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Industrial and Biomedical Applications Biobased Polymers of Polylactic Acid and Polyhydroxybutyrate: A Review

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Abstract

Polymers have been widely used by mankind for centuries in the form of textiles, ammunition, coatings, and adhesives. With the industrial revolution came widespread applications in plastic packaging, construction and electronics, as well as medical and agricultural applications. Their increased use has resulted in environmental pollution, triggering the search for innovative and eco-friendly bioengineered alternatives. This paper studies the industrial and biomedical applications of Polylactic acid (PLA) and polyhydroxybutyrate (PHB), which are bioengineered polymers designed to harness favourable characteristics of natural and synthetic polymers while minimizing undesirable environmental implications. These bioengineered polymers are commonly utilized in the production of biodegradable packaging materials for reduced environmental pollution and in medical capsules for safe and targeted drug delivery. The study showed that polylactic acid is more suited to applications in packaging and fabrication due to its chemical similarity with fossil-based counterparts such as polyvinyl chloride and polypropylene, while polyhydroxyalkanoates find greater application in pharmaceutical and medical applications due to their biocompatibility and degradation in animal or cell hosts. Both PLA and PHB were found to feature promising industrial prospects due to rising demands influenced by increased environmental awareness. However, their large-scale adoption is threatened by high production costs and scalability challenges which can be addressed by further research on efficient resource utilization, property enhancement and process optimization.

Keywords: *Biopolymers, bioengineered polymers, polylactic acid, polyhydroxyalkanoates, polyhydroxybutyrate.*

1.0 Introduction

Mankind has used polymers since ancient times in the form of natural materials such as starch, cellulose and rubber for domestic applications, industrial applications and several other applications [1-6]. Likewise, since the discovery of synthetic polymers in the 19th century, they have quickly evolved to suit applications in various industrial capacities such as packaging (plastics), paints, adhesives, electronics, automobiles, construction, agriculture and medicine; the widespread use of polymers in fast-evolving industries is possible due to their desirable characteristics which include but are not limited to weathering resistance, durability, weightlessness, low cost and transparency [7-9]. The abundance of polymers, especially plastics, has inadvertently contributed to environmental pollution especially due to non-biodegradability of conventional synthetic polymers, making the waste volumes closely approximate their production levels [10-12].

A large proportion of conventional polymers ultimately end up in landfills where they can persist for hundreds of years; in Nigeria, less than 12% of imported and produced plastics is recycled [13, 14]. The leaching of toxic additives from buried plastic waste leads to potential groundwater pollution and by extension, severe economic and ecological damage to marine environments [15, 16]. Meanwhile, fossil resource reserves are fast depleting due to rapid industrialization, leading to substitution with biobased polymers [17, 18]. These factors contribute to the necessity of a fundamental shift towards the development and utilization of bio-engineered polymeric materials with favorable environmental characteristics [19].

An exponential growth in population has further highlighted the need for sustainable approaches towards large-scale manufacturing and adoption of biobased polymers to meet growing industrial demands [20, 21]. In advanced countries, policies are continually being implemented to phase out single-use fossil-based plastics due to their environmental pollution potential and depletion of limited fossil resources [22-24]. In the same vein, researchers have undertaken the task of seeking alternative eco-friendly and biobased alternatives through bioengineering, thus producing advanced polymeric engineering materials which are instrumental to the global developmental process [25-27]. According to [28], blends of natural and synthetic polymers result in a new class of materials with improved mechanical properties and biocompatibility.

Among the pool of biopolymers, polylactic acid (PLA) and polyhydroxybutyrate (PHB) are known for their comparable mechanical properties and functionalities with their fossil-derived counterparts [18, 29]. While previous studies have distinctively highlighted the applications of PLA, PHB or both, this review uniquely

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combines a comprehensive analysis of their diverse uses in critical and industrial applications with a cursory examination of the persistent challenges that still hinder their widespread adoption.

The review fills a critical gap by providing a forward-looking perspective that not only summarizes the current state of biopolymer technology but also analyzes the economic viability of production and the emerging environmental concerns, such as the formation of biodegradable microplastics (BioMPs). By integrating these diverse aspects into a single, cohesive narrative, this review serves as a valuable resource for both researchers seeking to overcome current limitations and industry stakeholders aiming to transition to sustainable, plant-based materials. The article's significance lies in its timely synthesis that bridges the gap between the theoretical potential of biopolymers and their practical, large-scale deployment.

2.0 Biobased Polymers

Biobased polymers are biologically-derived polymeric materials derived from natural (renewable) sources and are often specifically engineered to suit industrial, environmental or specialized applications by altering synthetic or natural polymers at molecular or macroscopic level [30, 31]. Table 1 presents some commercially available biopolymers (bioplastics) along with the fossil-based polymers they compete against.

Bioplastics generally exhibit comparable mechanical properties to their fossil-based counterparts, with high practicability in the production of films and sheets for packaging as well as injection moulded parts; though with marginally higher water footprint due to biomass feedstock, biobased plastics result in lower carbon footprint [17, 32, 33]. Among the range of bioderived polymers, polylactic acid and polyhydroxybutyrate (trade-marked Biopol), which is a prominent PHA, stand out due to their extensive use in industrial and biomedical applications respectively [34, 35].

