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Advancements in polylactic acid research: From material properties to sustainable applications

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Abstract: This review article provides a comprehensive examination of the latest advancements in the research and development of Polylactic Acid (PLA) and its composites, with a focus on enhancing material properties and exploring sustainable applications. As a biodegradable and bio-base polymer, PLA has emerged as a promising alternative to conventional petroleum-based plastics across various industries, including packaging, 3D printing, and biomedical fields. The review delves into studies investigating the effects of environmental conditions on PLA's hydrolytic stability and structural integrity, as well as the benefits of blending PLA with other biopolymers to improve its mechanical properties. It also covers research on optimizing three dimensional printing parameters for PLA, underscoring the importance of raster orientation and print layer thickness in achieving desired mechanical strength and object durability. Additionally, the incorporation of nanofillers and copolymers is discussed as a strategy for enhancing PLA's moisture resistance and overall performance. By summarizing key findings from a wide range of studies, this article aims to shed light on the significant progress made in PLA research, while pointing out future research directions to resolve existing limitations and fully capitalize on PLA's potential as a green material solution. To better cater to the needs of design engineers, this review highlights how advancements in PLA research can be directly applied to improve product design and functionality. Specifically, it discusses the enhanced mechanical properties, sustainability benefits, and versatility of PLA in various industrial applications, providing engineers with a deeper understanding of how to utilize PLA in eco-friendly design solutions.

Keywords: Additive manufacturing, three dimensional printing, polylactic acid, biodegradable polymers, mechanical properties, sustainable materials.

1. Introduction

Escalating environmental concerns associated with the accumulation of petroleum-based plastics have spurred the search for sustainable, biodegradable alternatives. Among these, Polylactic Acid (PLA) stands out as a frontrunner due to its bio-based origins and compostable nature. Derived primarily from renewable resources such as corn starch, or tapioca roots, PLA presents a reduced carbon footprint and an end-of-life biodegradability that positions it as an eco-friendly substitute for conventional plastics in numerous applications. This review article aims to explore the advancements in PLA research, focusing on its material properties, the enhancements achieved through blending and compounding, and its burgeoning applications in various domains of sustainability [1-12].

PLA's journey from a biopolymer primarily used in medical applications, due to its biocompatibility and biodegradability, to a broader utility in packaging, agriculture, textile, and notably, in three dimensional (3D) printing, underscores its versatility. However, despite its promising attributes, PLA's widespread adoption faces challenges, including its hydrolytic stability under humid conditions, mechanical strength, and thermal resistance, which can limit its performance in certain applications. Research efforts have been directed towards addressing these limitations, examining the effects of environmental conditions on PLA, and exploring the potential of PLA composites to enhance its property profile. Moreover, the role of 3D printing technology in expanding the applications of PLA has been significant. The ability to optimize printing parameters to tailor mechanical properties (MPs) of PLA objects offers a pathway to custom, on-demand manufacturing of biodegradable products. Concurrently, the environmental implications of PLA's life cycle, from production to degradation, warrant a comprehensive analysis to ensure its benefits are fully realized in the context of sustainability. This introduction

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sets the stage for a detailed review of the current state of PLA research, highlighting the innovative approaches being taken to overcome its inherent limitations and expand its utility. The following sections will discuss hydrolytic stability of PLA, the development of its mechanical properties, the optimization of 3D printing processes for PLA-based materials, and the environmental considerations that accompany the use of PLA. On the other hand, a holistic view of PLA's potential as a sustainable product will be presented [13-21].

1.1. Literatur surway

The burgeoning interest in sustainable materials has catalyzed a significant amount of research into biodegradable polymers, among which PLA has emerged as a particularly promising candidate. This literature survey aims to provide a comprehensive overview of the existing research on PLA, focusing on its synthesis, properties, modifications, applications, and environmental impact. As the demand for eco-friendly alternatives to petroleum-based plastics continues to rise, understanding the advancements and challenges associated with PLA becomes crucial for its successful integration into various industries. PLA, a biopolymer derived from renewable resources, offers a compelling combination of biodegradability, biocompatibility, and a relatively low carbon footprint [22-24]. These attributes make it an attractive material for applications ranging from packaging and disposable items to medical devices and 3D printing. However, the full potential of PLA is often hindered by certain limitations, including its MPs, thermal resistance, and hydrolytic stability, which can vary significantly depending on its crystalline structure and molecular weight. Recent studies have focused on overcoming these challenges through various strategies, including copolymerization, blending with other biopolymers or additives, and the development of PLA composites with enhanced properties. The literature also extensively explores optimization of processing techniques such as 3D printing, which has opened new avenues for customizing PLA's properties for specific applications. Moreover, environmental impact of PLA, from its production to post-use degradation, is a critical area of investigation. While PLA's biodegradability is a significant advantage over traditional plastics, the conditions under which it degrades and the by-products of this process require careful consideration to ensure its environmental benefits are maximized.

