

Application of Polylactic Acid in Clinical Medicine

Zhihan Zhou *

Guangzhou Foreign Language School, Guangzhou, China

* Corresponding Author Email: Angelzhou2008@qq.com

Abstract. Polylactic acid (PLA), a bio-based and biodegradable material, shows significant potential in environmental protection and clinical medicine. Derived from renewable resources, PLA's biodegradability reduces long-term environmental pollution by allowing it to decompose rapidly under specific conditions. This review explores PLA's applications in clinical medicine, emphasizing its mechanical properties, biocompatibility, and controlled degradation rates. The study covers PLA's extensive use in drug delivery systems, absorbable sutures, and tissue engineering scaffolds, highlighting its compatibility with human tissues and low immunogenicity. Research methods and designs, including in vitro and in vivo experiments, are discussed to evaluate PLA's efficacy and safety. The challenges of high production costs and specific degradation conditions are also addressed. Future research directions include developing new catalysts to improve synthesis efficiency and exploring renewable raw materials to reduce costs and environmental impact. As global awareness of sustainable development grows, the demand for PLA and other degradable plastics is expected to increase, expanding their applications in various fields. In conclusion, PLA offers substantial advantages in reducing reliance on fossil fuels and mitigating environmental pollution, while providing innovative solutions in the medical field. Technological advancements and increased production are anticipated to lower costs, making PLA more economically competitive and accelerating its application in both environmental protection and clinical medicine.

Keywords: Biodegradable plastics; clinical medicine applications; polylactic acid (PLA).

1. Introduction

Environmental protection is a long-term and important issue in human history. It not only affects the healthy development of humanity but also directly influences economic harmony and ecological sustainability. Faced with the overconsumption of resources and the destruction of ecosystems, environmental protection has urgently become one of the global challenges. In this context, governments worldwide have taken measures such as China's "Ten Measures for Air," "Ten Measures for Water," and "Ten Measures for Soil," which have become core policies for the country's environmental governance. Additionally, the European Union has formulated the "Plastic Strategy" to reduce plastic waste, the United States has implemented the "Clean Air Act" and the "Clean Water Act" to control pollution, and Japan has enacted the "Act on the Promotion of Effective Utilization of Resources" to promote resource recycling. These measures reflect the global emphasis and efforts on environmental protection.

Plastic pollution, as one of the main sources of environmental pollution, heavily relies on non-renewable resources during production and is difficult to degrade in natural environments, imposing a long-term burden on the environment. Polylactic acid (PLA), as a bio-based and biodegradable plastic, offers an effective solution. PLA not only derives from renewable resources, reducing dependence on fossil fuels, but also its biodegradability in natural environments provides a way to alleviate the long-term pollution caused by traditional plastics. Additionally, PLA's excellent mechanical properties make it a focus of research in many fields, especially in clinical medicine. Due to its good biodegradability, biocompatibility, hydrolysis resistance, and chemical stability, the application of PLA in clinical medicine shows great potential in improving surgical efficiency, biocompatibility, and safety. However, the degradation process of PLA requires specific environmental conditions, such as particular temperature and humidity, which are difficult to achieve in natural settings. Recent studies have shown that adjusting the copolymer composition of PLA can significantly improve its mechanical properties, making it competitive in more application scenarios.

In summary, PLA, as an environmentally friendly material, has great potential, but challenges such as high production costs and stringent degradation conditions need to be addressed for its widespread application. Future research should focus on PLA modification technologies and the formulation and implementation of relevant policies. This paper aims to deeply explore the application of PLA in clinical medicine and its contribution to environmental protection, particularly its efficacy and safety in specific clinical applications. By thoroughly examining the environmental advantages, challenges, and practical applications of PLA in clinical medicine, this study aims to provide a comprehensive theoretical framework to assess the actual value and application prospects of PLA in environmental protection and the medical field. Through a critical analysis of the latest research and policy literature, this paper strives to highlight the innovation in research, including new insights at the theoretical, methodological, and application levels.