Table 1: Biopolymers and competing fossil-based polymers [33]

Biopolymers	**Fossil-based Polymers**
Biopolypropylene, Bio PP	Polypropylene, PP
Biopolyethylene, Bio PE	Polyethylene, PE
Polylactic acid, PLA	Polyvinylchloride, PVC
Polyhydroxyalkanoates, PHAs	Polyurethane
Polytrimethylene terephthalate, PTT	Polyethylene terephthalate, PET
Cellulose acetate, CA	Polystyrene, PS
Nylon 11, PA11	Nylon 6, PA6
Thermoplastic starch, TPS	Polycaprolactone, PCL

2.1 Applications of Biopolymers

The comparable properties of biopolymers with their petrochemical counterparts facilitates their usage in a wide range of industries [36, 37]. Figure 1 highlights some key industries where biopolymers are increasingly being adopted.

2.2 Environmental and Sustainability Aspects

2.2.1 Life Cycle Assessment (LCA) of PLA and PHB

Life Cycle Assessment (LCA) is a critical tool for evaluating and quantifying environmental impacts as well as global biodiversity [38, 39]. For PLA production, studies indicate that biomass processing, pretreatment, and the solid-state fermentation (SSF) process contribute significantly to environmental impact, particularly in terms of energy consumption and CO_2 emissions [40-42]. Similarly, for PHB production, biomass processing and pretreatment are identified as highly energy-intensive stages that substantially contribute to overall environmental impacts [43]. Despite these energy demands, PLA production, especially with process improvements, can result in significantly lower greenhouse gas emissions compared to conventional plastics, with significant reduction in carbon emissions and a drop of fossil energy use by 95% [18].

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Figure 1: Applications of biopolymers

A crucial aspect of sustainability involves the valorization of waste materials, especially through its production of biopolymers from various waste streams [44-46].

2.2.2 Life Cycle Assessment (LCA) of PLA and PHB

The sustainability of biopolymers is intrinsically linked to their feedstock [47, 48]. PLA is primarily produced from starchy renewable resources like corn or sugarcane [49]. PHAs are synthesized by various microorganisms utilizing substrates such as molasses, wastewater activated sludge, food waste, lignocellulosic biomass, fats, glycerol, and whey [50, 51]. A critical aspect of sustainable biopolymer production involves avoiding direct competition with food or feed resources [52]. This has championed the utilization of agricultural waste materials, including lignocellulosic biomass and agri-food waste, as viable feedstocks [53]. This approach aligns with the concept of a "circular economy," where waste products are repurposed as valuable resources, transforming waste into useful materials and fostering new markets [53, 54].

Though waste feedstocks are often inexpensive and abundant, it is important to acknowledge that they frequently require costly and energy-intensive pretreatment processes [55]. Through approaches such as microbial biotechnology, these pretreatment requirements are minimized, further enhancing the sustainability and economic viability of biopolymer production [56, 57].

2.2.3 Biodegradation Conditions and Microplastics

The term "biodegradability" for biopolymers is often oversimplified in public perception. Though PLA and PHB can decompose and can be termed biodegradable, this typically occurs under specific industrial composting conditions [58, 59].

Generally, the conventional industrial composting conditions for biopolymers include elevated temperatures, relatively high water activity, and the presence of oxygen, meeting standards such as EN 13432, which mandates 90% disintegration within 12 weeks and 90% conversion to CO_2 within six months [60].

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An emerging concern that must be addressed is the formation of biodegradable microplastics (BioMPs) [16, 61]. The biodegradation of polymers can be substantially affected by various chemical-physical factors and biological factors [62, 63]. Under non-ideal conditions, biodegradable polymers can persist for extended periods and undergo weathering, leading to the formation of BioMPs [64]. BioMPs represent an emerging environmental threat, with potential negative impacts on various ecosystems and living organisms, including plant growth suppression, impaired nutrient penetration through roots, and ingestion by aquatic life, leading to skeletal development issues and oxidative stress in fish [15]. Therefore, it is essential to implement a methodological approach to detect and address BioMPs in biota and other ecological systems [15, 65, 66].

3.0 Polylactic Acid (PLA)

Polylactic acid (PLA) is a thermoplastic polyester produced from starchy renewable resources, resulting in a highly versatile biopolymer with excellent functionalities [67, 68]. A lot of progress has been made in polylactic acid research and production, with recent strides recorded in its 3D printing [69-71]. Globally, the PLA market was valued at $535.6 million in 2019 and is expected to expand by 15.9% from 2020 to 2027 [67].

Biorenewable chemicals and their products, including PLA plastic, can be produced from both edible and inedible feedstock [72-74]. Avoidance of food competition has championed its production from agricultural waste materials such as lignocellulosic biomass [72, 74]. In [75], an integrated approach was employed to produce both biodiesel and polylactic acid from food waste; techno-economic analyses and process reviews on the production of lactic acid, lactide and PLA have also been published [76, 77]. Polylactic acid has also been produced through the valorisation of algal waste biomass, while studying its environmental footprint and exergo-economic implications [78-80].

