopolymers, PLA is a well attracted one, but some disadvantages limit its performance. Fast hydrolytic degradation is one such drawbacks which limits its application as a food packaging material. It is important to improve the barrier properties against moisture while acting as a packing material. To enhance the barrier properties, several methods may be adopted. Coating of biopolymer with materials which improve hydrophobicity is a method to overcome the issue. But these drawbacks can be successfully nullified by blending PLA with natural fillers making composites. PLA-polyethylene glycol and PLA-polycaprolactone blends are some examples.

While used as food packaging materials, in addition to biodegradability, both flexibility and hardness are significant parameters for excellent handling. In the form of film or food tray, the packaging material should ensure sealability. PLA and its blends are well known to be used as food tray and packaging films as they possess the abovementioned features. Technological parameters should be optimized to regulate the processing features and are varied according to their applicability. Figure 12 shows the various steps for obtaining food packaging system from biopolymers.

Automotive Applications of PLA

Plastic materials cover a major portion of automotive applications, and currently, composites of synthetic polymers are in high demand in this sector on account of the reduction of vehicle weight upon their usage. Composites containing organic fillers are found to be easy to recycle. Hence, environmental concerns also favor the utilization of such bioplastics and their composites. Recently, natural fibers are composited with polymers like PLA to attain a biodegradable matrix for use as automobile parts. In such cases, measures have to be taken to enhance the interfacial adhesion between fiber and polymer matrix to achieve the best results. Ductility and

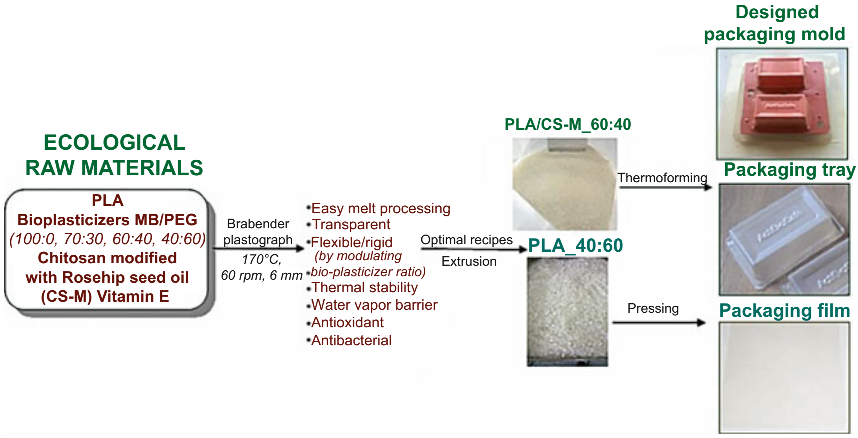

Fig. 12 Steps for obtaining food packaging system from biopolymers and blends (Darie-Niță et al. 2021)

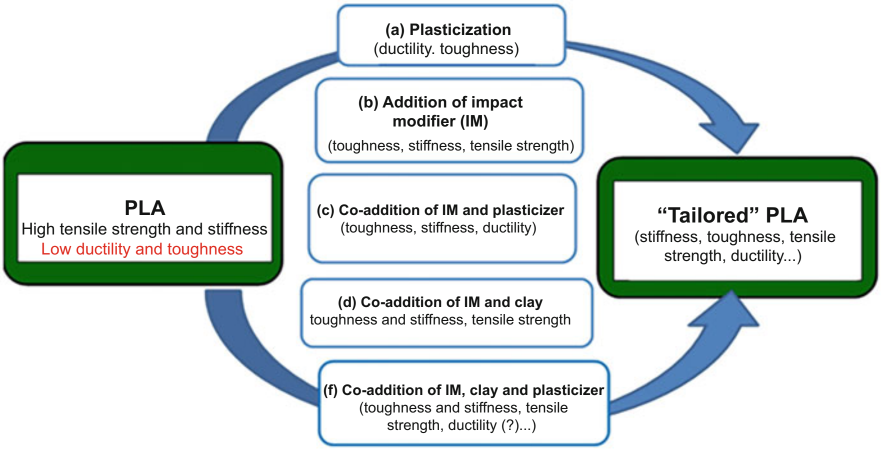

Fig. 13 Tuning PLA features for automotive applications

toughness also need to be improved, which is generally attained by plasticization (Balieu et al. 2013). Among the various plasticizers, those with good mobility and high molecular weight are usually preferred. As seen in Fig. 13, different methods may be adopted to enrich the properties of neat PLA.

Textile

PLA being biodegradable, it finds many applications in textile industry. The degradation process is also comparatively easy as it needs only cleavage of ester linkage.

