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A Review of Polylactic Acid as a Biodegradable Polymer

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***Abstract*—Traditional petroleum-sourced materials are not biodegradable, and plastics that are difficult to degrade cause environmental pollution, plastic buildup, and ecosystem threats. PLA materials are made from lactic acid, a fully degradable material. It is therefore immune to these problems and has a low environmental impact. Advantages of PLA materials over traditional plastics include degradability, environmental friendliness, and renewable resources. Therefore, the topic of this review is the properties and applications of PLA material. In the literature review, we first introduced the basic properties and degradation process of PLA. Then the processing and applications of PLA are reviewed. In this part, hot-melt extrusion, injection molding, blow molding, and thermoforming are the four major techniques for PLA processing. In addition, four main application fields of PLA, namely the medical/biomedical industry, packaging/food packaging, automotive industry, and agriculture were introduced. Finally, from the perspective of applications, a global market overview is provided, mainly including domestic and overseas markets. This paper analyzed the advantages and drawbacks of PLA materials and further discussed the extended applications of PLA material, including new products and manufacturing technologies. Notably, 3D printing technology is a promising and advanced manufacturing technology and has the potential to be applied in many aspects of PLA production in the future.**

***Keywords*—Polylactic Acid (PLA), biodegradable, polymer, plastics, composites**

I. Introduction

Recalling nineteenth-century London, John, a printer, created a material that was extremely flexible, hard but not brittle, and could change shape at will under hot pressure. He named the material celluloid and used it to make billiard balls instead of ivory. After him, the Belgian Bécquerne built a laboratory to invent phenolic plastics in 1907. Nylon, polyethylene plastics, and other familiar materials followed. The plastics industry is driven by the desire to make money and war. 50 years ago, the world could only produce tens of thousands of tons of plastics per year; today, the world produces more than 100 million tons of plastics per year. The United States produces more plastic than steel, aluminum, and copper combined.

Plastic, which has cemented its place in manufacturing because of its low cost, high output, ease of processing, and reliable durability, is impossible to deny this ubiquitous and mundane substance. But because of plastic's low lifespan and waste disposal issues, it poses unimaginable environmental problems. Plastic has entered every industry because of its remarkable stability, and at the same time, it has brought these hard-to-biodegrade wastes to every corner of the world. Every year, about 8 to 10 million tons of plastic ends up in the oceans, where it is degraded into microplastics. These fragments enter the human body through bioaccumulation and cause serious health problems. Meanwhile, global warming is intensifying due to the effects of increased emissions of greenhouse gases such as carbon dioxide. It is speculated that at the current rate of emissions, within twenty to forty years, carbon dioxide concentrations will exceed 450 ppm and global temperatures will rise by one and a half degrees Celsius [1].

As early as 1913, French scientists attempted to synthesize lactic acid through polycondensation, but due to the high cost of production and low yield, the technology was not developed until 1932. Scientists Carothers polymerized lactic acid in a vacuum to produce PLA. However, due to the high production cost of the technology at that time, it was not possible to carry out the corresponding application, so he gave up the research on PLA. Since the 1990s, with the growing awareness of environmental protection, more and more attention has been paid to degradable PLA. The research in this period focused on the improvement of processing technology and achieved certain results. In 1987, Food company Cargill began investing in the development of a new PLA production process and the commercialization of a PLA product called "nature-works". Today, NatureWorks is the global leader in the PLA industry with the largest PLA production line.

According to public information, polylactic acid is made of starch raw material from renewable plant resources (such as corn). After the saccharification of glucose, the product will be converted to high-purity lactic acid by certain strains of bacteria fermentation. Then through the chemical synthesis method, a particular weight of PLA (Polylactic Acid). Among a range of recognized environmentally friendly materials, PLA has expectational good biodegradability that can be completely degraded and ultimately generate carbon dioxide and water which do not pollute the environment. Compared to other environmentally friendly materials PLA is widely available for daily use products because of its safer decomposition conditions. As a bio-based raw material, PLA can absorb carbon dioxide from the atmosphere and use the carbon dioxide to degrade. Therefore, PLA can be considered a better option to improve and alleviate the global issue because it has a higher speed of absorption of carbon dioxide.