This literature survey will delve into these key areas of PLA research, highlighting the latest findings, identifying gaps in current knowledge, and suggesting directions for future studies. By synthesizing the wealth of research on PLA, this survey aims to contribute to the ongoing efforts to develop sustainable materials that can meet the needs of a variety of applications while minimizing environmental impact.

Literature review has been categorized under subheadings according to the focal points of the study areas.

1.1.1 Material properties and stability

In their work, Letcher and Waytashek (2014) used a home-type 3D printer to apply tensile, bending, and fatigue tests to samples printed with commercial PLA filament, accessible to a home user. They printed samples at 0, 45, and 90° raster orientation angles to test the effects of part strength orientation, determined all sample sizes according to ASTM D638 standards, and printed the samples at 100% fill density. Tensile test samples were tested at room temperature with a displacement speed of 5 mm/min. They also conducted tensile tests on PLA filaments, performing experiments at inter-head distances of 200 mm and pulling speeds of 500, 200, 50, and 5 mm/min. Tensile tests on printed samples found that 45° raster-oriented samples had the highest strength. In fatigue testing, 90° raster-oriented samples showed the least resistance to fatigue loads, while 45° and 0° raster-oriented samples had very similar fatigue lives, necessitating further research. They also examined the printed samples under a microscope and determined the sizes of voids formed during the printing process [25].

Kaygusuz et al., (2018) the effect of parameters such as fill density and nozzle temperature on MPs of materials printed with PLA in a 3D printer was examined. Tensile test specimens printed according to ASTM D638- Type 4 standard were tested at room temperature with a displacement speed of 5 mm/min. It was observed that an increase in nozzle temperature resulted in an increase in mechanical strength of specimens. Scanning Electron Microscope (SEM) images showed that the increase in nozzle temperature reduced the porous structure in the specimen. A decrease in fill density reduced tensile strength of the specimen, while SEM images also showed a significant reduction in the number of fibers carrying the load in direction of tension [26].

In a thesis by Çiçek (2019), the effect of fill rates on MPs of samples produced from PLA and Acrylonitrile Butadiene Styrene (ABS) filaments using Fused Deposition Modeling (FDM) technology was investigated. Samples produced at fill rates of 25, 50, 75, and 100% were subjected to tensile tests at a speed of 5 mm/min. This test revealed that the strength of ABS filament was higher than that of PLA. It was also reported that as the fill density increased, the strength of samples increased correspondingly. It was noted that samples made from ABS and PLA filaments broke in a brittle manner and showed limited elongation after exceeding yield strength in their tensile graphs [27].

Mansingh et al. (2023) the explore development of eco-friendly composites using 3D printing technology, combining chitin and chitosan with PLA. This study reveals that adding chitin and chitosan reduces strength and stiffness of PLA composites, with the lowest tensile and flexural strengths observed at a 0.5 wt% reinforcement concentration. Despite these reductions, the composites exhibit enhanced ductility compared to neat PLA, suggesting potential applications like food packaging, although further research is needed to optimize MPs and interfacial bonding [28].

1.1.2. Composite materials

Sajna et al. (2016) reported on the effect of moisture absorption and accelerated weather conditions on properties of graft copolymer compatible PLA bionanocomposites. They submerged the samples in distilled water baths at room temperature for 30 days, measuring the amount of moisture absorbed at each time interval. They noted that adding C30B nanoclay and graft copolymer to fiber-reinforced PLA composites reduced the rate of moisture absorption. They examined the changes in MPs caused by moisture absorption using tensile and impact tests, stating that exposure to moisture significantly reduced MPs. They characterized the morphology of biocomposites using SEM and bionanocomposites using Transmission Electron Microscopy (TEM), also reporting the effect of accelerated weather conditions on MPs and confirming the results with SEM analysis [29].

Arrieta et al. (2017) created blends from PLA and Polyhydroxybutyrate (PHB) materials through a melt blending approach for food packaging applications, as an alternative to traditional petrochemical-based polymers. They highlighted that PHB, with a similar melting temperature and high crystallinity properties, was a good candidate for blending with PLA. They mentioned that PHB acted as a nucleating agent for PLA, enhancing the mobility, mechanical strength, and barrier performance of the blend. Fouirer Transform Infrared Spektrofotometre tests indicated that the spectral profiles of PLA and PHB, being semi-crystalline polymers, were significantly influenced by their physical states and crystalline structures. The presence of PLA component accelerated the hydrolytic degradation of PHB, while PHB crystallized PLA, leading to materials with higher barrier performance and better mechanical strength [30].