Even though it is biodegradable, mechanical properties are comparable to plastics. It can be molded into decided shapes with a variety of features, as in the case of other plastics. Other parameters such as renewable origin, recycling possibilities, and ease of melting also make PLA an acceptable material in the textile industry. Thermal stability and resistance to shrinkage during ironing were also found to be highly advantageous while PLA stereocomplexes were formed. Another property is its comfort, as in the case of other natural fibers like silk, cotton, and so on. These properties make PLA fibers excel in various textile applications.

Spinning can be done to process PLA into fibers. Organic compounds can be absorbed easily, and this property can be utilized in fiber applications. It also has the ability to absorb moisture due to its polar nature, which makes it a good candidate for wiping applications. Potential wicking features of PLA can be used to generate disposable products. These properties of PLA increase its use in the textile industry, and nowadays it replaces many of the synthetic polymers such as polyethylene terephthalate and nylon. The use of PLA-cotton blends is wide in garment industries, and it is found that its buffering ability to sweat and thermal insulating properties enhance its usage in sports. Good resiliency of PLA is utilized in the manufacture of jackets also. Good crimp and retention features of PLA make it suitable for embroidered fabrics. PLA also finds applications in homeware products such as pillowcases and curtains. These significant features of PLA prove its potential in textile and fiber applications. Dyeing processes are done by varying different parameters such as pH, temperature, and time. It is a challenge to attain the suitable temperature in finishing as PLA is easily susceptible to degradation. Another limitation of PLA textiles is that their ironing temperature is comparatively lower than conventional textiles like cotton.

Some PLA composites were fabricated to enhance productivity and reduce waste to obtain some tailored products in textile industry. For instance, carbon black and carbon nanotube are composited with PLA to improve the adhesion properties for fabricating functional fabrics. In many works, 3D printing is done to develop such products. In such synthetic procedures, the various parameters of 3D printing, such as printing speed and temperature, influence the adhesion strength. Comfort and durability of a textile manufactured from polymeric composite materials are the major challenges during 3D printing. In a work, 3D printing was adopted to obtain PLA-carbon deposited into polyethylene terephthalate. The results show that tensile properties were affected during composite formation due to diffusion of the polymer, and that in turn led to a weak adhesion.

Agriculture

The use of flexible plastic films in the agriculture sector has increased immensely in the past few decades. Plastics like polypropylene and ethylene-vinyl acetate copolymer have been widely employed as greenhouse films, mulch films, silage films, stretch films, etc. This has helped the farmers in improving their crop quality, obtaining higher yields, minimizing water consumption, and reducing their ecological footprint (Rocha et al. 2018). According to a report by Sintim and Flury, plastic mulch films accounted for approximately 40% of the total plastic films used in agriculture (Sintim and Flury 2017). Plastic mulch helps to conserve soil moisture, reduces the loss of minerals, improves fertility of the soil, minimizes weed growth, protects the plants from insect attack, and keeps the fruits and vegetables clean. However, the incorrect post-use disposal of these nonbiodegradable plastic films poses a serious threat to the environment. Biodegradable mulch films are a superior alternative to plastic mulch films and can be discarded into the soil to be degraded by the action of microorganisms. This eliminates the cost and labor associated with the removal and disposal of plastic mulch and is safer for the environment. PLA, which can be composted without leaving any harmful residues in the soil, is a good option to prepare mulch films. PLA is blended with other polymers or fillers to improve their flexibility, and these blends are more suited for agricultural applications than virgin PLA. PLA-based plastic films can also be used to manufacture biodegradable sandbags, weed prevention nets, vegetation nets and pots, etc. (Malinconico et al. 2018; Rocha et al. 2018).

Jandas et al. reported the preparation of completely biodegradable agricultural mulch film made from PLA/poly(hydroxybutyrate) blend with maleic anhydride as the reactive compatibilizer. Flexibility and impact modification were considerably enhanced by the addition of poly(hydroxybutyrate) and maleic anhydride. The films were reinforced with nano-clays to improve their tensile strength and tensile modulus without affecting their ductility. These films also showed an increased rate of biodegradation compared to virgin PLA. Environmental sustainability studies as well as mechanical testing showed that these films could be used for short-term crops that can be completed within around 100–150 days (Jandas et al. 2013b).

Calcagnile and co-workers developed a completely biodegradable composite material from PLA and cellulose-based super-absorbing hydrogel. This material is capable of acting as a source of water and fertilizers and can release them into the soil in a controlled manner. This allows for more efficient management of water and fertilizer and causes less chemical damage to the plants (Calcagnile et al. 2019). Durpekova et al. also reported a similar super-absorbing hydrogel prepared by blending low molecular weight PLA, acid whey, and cellulose derivatives, which could be employed as a reservoir of water and nutritive whey agents for crops and also for measured release of fertilizers (Durpekova et al. 2022).