In the face of the increasing environmental impact of the traditional plastics industry, there is an urgent need to replace traditional petroleum-based plastic with bioplastic, and the European Union has presented to the world its vision of a more sustainable plastics industry by 2030, with more opportunities for the application of biodegradable plastics. PLA is considered a suitable alternative to petrochemical-derived products due to its excellent properties.

Apart from good biodegradability, PLA has excellent mechanical strength and durability making it a successful industrial and commercial material. These application advantages make PLA stand out from the crowd of biopolymers as the most commercially successful bioplastics. PLA has a 42% market share of all degradable plastic. Today, the plant of NatureWorks headquarters in North America has become the world's leading PLA production facility, and in 2015 it expanded with a capacity of 150,000 tons. Meanwhile, in China, Hisun added a 10,000-ton production line in 2017. PLA is deeply involved in industrial sectors including the medical industry, packaging industry, agriculture, and automotive manufacturing due to its easy processing characteristics.

Therefore, this manuscript will introduce the degradation process and products, application types, and application markets based on PLA as a biodegradable plastic polymer.

II. The Basic Properties and Degradation of PLA

A. Basic Properties and Synthesis Mechanism

Polylactic Acid (PLA) is a biodegradable, bioactive polyester consisting of lactic acid. The chemical formula of PLA is written as ($C_3H_4O_2$) n. It has a density of approximately 1.32 grams per cubic centimeter. PLA is insoluble in water but soluble in chlorinated solvents, hot benzene, tetrahydrofuran, and dioxane. The PLA has a crystal of 37%. As far as thermal properties are concerned/As far as thermal properties are concerned, the melting point of polylactic acid is in the range of 150 to 160 degrees Celsius. In addition, the glass transition temperature is in the range of 60 to 65 degrees Celsius [1].

As a polyester (polymer containing the ester group), PLA is made with 2 possible monomers: lactic acid and lactide. Two lactic acids can be produced by the bacterial fermentation of a carbohydrate source under particular conditions, or produce individual glucose by hydrolysis of corn starch [2]. For an industrial case, the options of carbohydrate sources are provided as corn starch, cassava roots, or sugarcane. In addition, the agricultural produce itself, such as crop residue which includes stems, straw, husks, and leaves can be processed and used as alternative sources. The unfermentable residue can be used as a heat source to reduce the use of fossil fuel-derived hydrocarbons. It is possible to produce PLA by the direct condensation of lactic acid. However, this procedure usually results in the less-desired low-density PLA. To gain high-density PLA, the lactic acid is heated in the presence of acid catalysts to form cyclic lactide. With the metal catalysts the lactide forms high-density PLA through a ring-opening polymerization process [3].

However, the above industrial and agricultural production processes may cause severe pollution and be high cost. To produce PLA more environmentally friendly and economic, advanced production technologies should be further developed.

B. Advantages and Limitations

PLA has many advantages including eco-friendliness, biodegradability, biocompatibility, and good processability. Among these aspects, the most significant benefit of using PLA is its eco-friendliness. This is because since this material can be obtained from renewable resources such as corn, wheat, or rice, the issue of resource depletion can be disregarded. In addition, it is biodegradable, which means it is recyclable and compostable. This indicates that PLA barely causes environmental impact during its degradation process. Moreover, PLA possesses good biocompatibility, which is a great superiority for biomedical applications. The biocompatibility of PLA is demonstrated by the fact that PLA is not toxic or carcinogenic to the human body. When it breaks down/degrades, it only produces water and carbon dioxide, which cannot interfere with tissue healing and cause inflammation/immune response. Lastly, PLA has better heat processability than biopolymers such as PHA, PEG, and PCL. This property allows PLA to better utilize its capabilities as a bioplastic. PLA saves more energy in processes including drying, film extrusion, blow molding, thermoforming, and casting films. According to related/relevant data, producing PLA bioplastics uses 25 to 55 percent less energy than traditional petroleum-based plastics. With technological advances, energy consumption can be reduced to less than 10% of the energy used in traditional processes [4].