Ausejo et al. (2018) researched the effects of print direction and hydrolytic degradation at 50 °C and 70 °C on properties of dumbbell-shaped samples produced by 3D printing from commercial PLA and Polylactic Acid/Polyhydroxyalkanoates (PLA/PHA) filaments. They printed the samples in both horizontal and vertical directions. They found that middle section of horizontally printed PLA/PHA samples, being at the same temperature as bottom layer's platform, had a higher crystallization rate than vertically printed samples. The middle part of vertically printed samples, being further from and cooler than the platform, showed the lowest crystallization rate. They determined that the contact time of the samples with 3D printer platform during printing led to an increase in the crystalline phase. They concluded that horizontally 3D-printed PLA and PLA/PHA samples were more regular and emphasized the importance of considering 3D printing direction as a significant parameter when designing applications for 3D printed materials [31].

Ayrilmis (2018) investigated the effect of print thickness on surface roughness and wettability of 3D-printed samples made from commercial wood flour/PLA filament (30% wood flour and 70% PLA by weight). They used four different print thicknesses: 0.05, 0.1, 0.2, and 0.3 mm for producing 3D-printed samples. They considered Ra, Rz, and Ry roughness values to evaluate the surface characteristics of the samples, which were measured using a surface roughness measurement device. They characterized the wettability behavior of the samples using the contact angle method (goniometer technique). They found that with decreasing print thickness, surface smoothness of the samples significantly increased, while the wettability of the samples significantly increased with increasing print thickness. They noted that as the print thickness decreased, production time increased due to longer print times, thereby increasing the total cost. Considering the test results and print time, they suggested that optimal print thickness for 3D-printed wood flour/PLA composite filaments should be 0.2 mm [32].

In his master's thesis, Patan (2019) used ABS and chopped carbon fiber-reinforced ABS filaments to produce tensile test specimens with a 3D printer according to ASTM D638-Type 1 code and experimentally examined their MPs. He applied load to the specimens in tensile test conducted according to ASTM standards at a pulling speed of 5 mm/min until failure occurred. Using the experimental results, he numerically analyzed maximum stresses and deformation energies of the specimens in ANSYS software according to von Mises criterion. Mechanical experiments showed that flexural and compressive strengths of carbon fiber-reinforced ABS specimens were respectively 23.9% and 14.75% higher than those of unreinforced ABS specimens. Analytical stress analyses conducted with experimental mechanical results as input modeled tensile, compressive, and bending behaviors of both types of specimens with minimal deviations [33].

Przekop et al. (2020) discussed the search for superior materials by composite making due to some disadvantages of PLA like low impact strength, poor gas barrier, and low crystallization rate, similar to other biopolymers. They identified graphite as a candidate for modifying PLA due to its low cost, excellent thermal, and electrical properties. They emphasized that graphite significantly improved the lubricating properties of polymeric materials, reducing friction and increasing wear resistance. They tested the wear, mechanical, and chemical properties of specimens produced with 1, 2.5, 5, 7.5, and 10% weight ratios of graphite, also conducting measurements after aging. They took SEM images of the specimens before and after friction tests. They found a significant reduction in wear with increasing graphite content and determined that PLA+10% graphite composite specimen had a wear rate three times lower than the reference PLA specimen. After aging, PLA+10% graphite composite specimen had 11% lower breaking stress, 47% lower impact strength, and 21% higher Young's modulus compared to the reference PLA specimen. Additionally, the addition of graphite significantly increased hydrophobic properties of composites and raised the material's glass transition temperature [34].

Uzun and Erdoğdu (2020) worked on 1.75 mm diameter composite PLA filaments reinforced with 20% copper and 20% carbon fiber, as well as Frosch brand PLA filaments. They produced tensile specimens from each filament using FDM method in a 3D printer and obtained TEM images of the fracture surfaces of test result specimens. Following their experiments, they determined that tensile strengths of composite filaments produced by reinforcing PLA material with copper and carbon fiber decreased. They emphasized that this decrease in strength was due to the reinforcements reducing the continuity of the matrix and weakening the interface adhesion. While PLA specimens broke more ductilely compared to copper and carbon fiber-reinforced specimens, copper-added composite PLA specimen broke in a brittle manner [35].

Thakur et al. (2024) conducted a study on the optimization and machine learning prediction of MPs in hybrid additive manufacturing of PLA-CF-PLA sandwiched composite structures. The research focused on enhancing MPs of these composites through the manipulation of fabrication parameters such as carbon fiber orientation, nozzle temperature, and bed temperature. Utilizing Classification and Regression Trees for machine learning, the study successfully predicted optimal settings for manufacturing, highlighting significant implications for the application of these composites in aerospace, automotive, and biomedical engineering [36].