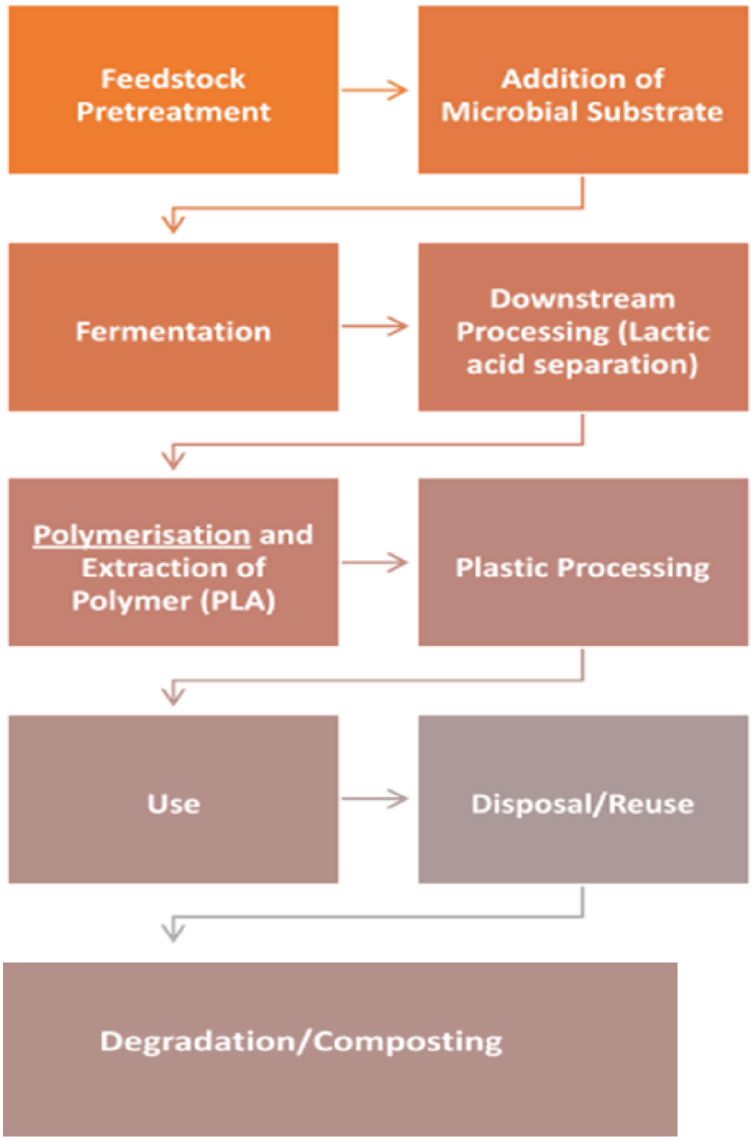

Figure 2: Summary for polylactic acid processing and end-of-life [35]

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The synthesis of polylactic acid is generally achieved by direct condensation of free acids or polymerization of its precursor, lactic acid ($C_3H_6O_2$), which is produced either by chemical synthesis of acetaldehyde or by the biological fermentation process of carbohydrates via the Cargill-Dow's process [67, 81, 82]. Cargill, the pioneer of large-scale PLA production, began researching PLA production technology in 1987, and began production of pilot plant quantities in 1992, after which commercial scale production began in 2002 [83, 84]. Figure 2 shows a summary of polylactic acid production processes. Figures 3 and 4 show the schematics of the bio-based production of biodegradable polylactic acid and a typical process flow diagram for a large-scale commercial PLA production plant respectively.