Paschoalin et al. developed a wearable electrochemical sensor based on PLA for the detection of bipyridinium and carbamate pesticides on the surface of food and agricultural samples. This economic device consists of a three-electrode system which is deposited on solution-blow spinning mats of PLA by screen-printing technology. The flexibility of these sensors allows them to be on flat, curved, and irregular surfaces of leaves, fruits, and vegetables. The researchers could attain a detection limit of 57 nM and 43 nM for diquat and carbendazim, respectively, using this device. This sensor could also differentiate and measure the amount of carbendazim and diquat on cabbage and apple skins without any interference from other pesticides (Paschoalin et al. 2022).

Crop mulching promotes root development by promoting soil warming. This process reduces the usage of herbicides and improves production quality. In traditional agricultural methodologies, low-density polyethylene is used as mulching materials. The good mechanical and optical properties of these conventional materials enhance the growth of agricultural crops. But, when environmental sustainability is concerned, the exceptional mechanical properties and long life of these mulching materials pose a threat. Various climate agents spread these materials to different locations, and these residues may in turn cause contamination of the soil. Poor agricultural methods and repeated use of these mulching agents cause adverse effect on the environment. Hence, it was a necessity to replace these conventional mulching agents with some biodegradable materials in a reliable method. Degradation of a mulching agent which should be done in a fast time is the solution to the problem. In such a case, it is possible to rely on biodegradable PLA and its derivatives to avoid such issues. Complete degradation of PLA films is possible by the activity of soil bacteria if there is moisture content in the soil.

Electronic Appliances

The upgradation of electronic devices at a very fast pace is resulting in a huge accumulation of electronic waste. The use of plastic materials for preparing lightweight flexible electronics is adding up to this crisis. Developing greener electronic devices using degradable polymers is a solution to this problem. Among bio-based polymers, PLAs are potential candidates for the manufacture of electronic appliances (Shi et al. 2017). However, reports on the use of PLA for making electronic devices are limited in the literature. This may be due to their low glass transition temperature, brittleness, low impact strength, low heat resistance, and unsatisfactory dielectric properties. Properties of PLA can be altered through orientation and annealing. This increases the crystallinity, mechanical performance (increased strength, stiffness, and ductility under tension), and thermal stability of PLA films. Addition of nucleating agents such as microcellulose, talc, and nanocomposites can also enhance the mechanical strength and crystallinity of PLA (Luoma et al. 2021). The heat resistance of PLA can be increased by blending with resins having a higher thermal resistance like acrylonitrile butadiene styrene (ABS) and polycarbonate (PC). Integration of glass fiber, plant fiber, and inorganic filler particles into the PLA matrix or the use of stereocomplex of PDLA and PLLA can also improve the thermal resistance of PLA. The effects of metal hydroxides and phosphorus reagents on the flame-retardant property of PLA have also been investigated (Obuchi and Ogawa 2010).

Some major companies have adopted PLA as parts of their electronic gadgets. For example, Sony used the injection-molding technique to make the casing of its Walkman in 2001. Sanyo Marwick Media manufactured CD/DVD discs and cases made of PLA. Toshiba and Samsung used PLA for their remote control and phone chassis. Fuji Xerox successfully used PLA-based interior drum cover for several copying machines in 2007. PLA was used by Fujitsu and PEGA for the hard shell case of their notebooks (Obuchi and Ogawa 2010).

Recently, Luoma et al. studied the performance of the different grades of PLA films in printed electronics processing. They observed that orientation and annealing increased the crystallinity of the PLA films and enhanced their mechanical and thermal properties. These PLA films were used as eco-sustainable substrates for functional light-emitting diode foils with screen-printed silver conductors and die-bonded LED chips (Luoma et al. 2021).

Utilizing the flexibility, biocompatibility, and biodegradability of their own PLA, Prontera et al. showed that it is possible to produce optoelectronic devices on PLA layers. The PLA substrates prepared by melt extrusion showed ~90% optical transmittance in the visible region and 12 nm surface roughness, which are suitable parameters for OLED applications. Using hybrid technology, various structures were created on top of the PLA substrates using solution-based and thermal evaporation deposition techniques. Biocompatibility assays of the devices prepared showed that PLA is a strong contender for making bioelectronic devices (Prontera et al. 2022).

Carbon nanotube-loaded poly(lactic acid)/ethylene-vinyl acetate copolymer blends were used to make broadband microwave absorbing materials by Soares and co-workers. These composites showed excellent microwave absorption properties and a wide absorption bandwidth at low concentrations of carbon nanotubes and can be considered as potential candidates for flexible materials suitable for shielding electronic devices in wide frequency ranges (Lopes Pereira et al. 2022).