1.1.3. Biodegradability and recycling

Rajeshkumar et al. (2021) present a comprehensive review on the development and application of environmentally friendly, renewable, and sustainable PLA-based natural fiber reinforced composites. This study examines the synthesis, degradation, applications, and manufacturing methods of PLA composites, emphasizing the beneficial impact of natural fiber reinforcements on properties of PLA. It aims to provide a holistic understanding of PLA-based biocomposites for academicians, industry personnel, and researchers, highlighting their significance in promoting sustainable and eco-friendly material solutions across various industries [37].

Rezvani Ghomi et al. (2021) conducted a life cycle assessment for PLA to position it as a low-carbon material, addressing its entire life cycle from production to end-of-life options. The study highlights the potential of PLA to reduce greenhouse gas emissions and its dependency on energy sources by optimizing the conversion process. The research underlines the significant role of PLA in the shift towards more sustainable materials, emphasizing the importance of improving recycling infrastructures and processes to further minimize its environmental impact [38].

Zhang and Thomas (2011) investigated the biodegradation, thermal, and MPs of PLA/PHB biopolymers mixed in ratios of 25, 50, 75, and 100%. According to their SEM imaging, PHBs exhibited irregular fractures, while PLAs had typical surface fractures seen in an amorphous polymer. They argued that the irregular fractures in PHBs were due to their crystalline structure [39].

Kamau-Devers et al. (2019) investigated the hydrothermal degradation, moisture absorption, morphology, and thermal conductivity of wood flour-filled PLA bio-composites. They conditioned composites containing 0, 10, and 30% by weight wood flour either fully immersed in water or in a completely dry state at four temperatures (7, 25, 35, and 47 °C). They noted that the increase in temperature led to an increase in moisture uptake and crystallinity amount. The drops in glass transition and melting temperatures associated with the increases in crystallinity levels of water-immersed samples were clearly determined compared to dried PLA samples [40].

Kakanuru and Pochiraju (2020) studied the moisture absorption and age-related degradation of parts made from PLA, Silicon Carbide (SiC) filled PLA composites, and ABS using Fused Filament Fabrication (FFF). They compared the hygroscopic stability of PLA and PLA/SiC composite specimens with ABS specimens. Both filaments and tensile test specimens were aged in distilled water at 50 °C and 70 °C for 140 days or until complete degradation. They defined the degradation of the polymer by observing differences in moisture absorption-desorption characteristics and deterioration in tensile strength. Experimental results showed that PLA and 20% SiC/PLA specimens degraded within 58 days at 50 °C, while SiC/PLA specimens with a higher SiC content maintained their stability for 140 days. They observed large voids in the material due to decomposition, with SEM images confirming the void geometry between aged and unaged specimens [41].

In review study of Nandhini et al. (2023), authors focus on the production and application of lignin and PLA for bioplastics and valuable chemicals, emphasizing their potential in mitigating global warming and plastic pollution through sustainable solutions. The document covers various production techniques, microbial degradation pathways, and conversion of these biopolymers into high-value chemicals such as muconic acid, hydrouronic acid, adipic acid, and terephthalic acid. Highlighting the environmental benefits, the review discusses the significance of deriving biopolymers from bioresources and organic waste, showcasing advancements in biopolymer production technology, degradation mechanisms, and their wide-ranging industrial applications. Unfortunately, specific author and publication year details were not captured in the quoted text [42].

1.1.4. Application areas

Siracusa et al. (2020) aimed to produce entirely bio-based blends based on two polyesters, PHB and PLA, as real competitors to replace petroleum polymers in the packaging industry. They highlighted PHB, main and most commonly used member of PHA family, showing great potential to replace fossil-based synthetic packaging. They prepared PHB/PLA blends in different ratios. They noted that in its homopolymeric state, PHB exhibited a high stereoregularity leading to a high degree of crystallinity up to 70-75% by weight. They stated that the optimal combination of biopolymer crystal entities (crystals, lamellae, spherulites) and inter-crystalline tie chains supported suitable MPs such as a high modulus of elasticity around 2.5-3 GPa and tensile strength at break around 35-40 MPa. They emphasized that the expansion lamellae and spherulite morphology of this biopolymer formed a good barrier structure with suitable low permeability values for atmospheric gas components and water vapor [43].