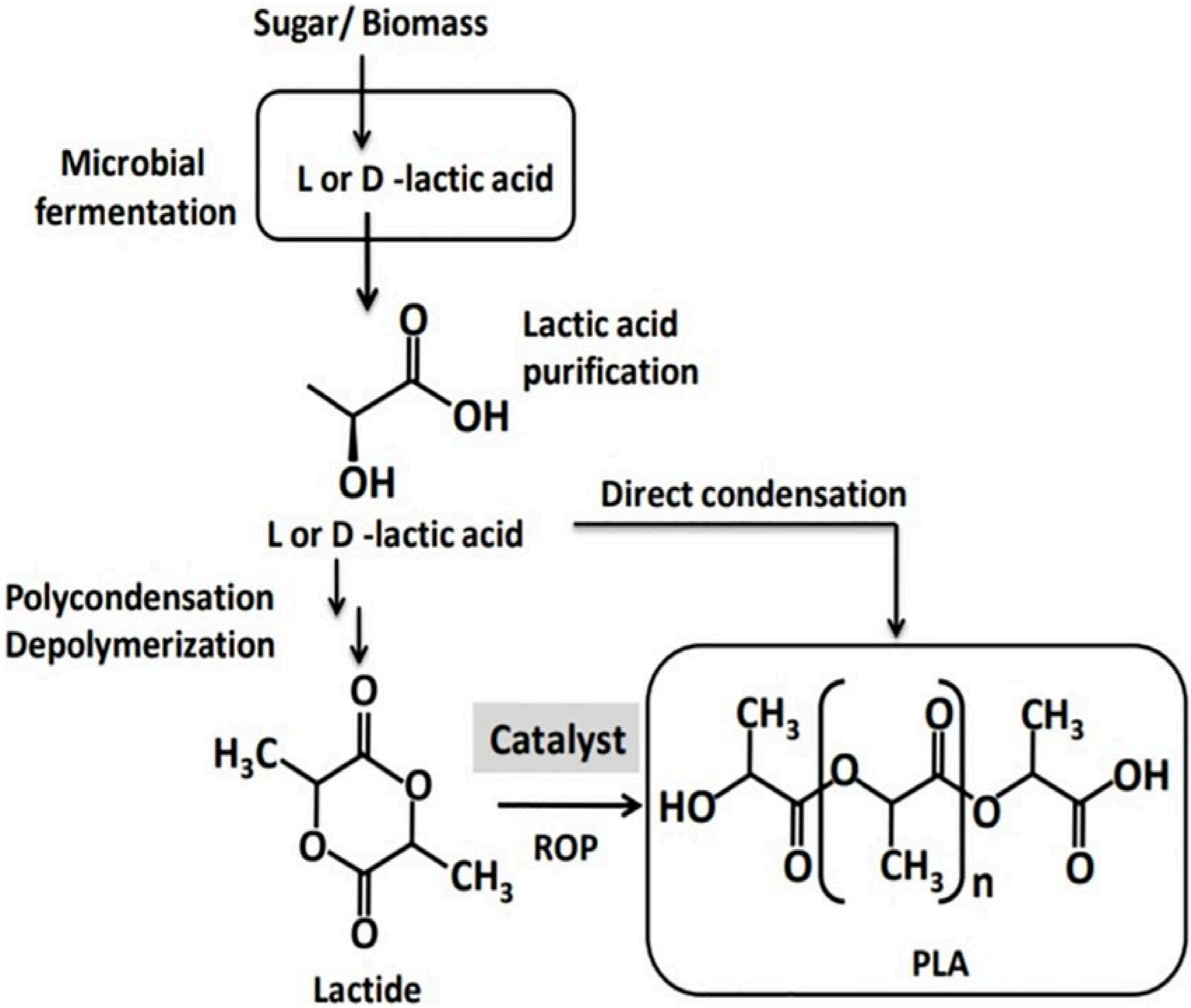

Figure 3: Schematic presentation of polylactic acid production from lactic acid by ring-opening polymerization (ROP) and direct condensation [85]

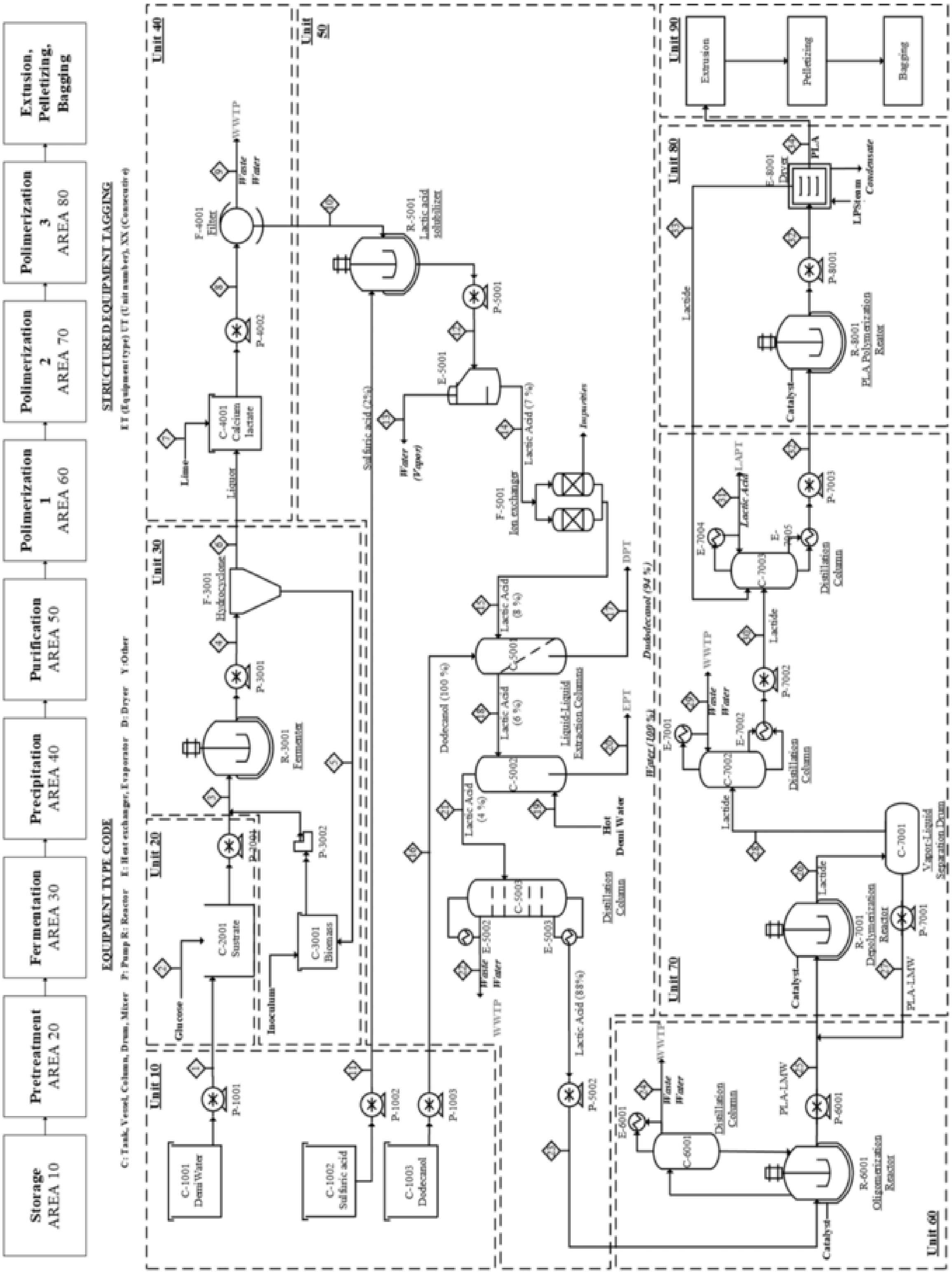

Figure 4: Process flow diagram of the PLA production process [86]

3.1 Polylactic Acid Industrial Applications

The biodegradability of Polylactic acid (PLA) makes it an eco-friendly alternative to nonbiodegradable and/or non-recyclable polymers such as polypropylene (PP) and polystyrene (PS), leading to its multifarious applications in various industries [35, 82, 87]. In addition, due to the competitive material and processing costs of PLA for bioplastic production as well as its comparable mechanical properties, PLA foams and composites could potentially replace the highly-polluting polystyrene (PS) foam products in a wide array of applications such as packaging, cushioning, construction, thermal and sound insulation, and plastic utensils [69, 84].