First, this paper reviews the environmental impact of traditional plastics and emphasizes the importance of introducing biodegradable materials such as PLA. Then, it discusses the good compatibility of PLA with clinical medicine in detail, including its application in supporting cell growth and tissue regeneration, and how PLA's biocompatibility and degradability can improve the efficiency and safety of clinical surgeries. Additionally, the research methods and design will be explored to ensure readers fully understand the execution framework and originality of this study.

By highlighting the potential application of PLA in clinical medicine, this paper not only contributes to the existing knowledge system but also emphasizes its significance in practical fields, particularly environmental protection and clinical medicine. In the future, further research and application of PLA and other degradable plastics are expected to achieve breakthroughs in medical devices, medical packaging, and other fields, providing more solutions for current clinical medicine and contributing to the goal of sustainable environmental development.

2. Environmental Friendliness of PLA

PLA is a bio-based plastic produced from renewable resources through a fermentation process. It is highly compatible with the surrounding environment, as it can be biodegraded and absorbed without causing any adverse effects on the environment [1]. The bio-based nature of PLA indicates that its raw materials are derived from natural sources, which helps to reduce dependence on petroleum resources during production.

The biodegradability of PLA allows it to be decomposed by microorganisms into water, carbon dioxide, and organic fertilizers under specific conditions, such as in industrial composting facilities. This characteristic makes PLA an environmentally friendly material that can return to nature through biodegradation after use, thus reducing long-term environmental pollution. In industrial composting facilities, PLA can decompose relatively quickly, releasing water and carbon dioxide without producing toxic substances. This property minimizes the likelihood of plastic waste persisting in landfills, thereby reducing the potential risk of environmental pollution. Furthermore, since PLA can be sourced from agricultural waste materials, such as sugars and grains, its production can help achieve resource utilization of agricultural waste, further decreasing reliance on fossil fuels. In contrast, the production and disposal of traditional plastics generate more greenhouse gas emissions.

In life cycle assessment (LCA), because PLA does not release excess carbon dioxide into the atmosphere during its entire production and use process, its production process typically shows a lower carbon footprint [2]. Carbon degradation is the process by which microorganisms transform and migrate the carbon elements in organic carbon compounds, thereby accelerating the cycling of carbon elements in nature. When PLA is eventually biodegraded, the amount of carbon dioxide released is roughly equal to the amount fixed during its growth, forming a relatively closed carbon cycle. Studies have found that the presence of PLA can increase the abundance of genes related to carbon degradation while reducing the abundance of genes related to carbon fixation [3].

However, the biodegradability of PLA also means that it has poor stability in natural environments and is easily attacked by microorganisms. Additionally, PLA has weak nucleation ability and low

crystallization rate under homogeneous conditions, resulting in mechanical properties, such as tensile strength and impact strength, that are generally lower than those of traditional plastics [4]. The degradation process of PLA includes abiotic processes, such as hydrolysis shown in Figure 1, oxidation, and photolysis, as well as biotic processes like microbial digestion.

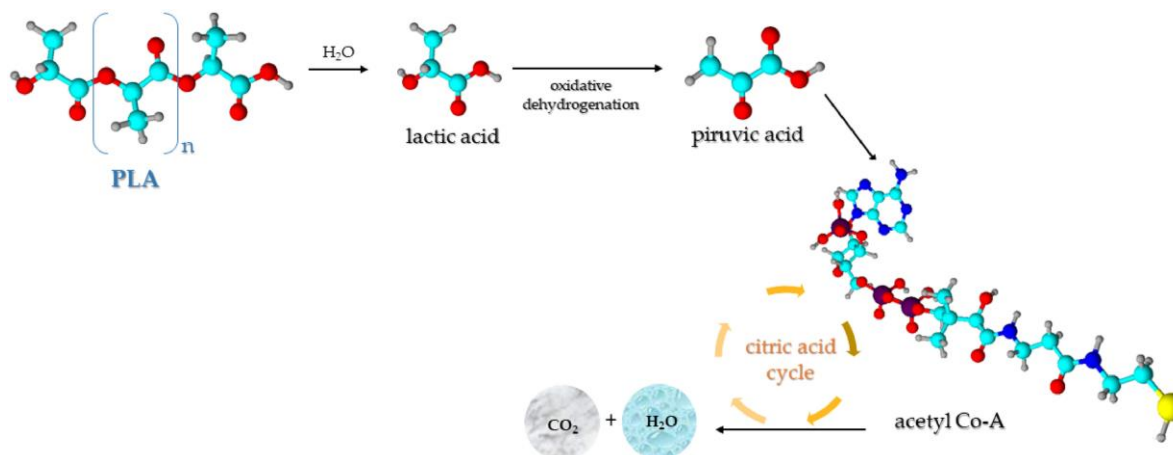


Fig 1. Metabolic pathways of PLA degradation [5]