Johansson et al. (2023) examine the impact of lignin acetylation on MPs of lignin-PLA biocomposites, aiming to enhance sustainability in applications such as automotive and aerospace. The study demonstrates that acetylation improves interfacial adhesion between lignin and PLA, resulting in increased impact strength, thermal stability, and moisture repellency. These findings suggest acetylated lignin's potential in creating lighter, sustainable composite materials without compromising performance, marking a significant step towards the development of environmentally friendly biocomposites [44].

Tripathi et al. (2021) review durable PLA-based blends and biocomposites, emphasizing their role in supporting a low carbon economy. They discuss the environmental impact of traditional plastics and potential of PLA-based products to reduce the carbon footprint by replacing fossil carbon with renewable carbon. The review covers recent advancements in enhancing PLA durability, including the use of synthetic plastics, fibers, natural fibers, and biocarbon. It also examines the effects of various additives on PLA's processability, heat resistance, and MPs, alongside current and prospective applications in automotive, electronics, medical, textile, and housing sectors [45].

Ferreira et al. (2021) in "Sustainability" examine the production of eco-sustainable materials from PLA/High-density biopolyethylene bioblends, improved by compatibilizing agents like poly (ethylene octene) and ethylene elastomer grafted with glycidyl methacrylate, enhancing their mechanical, and morphological properties. This study contributes to the development of environmentally friendly materials, showcasing significant improvements in impact strength and thermal stability, highlighting the potential for creating new eco-materials for sustainable development [46].

1.1.5. Chemical modifications and innovations

In their study, Harris and Lee (2010) evaluated the durability of PLA by exposing it to high temperature and humidity conditions over several weeks. Samples were exposed to conditioned environments for 1, 4, 8, and 12 weeks, during which the crystallinity content increased from 10.8% to 51%. They determined that this was due to the preferential hydrolysis of the amorphous material, increased crystallization of shorter chains, and plasticization with moisture, indicating that these results meant increased chain mobility during conditioning [47].

Porfyris et al. (2018) worked to establish a basic degradation mechanism and kinetics for the accelerated hygrothermal aging of two commercial grades of PLA, one semi-crystalline and one amorphous. During moisture and temperature conditioning at 70 °C and 80% relative humidity, they monitored water uptake, molecular weight, carboxylic end group concentration, and thermal properties, observing significant chain scission. They used an epoxy-based chain extender, an aromatic carbodiimide, and aromatic and aliphatic poly carbodiimides as additive materials. While the epoxy-based additive showed no stabilizing effect, the other three carbodiimide-based additives were found effective as anti-hydrolysis agents at a 1% concentration, especially in the amorphous grade [48].

Guo et al. (2019) aimed to enhance electrical and thermal conductivity of PLA/wood flour/thermoplastic polyurethane composites using FDM. They noted that the fracture surface of pure PLA was smooth, indicating a typical brittle fracture. Graphite appeared as flake-like layers, and graphite flakes were randomly distributed within the polymer matrix. Mechanical tests on the samples showed that tensile strength and elongation at break of composites increased with addition of 5-20% by weight of graphite, reaching a maximum with 10% graphite addition. They observed that as the graphite content increased, the continuity of matrix changed, and due to poor dispersion caused by agglomeration, the toughness of the composite decreased, and brittleness increased, similar to other studies in the field [49].

The study by Alkan Goksu (2024) explores enhancing the sustainability of PLA via ketene-based chain extension. This innovative approach addresses PLA's limited stability by increasing its molecular weight and melt viscosity through the introduction of branching. Utilizing a modular chain extender that forms highly reactive ketene intermediates, the research demonstrates a notable increase in PLA's molecular weight and improved thermal properties. These advancements suggest potential applications in packaging, highlighting the chain extender's versatility in tailoring PLA's structure for diverse applications, thereby advancing its sustainability and utility [50].

Ramezani Dana and Ebrahimi (2023) present a comprehensive review on PLA-based polymers, discussing their synthesis, properties, and applications. They delve into polymerization methods, highlighting lactic acid condensation, azeotropic dehydration, and ring-opening polymerization as key techniques. The review emphasizes PLA's mechanical, rheological, and biodegradation properties, showcasing its versatility for applications in biomedical, packaging, and additive manufacturing sectors. Authors also explore strategies for enhancing PLA's performance, such as blending and copolymerization, underscoring its potential as a sustainable alternative in various industries [51].