Table 2: Industrial usage of polylactic acid

Usage	Function	Reference
Packaging	Films, trays, cups and other (disposable) items for preservation of food items and other consumer goods.	[35, 88]
Textile	Raw material (fibers) for production of clothing, wipes, upholstery and carpets.	[89-91]
3D Printing	Eco-friendly filaments for 3D printing with low melting temperature.	[70, 71]
Mulch Films and Pots	Decomposable mulch covers and pots to ease weed control and transplanting.	[92-95]
Automotives and Electronics	Lightweight interior parts and electronic casings, especially for short-life applications.	[35, 96, 97]

3.2 Polylactic Acid Biomedical Applications

Owing to its favourable biocompatibility, low molecular weight, solvent-based solubility and safe degradation products, Polylactic acid (PLA) is used in a wide range of pharmaceutical and medical industries [82, 98-100]. According to [101], polylactic acid is the most commonly used biodegradable polymer in clinical applications. Its applications range from combating drug delivery efficiencies to bioengineered materials such as the patented retinal nerve scaffold reported by [102]. The different categories of PLA use in biomedicine are shown in Table 3.

Table 3: Biomedical usage of PLA

Usage	Function	Source
Surgical Sutures and Implants	Safely-degrading PLA-based drug-eluting implants for localized treatment of chronic conditions	[101, 103, 104]
Tissue Engineering	PLA scaffolds are used in tissue engineering due to their ability to mimic extracellular matrices, supporting cell growth and tissue regeneration.	[104-107]
Drug Delivery	PLA nanoparticles enhance the stability and delivery of vaccines, improving immune responses.	[37, 101, 108]

4.0 Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs) are biodegradable and biocompatible polyesters which are produced by various microorganisms under nutrient-limiting conditions [109-111]. PHA can be synthesized by over 30% of soil-inhabiting bacteria on a wide range of substrates such as molasses, wastewater activated sludge, food waste, lignocellulosic biomass, fats, glycerol and whey [112-114]. In a one-pot experiment, chitin biomass was used for simultaneous production of electricity, n-acetylglucosamine and polyhydroxyalkanoates in microbial fuel cell using novel marine bacterium [115]. The synthesis of polyhydroxyalkanoates has also been produced from *Ceiba pendantra*, a non-edible feedstock [116].

4.1 Polyhydroxybutyrate

Over 150 PHA monomers have been reported, with four operation modes commonly employed: batch, Fed batch, two-stage and continuous [117-119]. Polyhydroxybutyrate (PHB) is a prominent homopolymer of PHA, highlighted for its biodegradability, eco-friendliness and favorable cross-industry applications [120, 121]. A biotechnological pathway is often employed in the production of PHBs [122]. Figure 5 shows a simplified schematic of PHA production from 2-Acetyl-CoA.

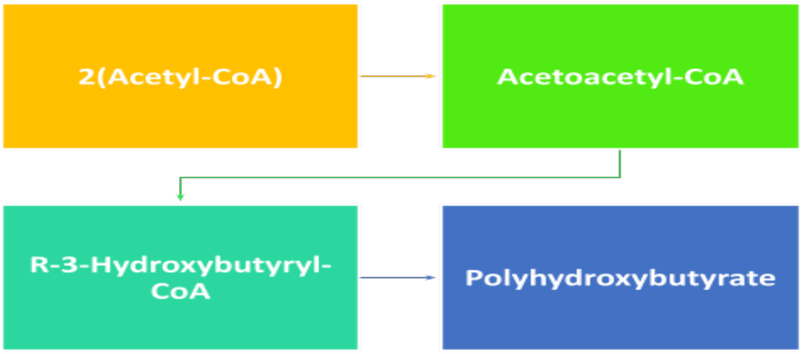

Figure 5: Simplified schematics of Polyhydroxyalkanoates synthesis from Acetyl-CoA

The production of Polyhydroxybutyrate is often produced by Two-Step Fermentation [123]. Figure 6 shows a comparison of the chemical structure of PHB and some conventional fossil-based polymers, while Figure 7 shows a typical process flow diagram of the PHB production process.

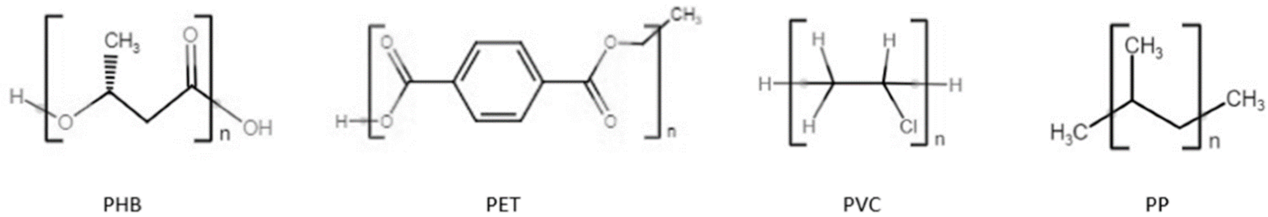

Figure 6: Chemical structures of (PHB) in comparison to commonly used petroleum-based polymers (polyethylene terephthalate (PET), polyvinylchloride (PVC), and polypropylene (PP) [124].