However, PLA has its drawbacks. First, it is very brittle, with less than 10% elongation, which limits its applications. For example, it cannot be used as screws and fracture fixation plates in the biomedical field [4]. Secondly, PLA has a very low degradation rate and it can exist in the human body for 3 to 5 years. Moreover, PLA is strongly hydrophobic. The contact angle of static water with it is about 80 degrees. It may cause an inflammatory response in the host when it comes into direct contact with biological fluids [2]. Finally, PLA has a relatively higher gas permeability than other packaging plastics, which suggests that it does not have excellent barrier properties.

C. Degradation Process and Decomposition of Products

PLA is commonly degraded by two processes: by a hydrolysis reaction followed by microbial decomposition [5]. The hydrolysis reaction is the main part of this and consists of four main stages: water absorption, breaking of ester bonds, diffusion of soluble polymers, and fragmentation. Macroscopically, the overall structure of the material is destroyed, becomes smaller, gradually turns into fragments, and finally dissolves completely and is absorbed by microorganisms. The microorganisms secrete extracellular enzymes that erode the small polymer molecules and convert them into their final metabolites: water and carbon dioxide [6].

The degree of PLA degradation also depends on the water diffused into the polymer matrix and the temperature. Temperature and autocatalytic behavior of PLA are the main parameters controlling the degradation process. In addition, the degradation of PLA is very fast under highly alkaline and highly acidic media [7].

In the microsome of natural soil, PLA is not susceptible to microbial attack. Land burial experiments have shown that the degradation rate of PLA is quite slow. Currently, the majority of microorganisms capable of degrading PLA degrees are actinomycetes, with a small percentage belonging to bacteria and fungi. Analyzing 41 actinomycete genera based on 16SrRNA sequences, it was found that PLA-degrading agents were restricted to members of Pseudoarthrospiraea and related genera, they include Amycolatopsis, Saccharothrix, Lentzea, Kibdelosporangium, and Streptoalloteichus [8]. Apart from certain kinds of bacteria and fungi that degrade PLA, several kinds of enzymes from microorganisms also play a crucial role in biodegradation. PLA degrading enzymes from microorganisms are mainly proteases, some of which are keratases and lipases. The maximum activity of these enzymes depends on the optimal pH, temperature, and PLA properties (chain stereochemistry and material crystallinity). According to the analysis of the catalytic mechanism of PLLA by proteinase K, the catalytic process is divided into four stages: substrate binding, nucleophilic attack, protonation, and ester hydrolysis. A lactic acid as a monomer with a normal carboxyl group is formed. In consequence, lactic acid can be further metabolized to water and carbon dioxide by these microorganisms or living bodies, indicating that PLA is completely degraded.

III. The Processing Techniques and Applications of PLA

A. The Processing Techniques of PLA

To date, there are many kinds of products made of PLA material for versatile applications, which require suitable manufacturing processes for production. There are mainly four main types of manufacturing processes used in industry, namely Hot-melt extrusion, Injection molding, Blow molding, and Thermoforming [4].

Hot-Melt Extrusion (HME)

Heat converts the plastic raw materials into a molten state, and then by forcing them through molds they are made into products of uniform shape and density. This method is generally used in food processing and plastics manufacturing. Heat transfer and curing occur when the melts can hold their shape long enough. HME is divided into four stages. (1) passage of raw materials through a hopper, (2) mixing, grinding, venting, and particle reduction, (3) flow through a mold, and (4) extrusion before further processing [9].

Injection Molding

Injection molding is one of the most efficient methods of manufacturing thermoplastics on a large scale. The process starts with the feeding of plastic pellets into the screw from the feed hopper, and the plastic that comes out from the screw is fully melted, desired, and dried by high pressure. The melt is filled up on a mold, and extra melts are also added to compensate for shrinkage. Two halves are clamped together to make up the mold cavity.

In this process, additional steps are usually not required. The raw material will be heated above its melting point and then the melt is injected into a mold and formed into the desired shape. The most important mechanisms in this process are pressure flow and heat transfer. In common cases, components made by injection molding do not require further finishing, as long as the entire production process is well completed. As a result, it is possible to manufacture large quantities of components at a more manageable cost.