Table 1. Synthesizing some research efforts on PLA and its composites

Study References	Main Focus	Key Findings	Implications
Letcher and Waytashek (2014) [25]	Effects of raster orientation in 3D printing with PLA.	Orientation affects mechanical strength; 45° orientation shows highest strength.	Optimization of 3D printing parameters for desired properties.
Mansingh et al. (2023) [28]	Development of eco-friendly composites with chitin, chitosan, and PLA.	Reduction in strength and stiffness but enhanced ductility with chitin and chitosan reinforcement.	Suggests potential in food packaging, with a need for further research on MPs and interfacial bonding.
Sajna, Nayak and Mohanty (2016) [29]	Impact of nanoclay and copolymers on PLA composites' moisture absorption.	Reduced moisture absorption and mitigated mechanical property degradation.	Enhances PLA's use in environments prone to moisture.
Arrieta et al. (2017) [30]	Use of PLA and PHB blends for food packaging.	Improved barrier and MPs; potential for food packaging applications.	Provides a sustainable alternative to conventional packaging.
Ausejo et al. (2018) [31]	Print direction and layer thickness in 3D printed PLA objects.	Direction and thickness affect crystallization and MPs.	Importance of print settings in 3D printing applications.
Ayrilmis (2018) [32]	Surface roughness and wettability of 3D-printed wood flour/PLA composites.	Print thickness impacts surface smoothness and wettability.	Optimal print settings for specific application needs.
Przekop et al. (2020) [34]	PLA composites with graphite for enhanced properties.	Graphite improves wear resistance and thermal conductivity.	Expands PLA's utility in electrical and thermal applications.
Uzun and Erdoğdu (2020) [35]	MPs of copper and carbon fiber-reinforced PLA.	Reinforcements decrease tensile strength but modify PLA's mechanical properties.	Considerations for PLA composites in structural applications.
Thakur et al. (2024) [36]	Optimization of MPs in PLA-CF-PLA composites.	Successful prediction of optimal manufacturing settings via machine learning.	Significant implications for aerospace, automotive, and biomedical engineering applications.
Rajeshkumar et al. (2021) [37]	PLA-based natural fiber reinforced composites.	Highlighting the beneficial impact of natural fiber reinforcements on PLA properties.	Promoting sustainable and eco-friendly material solutions across various industries.
Rezvani Ghomi et al. (2021) [38]	Life cycle assessment of PLA.	PLA's potential to reduce greenhouse gas emissions and energy dependency.	Importance of improving recycling infrastructures and processes to minimize environmental impact.
Johansson et al. (2023) [44]	Impact of lignin acetylation on PLA biocomposites.	Acetylation improves interfacial adhesion, impact strength, thermal stability, and moisture repellency of lignin-PLA biocomposites.	Advances in creating sustainable, high-performance composite materials for automotive and aerospace applications.
Tripathi et al. (2021) [45]	Durability of PLA-based blends and biocomposites.	Advancements in enhancing PLA durability and reducing carbon footprint.	Support for a low carbon economy with potential applications in various sectors.
Ferreira et al. (2021) [46]	Production of eco-sustainable materials from PLA bioblends.	Improvements in mechanical, thermal, and morphological properties through compatibilizing agents.	Contribution to the development of new eco-materials for sustainable development.
Ramezani Dana & Ebrahimi (2023) [51]	PLA-based polymers synthesis, properties, and applications.	Discussion on polymerization methods and PLA's versatile properties.	Emphasizes PLA's potential as a sustainable alternative in biomedical, packaging, and additive manufacturing sectors.

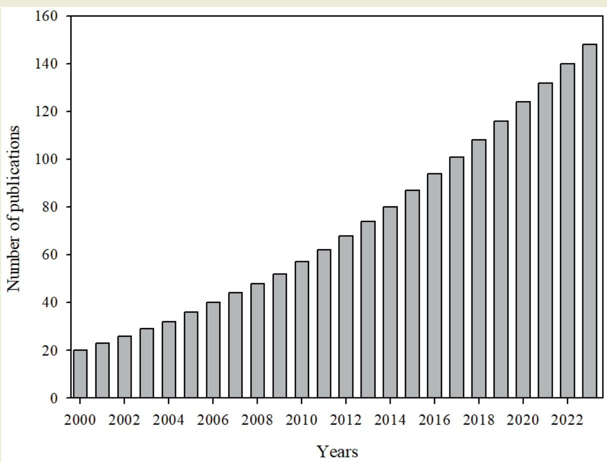

Figure 1. Number of publications on PLA sustainable applications (2000-2023 years)

Table 1 synthesizes the research efforts into PLA and its composites, emphasizing the versatility of PLA as a material for various applications, from packaging to 3D printing and beyond. It also underscores the ongoing research needs to enhance PLA's properties for specific uses, ensuring it remains a viable and sustainable alternative to traditional polymers. Figure 1 shows the developments in the number of comprehensive studies on PLA applications between 2000 and 2023.