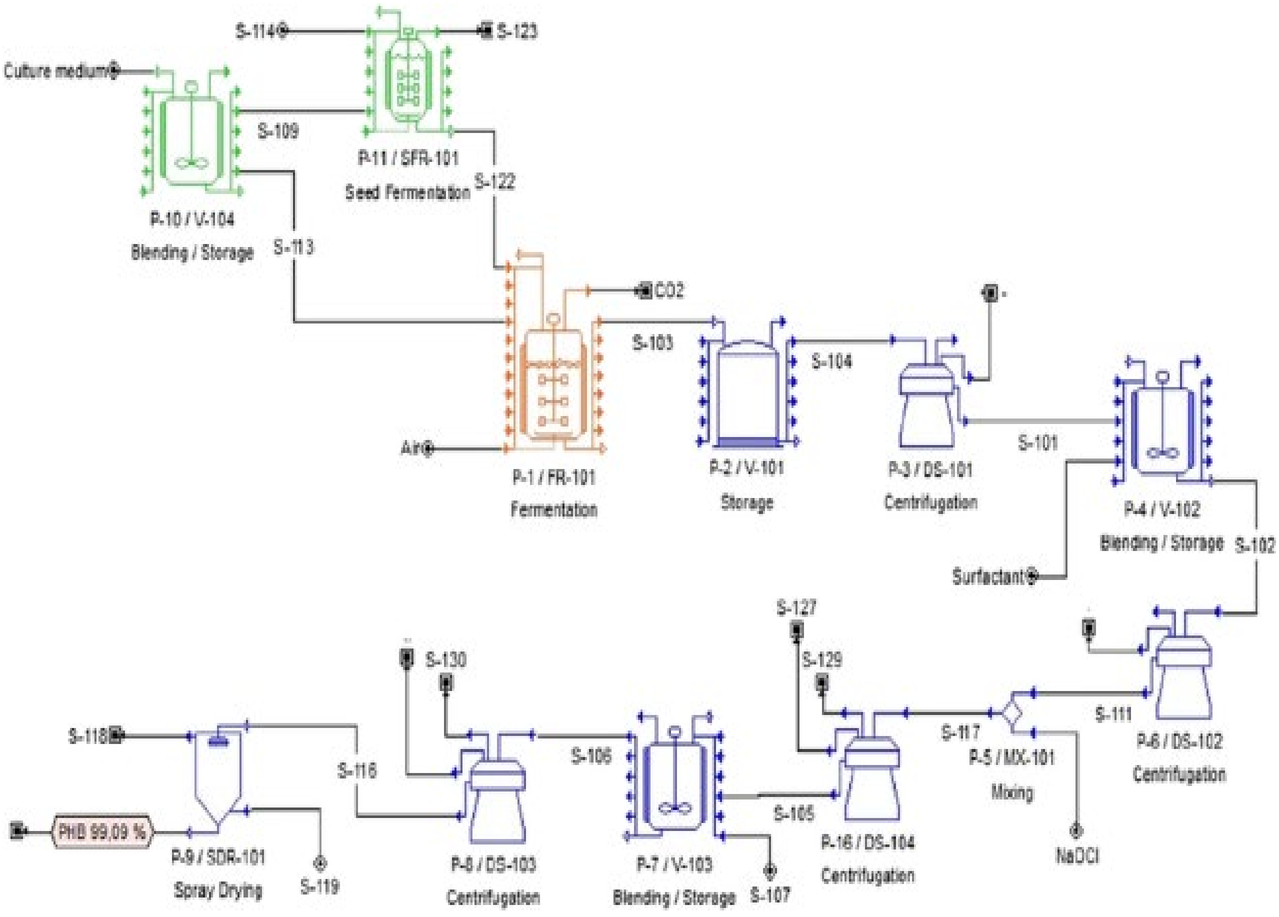

Figure 7: Process flowsheet of the PHB production model by R. eutropha in concentrated vinasse-based culture medium [123]

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4.2 Polyhydroxybutyrate Industrial Applications

As plastic "made and degraded by microorganisms," polyhydroxybutyrates are suited for various industrial applications [120]. Such applications leverage the thermal and mechanical properties of PHBs [124, 125]. Industrial uses of polyhydroxybutyrates are outlined in Table 3.

Table 3: Industrial usage of Polyhydroxybutyrate

Usage	Function	Source
Packaging Materials	PHB is often used in hydrophobic non-toxic food packaging, that can be integrated with antimicrobial agents.	[114, 126-130]
Bio composite (Additives)	PHBs improve the strength and durability of bio composites used in automotive and construction industries.	[131, 132]
Energy Storage Systems	Microbial fuel cells, batteries and capacitors to enhance the sustainability of energy storage solutions.	[112, 115]
Wastewater Treatment	PHA-producing bacteria act as carbon source and denitrifying agents in wastewater treatment processes, hence PHA production can be integrated in WWTPs.	[113, 122, 133]

4.3 Polyhydroxybutyrate Biomedical Applications

Polyhydroxybutyrates (PHBs) are biodegradable and biocompatible biological macromolecules with several medical applications such as drug delivery, surgical sutures, scaffolds and heart valves [134]. The biocompatibility of Polyhydroxybutyrate as well as its efficient degradation in animal media encourage its use in innovative medical applications [135, 136]. Some key biomedical applications of PHB are showcased in Table 4.