Sensing

Piezoelectric materials can generate electric charges on the surface when subjected to pressure or strain, converting mechanical energy into electrical energy making them attractive for sensing applications. Polymers with piezoelectric properties have the advantage of being lightweight, transparent, and flexible and can be used for the preparation of thin films. Semicrystalline PLLA and PDLA exhibit piezoelectricity when the polymer chains are highly oriented by the drawing process. Among these, PLLA is the more popularly researched stereoisomer. Racemic PDLLA, which is amorphous, does not show piezoelectric effect. PLA has an inherent chiral molecular conformation which has different optical properties for each substituent group. The coordinated motion of the permanent dipoles present on the helical chain molecules of PLLA is the source and main reason for its piezoelectricity. When a shear stress is applied to the chain molecules in PLLA with a 10/3 helical structure through its methyl groups, it causes the displacement of all the atoms present in the chain. In particular, C=O bonds with large dipole moment will rotate, which changes the polarization of the entire long-chain molecule, generating the shear piezoelectricity of PLLA. PLLA and PDLA have helical structures due to the presence of chiral carbon. PLLA has left-handed helical structure, and PDLA has right-handed helical structure. As the helical structures of PDLA and PLLA have oppositely oriented clockwise and counterclockwise spirals, respectively, their piezoelectric constants have the opposite sign. Unlike poly(vinylidene fluoride), another popular piezoelectric polymer, PLLA does not exhibit pyroelectricity (ability to generate a temporary voltage on heating or cooling) (Tajitsu 2017).

Piezoelectric elements are key components of human-machine interfaces (HMIs) in new smart devices. A requirement for these materials is that they should not exhibit pyroelectricity. It is impossible to tell whether the signal comes from the pressure or the heat of the operator’s hand if a piezoelectric sensor material displays pyroelectricity since it can instantly detect heat from a finger when it is used as an HMI. PLLA does not have intrinsic polarization, and hence it does not show pyroelectricity, and therefore it finds a place in developing HMIs. PLLA films also have a larger shear piezoelectric constant (~10 pC/N) compared to other polymers. Hence, they can sense bending and twisting motions with satisfactory sensitivity. If this unique function is utilized, PLLA can be used in sensor applications to allow intuitive control in HMI. Taking advantage of this special function, Murata Manufacturing and Mitsui Chemicals Inc. developed a TV remote control that combined a PLLA sensor with radio and power supply circuits, which could be controlled by the user’s motion. The dye-sensitizing-type photoelectric cell fitted in this remote control produced enough electric power due to the high transparency of PLLA. The extra electric power generated by the photoelectric cell could be stored in a capacitor eliminating the need for batteries (Ando et al. 2012).

Murata Manufacturing Co., Ltd., also utilized piezoelectric PLLA films for designing piezoelectric PLLA fabrics having a strong antibacterial effect. This fabric is made of left-handed PLLA helical yarn (S-yarn) and right-handed PLLA helical yarn (Z-yarn). Application of stress on the fabric generates a strong electric field between the yarns which is caused by the reversal of the electric polarity of the yarns. The strong electric field resulting from the extension and contraction of the fabric is the reason for its antibacterial activity (Ando et al. 2017).

Wang et al. developed a visualized tactile sensing electronic skin (VTSES) made of poly(vinylidene fluoride-trifluoroethylene)/thin-film transistor /PLLA arrays. This device can detect static contact, dynamic force, and thermal transduction. The piezoelectric PLLA component of this device enables dynamic slide detection (Wang et al. 2022).

Dahiya and co-workers reported a wireless pressure sensing bandage based on inductor-capacitor resonant tank. This resonant tank is screen printed on piezoelectric PLLA nanofiber substrate which is connected in parallel with a planar inductor forming a LC circuit. The PLLA component provides a better conformal contact with the skin and increases sensitivity under the pressure due to its piezoelectric property. These smart bandages can be used for fast wound healing which is facilitated by the electroceutical arrangement due to piezoelectric PLLA substrate (Nikbakhtnasrabadi et al. 2022).

Conclusion

This chapter summarizes the properties and various applications in different fields. It is a promising candidate in many biomedical or industrial applications. Biodegradable, biocompatible, and bioabsorbable polymers have always attracted the attention of current researchers. Neat PLA and its blends and composites with its low cost and excellent biocompatibility find applications in biomedical as well as packaging industry. It was observed that biomedical industry is the major area of research utilizing the features of PLA. Among the biomedical applications, tissue engineering is considered as the prominent one since PLA composites can be conveniently used to produce specific biodegradable body parts. It is expected that PLA composites will substitute conventional scaffolds in the near future. PLA and its composites owing to their exceptional properties are a promising research field in the future.

The chapter discusses the applications of PLA in numerous fields such as biomedical, automotive, textile, packaging, and sensing. Furthermore, enormous research is going on to design value-added products from PLA nanostructure. These efforts will establish the material in a wide range of applications which may throw back the sector of plastics in the near future.

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