1.1.6. Applied examples and industrial collaborations

Showcasing various case studies and partnerships that highlight PLA's potential in replacing traditional petroleum-based plastics across diverse industries. For instance, in the packaging industry, a collaboration between academic institutions and major companies has led to the development of PLA-based biodegradable packaging, which significantly reduces carbon footprints compared to conventional materials. In the automotive sector, a project with a leading automotive manufacturer demonstrates the use of PLA composites for interior components, achieving a notable reduction in part weight and enhancing end-of-life recyclability. Additionally, in the biomedical field, collaborative efforts between research centers and medical companies have produced bioresorbable PLA implants that simplify surgical procedures and reduce overall healthcare costs. These examples not only validate PLA's versatility and sustainability but also underscore its growing acceptance and implementation in key sectors, effectively bridging the gap between research and practical deployment.

2. Discussions

The discussions around the studies on PLA and its composites touch on several critical aspects of material science, environmental sustainability, and technological advancements in polymer applications. Here are some key points of discussion derived from the findings of these studies:

Hydrolytic degradation of PLA under high humidity and temperature conditions, as observed by Harris and Lee (2010), raises important considerations for its outdoor applications or in environments where these conditions prevail [47]. This necessitates further exploration into additives or blending partners like PHB, which can enhance moisture resistance while retaining or improving PLA's biodegradability. The improvement in mechanical and thermal properties through the blending of PLA with PHB, as shown by Zhang and Thomas (2011), indicates a promising strategy for widening the use of biopolymers in more demanding applications [39]. This blending approach not only improves material properties but also supports the use of renewable resources, aligning with sustainability goals. The impact of raster orientation on MPs of 3D printed PLA objects, highlighted by Letcher and Waytashek (2014), underscores the importance of printing strategies in achieving desired performance characteristics [25]. This opens up discussions on the optimization of 3D printing parameters to tailor properties for specific applications, balancing between strength, flexibility, and material usage. Layer adhesion and porosity are critical factors affecting strength and durability of 3D printed PLA objects. The findings necessitate a deeper understanding of the relationship between printing temperature, speed, layer thickness, and the resulting microstructure of PLA objects to optimize print quality and functional performance. The studies emphasize PLA's biodegradability as a major advantage over conventional plastics, positioning it as a key player in reducing plastic pollution. However, discussions around the conditions required for PLA degradation (such as industrial composting facilities) highlight the need for improved waste management infrastructure to fully realize the environmental benefits. The addition of fillers and copolymers to PLA not only modifies its properties but also impacts its biodegradability and recycling processes. There is a need for comprehensive life cycle assessments to understand the trade-offs between improved material properties and environmental impact. The exploration of PLA composites with various fillers (such as nanoclay, graphite, and SiC) opens new avenues for research into bio-based materials with enhanced electrical, and MPs. These advancements could lead to PLA's increased adoption in electronics, automotive components, and other high-value applications. Food packaging applications of PLA and PHB blends, as researched by Arrieta et al. (2017), offer a sustainable alternative to petroleum-based packaging. Further studies could focus on the barrier properties, safety, and regulatory compliance of these materials to facilitate their acceptance and use in the food industry [30]. The role of advanced manufacturing techniques in customizing the properties of PLA for specific uses, particularly in the medical field for biocompatible implants and drug delivery systems, represents a significant area for future research. The ability to tailor PLA's degradation rate, mechanical strength, and interaction with biological tissues could lead to innovative healthcare solutions.

Mansingh et al. (2023) delve into the development of eco-friendly composites using 3D printing technology, combining PLA with chitin and chitosan. Although these additions reduce the strength and stiffness of PLA composites, they increase ductility, suggesting potential for applications such as food packaging, pending further optimization [28]. Thakur et al. (2024) focus on optimizing MPs in hybrid additive manufacturing of PLA-CF-PLA composites, employing machine learning to predict optimal fabrication parameters. Their work has significant implications for aerospace, automotive, and biomedical engineering, highlighting the versatility of PLA composites [36]. Rajeshkumar et al. (2021) and Rezvani Ghomi et al. (2021) focus on the development and life cycle assessment of PLA-based natural fiber reinforced composites, underscoring their environmental benefits and importance of enhancing recycling infrastructures [37,38]. Nandhini et al. (2023) underscore the potential of lignin and PLA in the production of bioplastics and high-value chemicals, such as muconic acid and adipic acid. Their review illuminates the environmental advantages of deriving these biopolymers from bioresources and organic waste, presenting advancements in production technologies and microbial degradation pathways [42]. Johansson et al. (2023) examine the impact of lignin acetylation on MPs of lignin-PLA biocomposites, demonstrating improvements in impact strength and thermal stability. This suggests acetylated lignin's potential in creating sustainable materials for automotive and aerospace applications [44]. Tripathi et al. (2021) and Ferreira et al. (2021) both highlight the production and development of eco-sustainable materials from PLA blends and biocomposites, emphasizing improvements in mechanical, and morphological properties and their role in supporting a low carbon economy [45,46]. Alkan Goksu (2024) explores the enhancement of PLA's sustainability through ketene-based chain extension, which improves its molecular weight and thermal properties.