In natural environments, PLA first undergoes hydrolysis reactions, where water molecules gradually penetrate the polymer chains, causing the polymer chains to break into smaller molecular fragments. Over time, these molecular fragments continue to be further broken down into smaller units, such as lactic acid monomers. Microorganisms, particularly bacteria and fungi, play a crucial role in the degradation of PLA. They secrete enzymes that catalyze the breaking of PLA molecular chains, accelerating the degradation process. These enzymes can specifically recognize and cleave PLA molecules, making them more accessible for microbial utilization.

The degradation of PLA depends not only on the characteristics of the sample, such as crystallinity, molecular weight, sample morphology, and molecular and supramolecular structure, but also on the surrounding environmental conditions, including the presence of water and moisture, temperature, acidity conditions, the presence of oxygen, and the type and activity of microorganisms. Under suitable temperature, humidity, and pH conditions, microbial activity is highest, and PLA degrades the fastest. Therefore, in tropical and subtropical regions, PLA may degrade more rapidly than in colder areas. The diversity and abundance of microorganisms in the soil also affect the degradation rate of PLA. Soils rich in nutrients and organic matter typically have higher microbial activity, thus promoting the degradation of PLA [6].

3. Application of PLA in Clinical Medicine

PLA materials have shown significant progress and potential applications in the field of clinical medicine due to their high mechanical strength, high modulus, biodegradability, biocompatibility, bioabsorbability, transparency, low toxicity, and ease of processing. These characteristics make PLA an ideal scaffold material for supporting cell growth and tissue regeneration [7]. Figure 2 illustrates some of the application properties of PLA in the medical field [8].

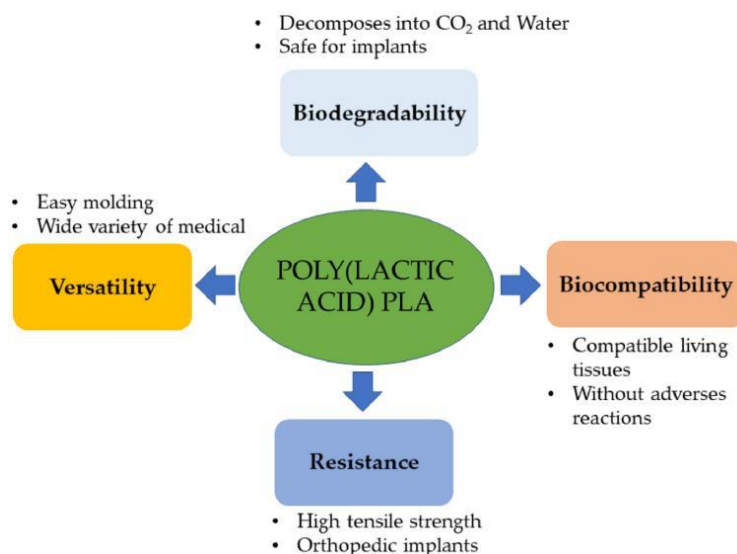


Fig 2. Medical application characteristics of PLA [8]