Blow Molding

Hollow products, especially bottles, are often made using blow molding techniques. In this method, a thermoplastic melt tube is inflated in the shape of a mold cavity and forms a hollow object. Finally, the molded object is cooled down to maintain its shape. There are three other sub-branches of blow molding technology, which are blow molding (for the production of stronger biaxially oriented jars), extrusion blow molding (pp bottles with hot-fill capability), and injection blow molding (relatively small bottles and wide-mouth jars). Among these three processes, extrusion blow molding is the most frequently used.

Thermoforming

Thermoforming techniques are often used to form simple functional parts. The material is heated to a flexible temperature, stretched into a film, and finally molded through a mold. By using infrared (IR) lamps, the initial heating of the PLA film would be done. Next, the thermoforming of PLA sheets passes through aluminum molds to form the products.

B. The Applications of PLA

Compared to other bioplastic, PLA has many excellent properties such as high mechanical strength and modulus. Biodegradability, biocompatibility, and easy processing open up more application possibilities for PLA. In the following industries, PLA is widely applied in commercial products:

Medical/Biomedical Industry

As PLA is further explored, this excellent material is becoming popular in the biomedical industry. Due to the hydrolysis mechanism of PLA, PLA can be completely degraded by the human body. Therefore, there is no need for a second surgery to remove the implants. As a result, the cost of surgery can be greatly reduced and the patients could make a recovery more quickly. The biocompatibility of PLA can also help reduce the incidence of immune reactions. This is because the degradation product only consists of lactic acid and short oligomers, which can be metabolized by the body [10].

However, pure PLA may not be able to fulfill all the needs of the field. Therefore, several PLA-based nanocomposites have been studied extensively. According to FDA guideline 2017, nanomaterials ranging from 1 to 1000 nm are similar to molecules as these nanoparticles can be absorbed by cells. Nanomaterials are opening up new potential for biomedical development due to their properties. Examples mainly include image contrast reagents and vaccine delivery systems. Meanwhile, some properties of PLA are expected to be improved due to the small-scale effect of nanomaterials. PLA-based nanomaterials are gradually replacing pure PLA materials in applications such as synthetic bone, drug delivery, and tissue engineering [11]. PLGA is a widely used material for the production of porous scaffolds and the repair of damaged bones. PLA-based nanomaterials have better bone adhesion and faster self-degradation rates than pure PLA materials. This can save the majority of patients from a second operation of implant removal.

Packaging/Food Packaging

PLA is an aliphatic polyester with excellent thermoplastic properties. The ratio of 2 optical isomers on the lactic monomer would determine the qualities and application direction of PLA as packaging materials. For instance, 100% L-PLA monomers brought high melting and crystallinity points. 90/10% D/L copolymers would satisfy bulk packaging conditions as they produce polymerizable melt about its Tg [4].

PLA can mimic the flexibility of polyethylene PET and PVC in terms of tensile strength modulus, and odor barrier. In addition to this, PLA has the temperature stability of PS. PLA can be used for container processing, film, and coating processing, and PLA can be recycled into the form of lactic acid for the next polymerization.

Based on a study observing the use of PLA materials in butter, yogurt, and cheese packaging, it was found that the packaging has good moisture and mechanical protection. During biodegradation, the diffusion of lactic acid into the product was very small. It was concluded that food packaging based on PLA materials is well suited for foods with short shelf life or high respiration. However, PLA has its drawbacks. Compared to traditional petroleum-based plastics (e.g., PET), PLA is more brittle and relatively more sensitive to thermal deformation. As a result, it is very much used in products that need to be heat-sealed [12]. There are several ways to address some of these issues, such as blending polymers or using high-blocking coatings. When PLA is coated with polyethylene oxide or poly PCL, the gas and water vapor barrier properties are improved.

Automotive Industry

In the automotive industry, the incorporation of natural materials into the parts thereof has been popular for many years and the trend is on the rise. These materials are widely used in the car body for lighter weight. At the same time, as the weight of the car body decreases, so does the emission of greenhouse gases. Twenty-three percent of total global carbon emissions are related to automobiles. For every 10% reduction in vehicle weight, fuel efficiency will increase by 7%. It follows that for every kilogram of vehicle weight saved, around 20 kilograms of CO_2 emissions will be reduced. As a result, PLA is widely used in the automotive industry, providing a double benefit: lower total weight and improved fuel efficiency [13].