Table 4: Biomedical usage of polyhydroxybutyrate

Usage	Function	Source
Microparticles and Nanoparticles	Targeted delivery of drugs, reducing systemic side effects.	[128, 132, 137, 138]
Implants	Biodegradable drug-eluting devices for localized therapy.	[34, 139-141]
Regenerative Medicine and Tissue Engineering	PHA scaffolds in regenerative medicine for their biocompatibility and ability to promote cell attachment and growth.	[142-144]
Antimicrobial Coatings	PHA-based materials used in coatings with embedded antimicrobial agents, enhancing their use in medical devices and surfaces.	[140, 145, 146]
Orthopaedic Support	Temporary structural support that degrades as bones heal.	[147-149]

5.0 Deployment Challenges

5.1 Economic Feasibility and Market Dynamics

Numerous challenges exist in the industrialization of bio-based polymers such as polyhydroxyalkanoates [118, 150]. Despite its favorable thermal and mechanical properties, the large-scale adoption of PLA is also challenged by significant bottlenecks [151-153]. In general, deployment challenges of bio-based polymers in large-scale industrial and biomedical applications include high production costs (especially due to substrate requirements and fermentation challenges), limited thermal stability, slow degradation rates under natural conditions, limited flexibility compared to synthetic polymers and scalability challenges in large-scale production [59, 150, 152, 154].

5.2 Competitive Analysis

High production costs remain a significant bottleneck for the widespread adoption of both PLA and PHAs [76, 155, 156]. The bioplastics industry has experienced challenges in scaling production to commercial levels and effectively competing with fossil-based counterparts [33, 157]. Economic competitiveness for bioplastics is not merely about raw material cost but encompasses the efficiency of the entire production process and the fluctuating market dynamics of competing fossil-based polymers [158]. Overcoming these economic barriers necessitates a holistic approach that includes both technological advancements and favorable market conditions.

5.3 Market Challenges and Growth Drivers

Recent shifts have revitalized the bioplastics industry, with a strong drive towards sustainability from brand owners, fueled by increasing consumer demand and supportive legislations [21, 159-161]. Global commitments to

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decarbonization, such as those spurred by COP28, are also pushing brand owners to expand their use of bioplastics, compelling manufacturers to increase production capacity [162]. The emergence of drop-in bio-based materials that can directly substitute incumbent fossil-based ones is facilitating an easier transition for manufacturers from fossil to bio-based plastics [163]. Furthermore, there is a growing willingness among consumers to pay a premium for sustainable bioplastic products [159, 160, 164].

Despite these positive trends, challenges persist. For instance, PLA's end-of-life processing presents difficulties [165, 166]. Industrial composting, while effective for degradation, offers no value to the resulting compost, which limits its appeal to composters [167]. Additionally, recycling PLA, unlike certain drop-in bio-based polymers, requires dedicated infrastructure that is currently uncommon and expensive to implement, often leading to mismanagement or landfill disposal [168]. Hence, it is pertinent to understand that the market for bioplastics is influenced by a complex interplay of policy, consumer behavior, corporate sustainability commitments, and infrastructure development, rather than solely by technological advancements or environmental benefits [157, 158, 169].

6.0 Future Research and Progressive Strategies

Ongoing research focuses on modifying natural and synthetic polymers for enhanced thermal, physical and mechanical properties through copolymerization and blending with other materials [129, 170, 171]. To this end, durable biocomposites for engineering applications were found to arise from polylactic acid (PLA)-based sustainable engineered blends [153]. Likewise, cotton-rich PLA blends have been handy in the production of sportswear and other textile materials [89, 90]. Polyhydroxybutyrate blends and biocomposites have also been used in a range of applications [129, 172].

Interestingly, blends of polylactic acid and polyhydroxybutyrate have been formulated in a bid to complement the favorable properties of the two in various industries, especially for load-carrying applications [29]. PLA/PHB composites produced via the melt quenching technique exhibited enhanced mechanical properties, excellent thermal stability, fast crystallization ability, and degradation rate [173]. Blends of the two polymers have also exhibited excellent properties suitable for use in food packaging, with favorable structural, thermal and mechanical properties when used for electrospun flexible materials [174, 175]. However, not much research has been conducted on the performance of such blends in biomedical applications. The following areas represent critical avenues for advancing the field of PLA and PHB biopolymers.

6.1 Material Property Enhancement

Future research should continue to focus on modifying the thermal, physical, and mechanical properties of PLA and PHB. This involves exploring advanced techniques such as copolymerization, blending with other materials, and incorporating nanocomposites. Specific emphasis should be placed on enhancing key properties like ductility and impact strength for advanced applications [25, 47]. Further investigation into the synergistic effects of various additives and blend ratios is necessary to optimize material performance for diverse applications.

6.2 Process Optimization and Cost Reduction

Reducing the high production costs of biopolymers remains a paramount research objective. Future efforts should target efficient resource utilization and the development of novel production techniques by leveraging advancements in microbial biotechnology for PHA formation and a reduction or elimination of the need for costly and energy-intensive pretreatment of raw materials, especially agricultural waste feedstocks.