PLA is widely used in the manufacturing of engineered tissue scaffolds. It can be processed into various shapes and sizes to meet the requirements of different tissue engineering needs. For example, PLA scaffolds can be used in bone tissue engineering, soft tissue engineering, and cardiovascular tissue engineering. In bone tissue engineering, PLA scaffolds can serve as fillers for bone defects, combined with other biomaterials, such as hydroxyapatite, to enhance osteoinductivity and support the growth and regeneration of bone tissue [9]. In soft tissue engineering, PLA can also be combined with other biomaterials, such as collagen to improve its mechanical properties and bioactivity and used for the repair and regeneration of soft tissues such as skin, muscles, and cartilage [10]. In cardiovascular tissue engineering, PLA scaffolds can be used to manufacture coronary artery stents, helping to restore vascular patency. Additionally, PLA can be combined with other biomaterials like polycaprolactone to enhance its affinity for vascular endothelial cells [11]. Compared to other stents, bioabsorbable stents, which degrade into water and carbon dioxide after functioning in the body, can effectively overcome issues such as in-stent restenosis, thrombosis, inflammation caused by long-term presence in blood vessels, and the need for antiplatelet medications [12].

The biocompatibility of PLA is evident in its non-toxic response to human tissues and low immunogenicity. This means that when PLA implants are placed inside the human body, they do not cause significant immune system reactions, such as inflammation or tissue rejection. Upon contact with biological media, the polymer begins to decompose, usually through hydrolysis, breaking down into lactic acid (LA) or carbon dioxide and water. These products are metabolized within cells or excreted through urine and respiration [13]. The low immunogenicity of PLA is related to its molecular structure. PLA molecules are linear polymers composed of lactic acid units linked by ester bonds, with a relatively simple structure lacking complex functional groups, reducing the likelihood of being recognized as foreign by the immune system. Additionally, PLA degrades in the body through normal metabolic pathways, and its degradation products, lactic acid and carbon dioxide, are normal metabolic products that can be absorbed and utilized by the body, further reducing potential immune reactions.

The degradable nature of PLA is crucial for avoiding secondary surgeries to remove implants. In many medical scenarios, such as fracture fixation, drug release, or tissue engineering, traditional non-degradable implants need to be surgically removed after completing their tasks, which increases patient pain, recovery time, and medical costs. In contrast, PLA implants gradually degrade after fulfilling their function, with the final degradation product being lactic acid, a naturally occurring substance in the human body that is non-toxic [14]. Over time, PLA implants are replaced by newly formed tissue, eliminating the need for secondary surgery. Furthermore, the degradation rate of PLA implants can be controlled by altering their molecular structure and preparation process. For instance, by adjusting the molecular weight, crystallinity, and copolymer composition of PLA, implants with

different degradation rates can be designed to meet the needs of various clinical applications. Additionally, the surface properties of PLA implants can be optimized through physical or chemical methods to improve cell adhesion, proliferation, and tissue regeneration [15].

4. Research Methods and Design

In the study of the efficacy and safety of PLA applications in clinical medicine, various research methods and designs have been employed to ensure the scientific rigor and reliability of the results. The following outlines the specific research methods and design steps:

To systematically evaluate the performance of PLA in clinical applications, a series of experiments were designed, including both *in vitro* and *in vivo* experiments. The *in vitro* experiments primarily included mechanical performance testing, degradation characteristics studies, and cell compatibility tests of PLA materials. The *in vivo* experiments mainly involved the implantation of PLA scaffolds in animal models to observe their degradation process and tissue regeneration effects in the body.

4.1. In Vitro Experiments

In vitro, experiments involved using PLA to assess its degradation characteristics and mechanical performance under different conditions. For example, tensile, compression, and bending tests were conducted to evaluate its mechanical strength and ductility [16].

4.2. Cell Compatibility Tests

Mechanical performance tests, including tensile tests, compression tests, and bending tests, were conducted to evaluate the mechanical properties of PLA materials, such as tensile strength, modulus, and elongation at break [17]. The experiments were carried out under standard environmental conditions to ensure the reproducibility and reliability of the results. PLA materials exhibited excellent mechanical properties, making them an ideal choice for medical devices such as bone fixation devices [18]. During the experiments, PLA materials of different specifications and compositions were selected to assess their suitability for various clinical applications. Sample preparation included PLA melt extrusion, solution casting, and 3D printing techniques. Different shapes and sizes of PLA scaffolds were prepared according to experimental requirements to adapt to various experimental designs and clinical application scenarios [19]. Using 3D printing technology, complex-shaped PLA scaffolds can be manufactured, enhancing their application potential in tissue engineering and regenerative medicine [20].