However, PLA still lacks thermal stability and is brittle. These problems have been overcome wherever possible by using suitable modifiers and additives such as PLLA. Ford, Mazda, and Toyota, all modern car manufacturing companies, use PLA-PLLA blends to make parts. They can also be used to make car interiors such as doors, pedals, and dashboards made by BIOFRONT.

Agriculture

PLA has been used in agriculture since the 1950s. The plastics used in agriculture are called plasticulture. Their main roles are mulch as protection of soil from insects and birds, use as drip irrigation pipes, and shielding of greenhouse tunnels [4].

As environmental issues intensify, biodegradable bioplastics such as PLA and PHA are gradually replacing traditional plastics in the agricultural sector. However, pure PLA is not widely used in this industry due to its poor thermal properties that limit its application range. Therefore, blends of PLA with other biodegradable polyesters have a wider market. However, plasticulture is still a pending development in agriculture. Not only because of the aforementioned performance limitations but also due to the high cost of polymers in general, the implementation of bioplastics in agriculture is still premature [14].

IV. The Market Overview of PLA

The global polylactic acid market size was estimated at USD 624.97 million in 2022 and is expected to grow at a Compound Annual Growth Rate (CAGR) of 21.4% from 2023 to 2030. The expanding use of bioplastics in packaging, automotive and transportation, agriculture, electronics, and other applications is expected to increase the demand for Polylactic Acid (PLA) during the forecast period. Demand for the product is high in end-use industries such as agriculture, textile, transportation, and packaging [15].

North America has the largest revenue share of over 41.0% in 2022. Europe is one of the major markets for polylactic acid followed by Asia Pacific. The Asia Pacific market is expected to grow rapidly due to factors such as shortage of fossil fuel resources, increasing demand for PLA in developing countries such as Indonesia, Malaysia, and Thailand, and fluctuating oil prices. China leads the Asia Pacific PLA market in terms of volume and revenue by 2020.

Compared to petroleum-based materials, it is biodegradable and does not produce hazardous gases during combustion; therefore, its demand in this application is expected to remain strong during the forecast period. Bioplastic packaging, especially one-off packaging, has gained significant legislative support due to the need to reduce Greenhouse Gas (GHG) emissions.

A. Domestic Market

On January 16, 2020, China’s National Development and Reform Commission (NDRC) and the Ministry of Ecology and Environment (MOE) jointly issued Opinions on Further Strengthening the Control of Plastic Pollution, which requires that the management system for the production, circulation, consumption and recycling and disposal of plastic products be perfected by 2025, and that the use of non-degradable plastics be gradually banned and restricted. This policy has greatly increased the demand for PLA materials in China [16].

The polylactic acid market has tremendous growth prospects in China. Due to the promotion of the policy, China’s domestic enterprises are competing to enter the hundreds of billions of biodegradable plastics markets. As of 2021, China’s PLA production capacity is about 520,000 tons per year. It is expected that in the next 3 to 5 years capacity will add 3.61 million tons [16]. This indicates that the domestic market has great development potential and could be the largest market globally in the future.

In addition, the domestic market has a close relationship with the overseas market. From January to June 2023, the ex-factory quotations of mainstream grades of PLA were stable at RMB 21–23 per kg.2022 For the whole year, China imported 19,563 tons of PLA, down 22.7% year-on-year, and exported 7,980 tons, up 28.7% year-on-year.2023 From January to May 2023, China imported 10,620.8 tons of PLA; and exported 3,189.8 tons [15]. According to the data, the Chinese market can meet the demand of many markets overseas apart from meeting domestic demands.

The rapid development of the domestic market depends on the development of relevant PLA enterprises. To date, there have been many enterprises producing PLA products. For example, Jindan Technology is mainly engaged in the research and development, production, and sales of lactic acid and its series of products, and can stably produce propylate products with qualified quality. At present, Jindan has a production capacity of 183,000 tons of lactic acid and its derivatives. At the same time the company formalized the construction of 75,000 tons of polylactic acid project, to be completed, Jindan Science and Technology will have a full industrial chain from corn to polylactic acid. The total production capacity of Jindan Technology and Anhui Fengyuan Enterprises accounts for 30.65% of the global total production capacity [16]. The strong competitiveness of these domestic PLA enterprises reflects the great influence and promise of the Chinese market over the world.