This approach opens up new possibilities for PLA in packaging applications, showcasing its increased utility and sustainability [50]. Ramezani Dana and Ebrahimi (2023) present a comprehensive review on PLA-based polymers, discussing their synthesis, properties, and various applications. Their review emphasizes the versatility of PLA and strategies for enhancing its performance, further underscoring PLA's potential as a sustainable alternative in multiple industries [51].

In summary, discussions surrounding PLA and its composites revolve around balancing material properties with environmental sustainability, leveraging technological advancements for customization, and addressing the infrastructural needs for biopolymer degradation. These conversations underscore the importance of interdisciplinary research and collaboration among scientists, engineers, policymakers, and industry stakeholders to overcome current limitations and unlock the full potential of PLA in various applications.

3. Conclusions

In this comprehensive exploration of the advancements, challenges, and potential applications of PLA and its composites, alongside lignin-based materials, we have delved into the significant strides made in the realm of bioplastics. The synthesis of research findings underscores the pivotal role these materials play in the development of sustainable alternatives to conventional plastics, catering to an array of industrial applications while addressing environmental concerns. This conclusion aims to encapsulate the essence of our findings, highlighting the innovation in bioplastic properties, advancements in production technologies, environmental implications of adopting these materials, and the challenges and future directions that research in this field is poised to take.

- Investigation reveals substantial enhancements in the physical properties of PLA through various strategies, including molecular structure modifications and incorporation of natural additives and composites. Such innovations extend PLA's utility beyond its traditional confines, enabling its application in demanding sectors such as automotive, aerospace, and advanced packaging solutions. The blending of PLA with PHB and the integration of nanoclay and graft copolymers illustrate the material's improved mechanical and thermal properties, making it a formidable contender to petrochemical-based plastics.

- Progression in production technologies for PLA and lignin-based materials marks a significant milestone in the bioplastics domain. Techniques such as chain extension and acetylation enhance mechanical, thermal, and morphological properties, showcasing the potential of these biopolymers to rival traditional plastics. These advancements are instrumental in propelling bioplastics into a competitive position, offering sustainable alternatives that do not compromise on performance.

- Environmental advantages of PLA and lignin-based materials are profoundly highlighted through life cycle assessments, which advocate for their role in mitigating global warming and reducing the carbon footprint. The adoption of these materials aligns with global sustainability goals, emphasizing their importance in the transition towards a low-carbon economy. Moreover, the biodegradability of PLA presents an eco-friendly solution to plastic pollution, although the conditions under which degradation occurs necessitate further exploration to optimize application and disposal strategies.

- Despite the promising advancements, the research underscores several challenges that need addressing. The sensitivity of PLA to moisture and environmental stressors, alongside the need for enhanced MPs and durability, presents significant hurdles. Future research must focus on optimizing formulations and processing conditions for specific applications, including 3D printing and packaging, to overcome these obstacles. Additionally, the development of efficient recycling processes and the exploration of microbial degradation pathways are crucial for integrating PLA and lignin-based materials into a circular economy.

In conclusion, body of research on PLA, its composites, and lignin-based materials paints an optimistic picture of future of bioplastics. With their potential to replace conventional plastics in numerous applications, these materials stand at the forefront of the sustainability movement. However, the realization of their full potential requires a concerted effort in research and development to address the existing challenges. The path forward involves not only enhancing the properties of bioplastics but also establishing a comprehensive framework for their production, application, and disposal that prioritizes environmental integrity. As we continue to innovate and refine these materials, their role in fostering a sustainable future becomes increasingly evident, marking a significant step towards reducing our reliance on fossil-based plastics and mitigating the environmental impact of plastic pollution.

This review has collated key advancements in the development of PLA and its composites, demonstrating its potential as a sustainable alternative to petroleum-based plastics. The study emphasizes PLA's improved mechanical properties, its applicability in diverse fields like 3D printing and biomedicine, and its environmental benefits. Future research should focus on overcoming its existing limitations such as moisture sensitivity and thermal resistance, and on enhancing its recyclability. Addressing these challenges will further establish PLA as a cornerstone of sustainable material solutions.

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Author Contributions

The author(s) accept full responsibility for the content of this article and have approved its submission.

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The author(s) declare that there are no competing interests.

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