4.3. Animal Model Experiments

In animal models such as rats or rabbits, PLA scaffolds were implanted to observe their degradation process and tissue regeneration effects *in vivo*. Histological analysis and imaging techniques were used to evaluate the degradation rate of PLA scaffolds, the distribution of degradation products, and the response of surrounding tissues. The experimental results were used to guide the optimization design of PLA materials and the formulation of clinical application plans. In animal experiments, PLA scaffolds showed good tissue regeneration effects and biocompatibility, indicating their potential in clinical applications [18].

4.4. Mechanical Performance Tests

Mechanical performance tests, including tensile tests, compression tests, and bending tests, were conducted to evaluate the mechanical properties of PLA materials, such as tensile strength, modulus, and elongation at break. The experiments were carried out under standard environmental conditions to ensure the reproducibility and reliability of the results. PLA materials exhibited excellent mechanical properties, making them an ideal choice for medical devices such as bone fixation devices [19]. During the experiments, PLA materials of different specifications and compositions were selected to assess their suitability for various clinical applications. Sample preparation included PLA

melt extrusion, solution casting, and 3D printing techniques. Different shapes and sizes of PLA scaffolds were prepared according to experimental requirements to adapt to various experimental designs and clinical application scenarios. Using 3D printing technology, complex-shaped PLA scaffolds can be manufactured, enhancing their application potential in tissue engineering and regenerative medicine [20].

4.5. Safety Assessment

Based on animal experiments, the biosafety of PLA materials *in vivo* was evaluated, including inflammatory responses, immune responses, and tissue compatibility after long-term implantation. Long-term observation and periodic sampling were conducted to ensure the safety of PLA materials in practical clinical applications. Long-term animal experiments indicated that the degradation products of PLA materials did not cause significant inflammatory or immune responses in the body, confirming their biosafety [21].

5. Opportunities and Challenges of PLA

The production process of lactic acid, the raw material for PLA, is relatively complex, leading to higher production costs. Additionally, the synthesis of PLA requires specific catalysts and special conditions, further increasing production costs. For instance, research shows that the production cost of PLA is several times higher than that of traditional non-biodegradable plastics [22]. These factors limit the widespread adoption of PLA in large-scale clinical applications, particularly in developing countries and resource-limited regions. Furthermore, the production process of PLA significantly influences its production cost. PLA is typically synthesized through polycondensation reactions, which require precise control of conditions such as temperature, pressure, and pH to ensure that the polymer's molecular weight and molecular weight distribution meet clinical application requirements [23].

The synthesis of PLA results in a relatively wide molecular weight distribution, and PLA itself is a linear polymer, which often results in material strength that fails to meet requirements. PLA exhibits high brittleness, low heat distortion temperature, and poor impact performance [24]. Additionally, the low crystallinity of PLA leads to generally low impact strength, making it prone to breakage under sudden impacts. This limitation restricts its application in areas requiring impact load resistance, such as sports equipment and automotive parts [25].

Several feasible solutions have been proposed to address the high production cost of PLA. Firstly, optimizing the synthesis methods of PLA by using more efficient catalysts and optimizing reaction conditions can significantly reduce production costs. Furthermore, developing continuous production processes to replace traditional batch production processes can also improve production efficiency and reduce costs [26]. Secondly, improving the pre-treatment and post-treatment processes of raw materials can increase raw material conversion rates, reduce raw material waste, and further lower production costs [27].

To address the issue of poor mechanical performance of PLA, some feasible solutions have also been proposed. Firstly, compounding PLA with materials that have good mechanical properties (such as glass fibers, carbon fibers) can enhance the mechanical performance of PLA. By adjusting the ratio of composite materials and processing techniques, the mechanical performance of PLA can be optimized to meet the needs of different applications [28]. Secondly, using nanotechnology to modify PLA, such as adding nano-fillers (like clay, diatomaceous earth), can significantly improve the mechanical performance and thermal stability of PLA. The addition of nano-fillers can also enhance the processing performance of PLA [29].