B. Overseas Market

The overseas market has also been rapidly development over the past decades. The world biodegradable plastics market is expected to more than double to $6.73 billion by 2025 from $3.02 billion in 2018.

According to the statistics of the European Bioplastics Association, in 2021, the global total production capacity of bio-based plastics is about 2.42 million tons. Among them, the annual production capacity of PLA is about 500,000 tons, and the producers mainly include the U.S. NatureWorks, the joint venture between Cobian and Total. Today, U.S.-based NatureWorks is the world’s leading industrial-scale PLA producer. It was founded in 2002 with a PLA production line capacity of 70,000 tons. In 2015, it expanded its capacity by 150,000 tons. The second-largest PLA overseas market is Thailand, which is part of a joint venture between Total and Corbion. It produced 75,000 tons of PLA. Next, Synbra built a 5,000-ton production line to make scalable PLA (BioFoam TM) [15].

The global market produces PLA products that are applied in many fields. Food packaging is one of the major applications of the PLA industry. PLA-based plastic bottles are disposable, durable, and offer properties such as gloss and transparency. In addition, stringent regulations on single-use plastics in countries such as Taiwan, the UK, Zimbabwe, New Zealand, and several states in the US (including New York, Hawaii, and California) are significantly driving the demand for PLA in the packaging end-use sector. The packaging segment dominated the end-use segment and accounted for the largest revenue share of over 36.0% in 2022 owing to the extensive use of PLA in the manufacture of cans, containers, and bottles as well as fresh food packaging. Global customer preference for filled and eco-friendly packaging has compelled manufacturers to use PLA in packaging.

Textiles is another major industry with a huge market penetration and growth rate, as PLA provides smooth and comfortable material. In addition, PLA offers breathability, drape, excellent moisture, and durability. These factors are expected to facilitate the integration of PLA into the textile industry over the forecast period. For instance, in May 2023, DuPont announced the acquisition of Spectrum Plastics Group. The proposed acquisition will add to DuPont’s existing product range in biopharmaceutical and pharmaceutical processing, packaging, and medical devices.

V. Summary of PLA Advantages, Disadvantages, and Applications

A. Discussion on the Advantages and Drawbacks of PLA Material

PLA as a material has many advantages and application prospects. First, it is environmentally friendly, can be derived from renewable resources, and has little to no negative impact on the environment during handling and processing. Secondly, PLA has good biocompatibility for biomedical applications and does not have toxic or carcinogenic effects on the human body. In addition, PLA has better thermal processing properties than other biopolymers and can be formed into bioplastics through a variety of processes.

However, PLA has some drawbacks. First, its brittleness limits its use in certain applications, such as in products that need to be plasticized under high stress, such as screws and fracture fixation plates in the biomedical field. Second, the low degradation rate of PLA, which has a long service life in the biomedical field, may trigger an inflammatory response of tissues to it [4]. In addition, PLA is highly permeable to gases, which means it has poor barrier properties in some packaging applications.

B. Discussion on the Applications of PLA Material

Polylactic acid possesses a wide range of application advantages, which makes its application in various fields very promising. In the medical field, PLA materials can be used to manufacture various medical devices, such as sutures, stents, repairing blood vessels, etc. These devices usually need to be left inside the human body for a long time, so they need to have good biocompatibility and biodegradable properties. Polylactic Acid (PLA) materials have an irreplaceable advantage in this field as they can be completely degraded and have no effect on the human body. With the continuous development of science and technology, PLA materials will be used in the manufacture of high-tech medical devices, such as smart medical devices, etc. Nanoscale medical devices made of PLA nanomaterials explore the body more deeply. They will assist people in solving more difficult problems, which will become an important trend in the future medical industry.