In the future, research directions for PLA can focus on the development of new catalysts. Research and development of new catalysts aim to improve the synthesis efficiency of PLA and reduce production costs. New catalysts can also improve the polymerization reaction of PLA, increasing the molecular weight and yield of the polymer [30]. Additionally, bio-based raw materials are another

key research focus for the future of PLA. Exploring the use of renewable bio-based raw materials to replace traditional petrochemical raw materials aims to reduce the production cost of PLA and decrease environmental impact, promoting sustainable development and a circular economy [31].

6. Conclusion

PLA, as a bio-based and biodegradable material, demonstrates broad application potential in environmental protection and clinical medicine. Its biodegradability and biocompatibility allow PLA to rapidly decompose in natural environments, reducing long-term environmental pollution. Additionally, PLA has been widely used in clinical medicine due to its good mechanical properties and controllable degradation rates, in areas such as drug delivery systems, absorbable sutures, and tissue engineering scaffolds.

As global awareness of sustainable development and environmental protection increases, the market demand for PLA and other degradable plastics is expected to continue growing. The application of these materials is likely to expand into more fields, such as agriculture, food packaging, and disposable products. Degradable plastics, as alternatives to traditional plastics, can significantly reduce environmental pollution. On the policy level, many countries have implemented regulations restricting the use of traditional plastics and encouraging the use of degradable plastics, providing strong support for the development of PLA and other degradable plastics.

In the field of clinical medicine, the application prospects of PLA are also very broad. With a deeper understanding of PLA's properties and the development of new applications, its use in the medical field will further expand. Particularly, the development of new catalysts and nanotechnology can improve the synthesis efficiency and mechanical properties of PLA, reduce production costs, and accelerate its application in clinical medicine.

In the future, with the expansion of production scale and maturation of technology, the cost of PLA and other degradable plastics is expected to decrease further, making them more economically competitive, and thereby accelerating their application in environmental protection and clinical medicine. PLA not only has significant advantages in reducing reliance on fossil fuels and decreasing environmental pollution but also offers innovative solutions in the medical field, promoting the development of medical devices, medical packaging, and other areas, thus contributing significantly to achieving sustainable environmental development goals.

References

- [1] Wang JY, Liang SR, Zhang MY, et al. Progress in the study and applications of polylactic acid fiber. *Journal of Textile Science and Engineering*, 2020, 37(2): 85-90.
- [2] LCA Confirms the Low Carbon Footprint of PLA. *Journal of Plastics Technology*, 2019, 47(11): 39.
- [3] Yu H. The ecological effects of typical microplastics on soil carbon cycle microorganisms[D]. Shandong Agricultural University, 2024.
- [4] Chen ZY, Fu Y, Zhang X, et al. Degradation behavior and application research of PLGA[J]. *China Plastics*, 2024, 38(01): 92-99.
- [5] Khouri N G, Bahú J O, Blanco-Llamero C, et al. Polylactic Acid (PLA): Properties, Synthesis, and Biomedical Applications-A Review of the Literature[J]. *Journal of Molecular Structure*, 2024, 138243.
- [6] Gong YH, Wang Shu. Study on the industrialization and implantation application of new biological medical material poly(lactic acid)[J]. *Contemporary Chemical Research*, 2024, 06: 24-26.
- [7] Zhou, H., & Ma, P. X. Biodegradable polymers in medical applications. *Progress in Polymer Science*, 2002, 27(10), 1019-1048.
- [8] SHI Biao, LI Yu Xia, YU Xhua, YAN Wang. Short-term load forecasting based on modified particle swarm optimizer and fuzzy neural network model. *Systems Engineering-Theory and Practice*, 2010, 30(1): 158-160.