In terms of packaging, PLA materials can also be used to make a variety of packaging materials, such as food packaging, and daily necessities packaging. It is foreseeable that PLA material will be the material of choice for many packaging needs. It has excellent durability and sealing performance, and can completely replace traditional plastic materials. In addition, with the continuous progress of production technology, PLA materials can be manufactured into a variety of different shapes of packaging materials, such as film materials, foam materials, and so on [9].

In the field of biomaterials, the application prospect of PLA materials is also very broad. PLA materials can be used to manufacture artificial organs and tissue repair materials, which can be gradually degraded and transformed by biomass inside the human body, reducing the damage to the human body. In addition, PLA materials can also be used to manufacture facial fillers, biodegradable sutures, etc. These materials can be more effective in realizing cosmetic and medical needs.

C. Future Perspectives

In addition to the above fields, PLA materials can also be used to manufacture a variety of other materials, such as fibers, films, coatings, and so on. As production technology continues to improve, the properties and applications of PLA materials will continue to expand. It is expected that in the next decade, the application prospects of PLA materials will be even wider and may cover more fields, such as 3D printing, self-assembling materials, and even venturing into the apparel industry.

Polylactic Acid (PLA) is a common bioplastic that can be used for 3D printing, and its 3D printed products have a smooth surface, do not warp, and have been widely used in biomedical applications including medical models, bone tissue recovery scaffolds, and drug delivery systems.

There have been successful cases of PLA disks fabricated using FDM13D printing technology and tested in vitro using human fetal osteoblasts, which showed no cytotoxicity of PLA disks, thus proving that the 3D printing process has no negative impact on the biocompatibility of PLA materials, which can be further used in reconstructive surgeries and the production of scaffolds of various shapes. Meanwhile, 3D printed PLA scaffolds fabricated using low-temperature plasma (CAP) treatment, which showed a significant increase in the hydrophilicity of the scaffolds, could positively affect the proliferation of synthetic osteoblasts. If we compare PLA with ABS, another thermoplastic most commonly used in FDM 3D printing, we see that the former generally does not have the same strength and flexibility as the latter, although it is also less prone to deformation. However, the use of PLA on parts with little mechanical complexity is recommended, as it is much simpler to use. Moreover, ABS releases toxic gases when heated during the manufacturing process. Therefore, it is much safer to use PLA, which is why it is a highly regarded 3D printing consumable [1].

When it comes to post-processing, PLA usually does not require complicated steps. When removing the part, you may encounter problems with the adhesion of the first printed layer. Therefore, it is recommended to use a special adhesive on the printing plate to facilitate the removal of the part. To improve the surface condition of the parts, the user can sand them and treat them with acetone if necessary. The supports can be easily removed with tweezers if used, or dissolved if a soluble support structure is used.

In summary, PLA material is a very promising material with excellent biodegradability, biocompatibility, and plasticity. It has a wide range of applications covering medical, packaging, biomaterials, and other fields. With the development of production technology, the properties and applications of PLA materials will continue to improve and expand. As a sustainable material, the application of PLA will promote the further development of environmental protection and human health.

VI. Conclusion

This manuscript investigates the basic properties of Polylactic Acid (PLA) materials as its main aim while exploring their probable real-life applications. The discussion primarily focused on the biocompatibility and biodegradability of PLA, highlighting their significance. Furthermore, other notable properties such as high machinability, processability, and its potential as a sustainable material were thoroughly examined. To effectively utilize PLA materials, both their advantages and limitations were taken into consideration. Various processing techniques, including hot-melt extrusion, injection molding, blow molding, and thermoforming, were then presented to showcase their applicability. Its main applications were categorized into biomedical, packaging, automotive industry, agriculture industries, and 3D printing. Additionally, a global market overview was provided to offer insights into the current state of PLA production and consumption. Based on current research and progress, the outlook for the future shows a wide range of possibilities. Of course, PLA has its limitations, and it cannot be asserted that it can completely replace traditional petroleum-based plastics. However, in the foreseeable future, PLA and its derivatives will have a broader future. With increasing environmental awareness, the demand for PLA as a sustainable materials will continue to grow. Overall, the further development of PLA will further promote the goal of sustainable development and play an important role in various fields.

Conflict of Interest

The author has claimed that no conflict of interest exists.

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