- [9] Khouri N G, Bahú J O, Blanco-Llamero C, et al. Polylactic Acid (PLA): Properties, Synthesis, and Biomedical Applications-A Review of the Literature[J]. *Journal of Molecular Structure*, 2024, 138243.
- [10] Kumar MNVR, Tandon RP. Biodegradable polymeric materials for tissue engineering and drug delivery. *J Mater Chem*. 2005, 15(17):1857-1880.
- [11] Tiwari S, Patil R, Bahadur P. Polysaccharide Based Scaffolds for Soft Tissue Engineering Applications. *Polymers*. 2019, 11(1):1.
- [12] Gong YH, Wang Shu. Study on the industrialization and implantation application of new biological medical material poly(lactic acid)[J]. *Contemporary Chemical Research*, 2024, (06): 24-26.
- [13] Da Silva D, Kaduri M, Poley M, et al. Biocompatibility, biodegradation and excretion of polylactic acid (PLA) in medical implants and theranostic systems[J]. *Chemical Engineering Journal*, 2018, 340: 9-14.
- [14] Khouri N G, Bahú J O, Blanco-Llamero C, et al. Polylactic Acid (PLA): Properties, Synthesis, and Biomedical Applications-A Review of the Literature[J]. *Journal of Molecular Structure*, 2024, 138243.
- [15] Wang WX. 3D printing of PLA/HA/Mg scaffolds for bone tissue engineering[D]. Qingdao University, 2023.
- [16] Hamad K, Kaseem M, Yang H W, et al. Properties and medical applications of polylactic acid: A review[J]. *Express polymer letters*, 2015, 9(5).
- [17] Chen T, Zhao X, Weng Y. Self-assembled polylactic acid (PLA): Synthesis, properties and biomedical applications[J]. *Frontiers in Chemistry*, 2023, 10: 1107620.
- [18] Shi H, Gan Q, Liu X, et al. Poly (glycerol sebacate)-modified polylactic acid scaffolds with improved hydrophilicity, mechanical strength and bioactivity for bone tissue regeneration[J]. *RSC advances*, 2015, 5(97): 79703-79714.
- [19] Davachi S M, Kaffashi B. Polylactic acid in medicine[J]. *Polymer-Plastics Technology and Engineering*, 2015, 54(9): 944-967.
- [20] Tyler, B., Gullotti, D., Mangraviti, A., Utsuki, T., & Brem, H. Polylactic acid (PLA) controlled delivery carriers for biomedical applications. *Advanced drug delivery reviews*, 2016, 107, 163-175.
- [21] Conn R E, Kolstad J J, Borzelleca J F, et al. Safety assessment of polylactide (PLA) for use as a food-contact polymer[J]. *Food and Chemical Toxicology*, 1995, 33(4): 273-283.
- [22] Zhou H, Zhang X, Li Y. A review of the production methods and applications of polylactic acid (PLA) in biomedical engineering. *Materials Science and Engineering: B*. 2019, 245:117674.
- [23] Lunt RR. Biodegradable aliphatic polyesters: Part I. Poly(lactic acid). *J Macromol Sci Phys B*. 1998, 35(5):975-988.
- [24] Wang J, Cui FD. Synthesis and application study of polylactic acid [J]. *Jiangxi Chemical Industry*. 2023, 39(04):5-8.
- [25] Athanassiou N, Galiotis C, Bourmpakis K. Mechanical properties of polylactic acid based biomaterials. *J Biomater Appl*. 2010, 25(2):121-128.
- [26] Zhou H, Zhang X, Li Y. A review of the production methods and applications of polylactic acid (PLA) in biomedical engineering. *Mater Sci Eng B*. 2019, 245:117674.
- [27] Lim SW, Hui D, Teo EL. The effect of processing conditions on the mechanical properties of injection moulded poly(lactic acid). *J Mater Process Technol*. 2008, 203(2):367-373.
- [28] Chen J, Wang Q. Mechanical properties of PLA-based composites and their applications in biomedical fields. *Composites Part B: Engineering*. 2019, 168:123-141.
- [29] Ray A, Okamoto Y. Biodegradable polymers for medical applications. *Prog Polym Sci*. 2003, 28(7):603-632.
- [30] Zhou H, Zhang X, Li Y. A review of the production methods and applications of polylactic acid (PLA) in biomedical engineering. *Mater Sci Eng B*. 2019, 245:117674.
- [31] Domingo F, Ojeda A, Martínez-Izquierdo A, Iñiguez-Rodríguez M. Biodegradable and bioactive polylactic acid based materials for bone tissue engineering. *Mater Sci Eng C*. 2012, 32(7):3075-3083.