The economic viability of recycled PLA (rPLA) has shown substantial cost reductions compared to virgin PLA [176]. Research into distributed recycling systems for PLA can therefore significantly contribute towards reduced energy consumption associated with collection and transport. Continued focus on process optimization, including fermentation and purification, is crucial to make biopolymers more competitive against fossil-based products [18, 116, 177].

6.3 Expanded Applications and Design for End-of-Life

While industrial and biomedical applications of PLA and PHB are well-established, further research is needed to explore more cutting-edge applications of the two and their blends [153, 171]. Crucially, future bioplastics must be designed with their end-of-life scenarios explicitly in mind, thereby addressing and managing the threat posed by the emergence of BioMPs [178]. This can be achieved by developing materials that reliably degrade under a wider range of natural conditions or by improving dedicated recycling and composting infrastructure for post-consumer use bioplastics [176].

6.4 Smart and Functional Biopolymers

The integration of cutting-edge technologies like machine learning (ML) and artificial intelligence (AI) in biopolymer design offers promising avenues for accelerating the discovery of new materials with desired properties [179-182]. Furthermore, research into cell culturing and drug delivery holds significant potential for creating highly functional and responsive biomaterials [37, 183]. Developing these smart and functional biopolymers will broaden their applicability and enhance their performance in complex biological and industrial systems [184, 185].

7.0 Conclusion

Polylactic acid (PLA) and polyhydroxybutyrate (PHB) represent compelling alternatives to conventional fossil-based polymers, offering favorable attributes for both human applications and environmental sustainability. Their mechanical and thermal properties are often comparable to their petrochemical counterparts, making them versatile materials. PLA, known for its durability, finds extensive utility in industrial sectors ranging from packaging and textiles to electronics. Conversely, PHB, due to its microbial origin and excellent biocompatibility, is highly applicable in the biomedical field, including drug delivery systems and tissue engineering. These biopolymers contribute significantly to sustainable development goals by reducing plastic waste and facilitating safer biotechnological innovations through their inherent biodegradability.

However, despite their promising attributes, the large-scale adoption of PLA and PHB faces significant deployment challenges. These include high production costs, which are influenced by substrate requirements and fermentation complexities, as well as limitations in thermal stability and flexibility compared to some synthetic polymers. Furthermore, their biodegradation requirements, particularly the conditions required for complete decomposition and the emerging concern of biodegradable microplastics under non-ideal environmental conditions, necessitate careful consideration. Scalability issues and market inertia also present substantial barriers to their widespread industrialization.

To overcome these challenges and fully realize the potential of PLA and PHB, continued research and development are essential. Future efforts must focus on enhancing material properties through advanced blending and composite formulations, optimizing production processes to reduce costs and improve efficiency, and expanding their application portfolio into next-generation functional materials. Crucially, designing biopolymers with specific end-of-life pathways in mind and improving waste management infrastructure will be vital. By addressing these multifaceted challenges through scientific innovation and strategic market development, PLA and PHB can become even more competitive against conventional products, especially in industrial and biomedical applications, thereby facilitating their sustainable adoption and contributing to improved environmental conditions globally.

References

[1] R. B. Seymour and H. F. Mark, *Applications of polymers*. Springer, 1988.

[2] R. O. Ebewele, *Polymer science and technology*. CRC press, 2000.

[3] R. E. Hummel and R. E. Hummel, "From natural fibers to Man-Made plastics," *Understanding Materials Science: History· Properties· Applications,* pp. 326-365, 2004.

[4] A. R. Kukoyi, "Economic impacts of natural polymers," *Natural Polymers: Industry Techniques and Applications,* pp. 339-362, 2016.

[5] K. N. Keya, N. A. Kona, F. A. Koly, K. M. Maraz, M. N. Islam, and R. A. Khan, "Natural fiber reinforced polymer composites: history, types, advantages and applications," *Materials Engineering Research,* vol. 1, no. 2, pp. 69-85, 2019.

[6] M. Selvamurugan and S. Pramasivam, "Bioplastics – An Eco-friendly Alternative to Petrochemical Plastics," *Current World Environment,* vol. 14, pp. 49-59, 04/28 2019.

[7] Maulida, M. Siagian, and P. Tarigan, "Production of Starch Based Bioplastic from Cassava Peel Reinforced with Microcrystalline Celllulose Avicel PH101 Using Sorbitol as Plasticizer," *Journal of Physics: Conference Series,* vol. 710, no. 1, p. 012012, 2016/04/01 2016.

[8] K. Shaker, Y. Nawab, and M. Jabbar, "Functional Polymers and Composites for Zero Gravity," in *Advanced Functional Polymers: Synthesis to Applications*: Springer, 2023, pp. 167-182.

[9] Q. Fan, H. Duan, and X. Xing, "A review of composite materials for enhancing support, flexibility and strength in exercise," *Alexandria Engineering Journal,* vol. 94, pp. 90-103, 2024.

[10] M. T. A. Pawar, "Environment and Sustainability Volume IV," 2022.

[11] L. Seuront *et al.*, "A whale of a plastic tale: A plea for interdisciplinary studies to tackle micro- and nanoplastic pollution in the marine realm," *Science of The Total Environment,* vol. 846, p. 157187, 2022/11/10/ 2022.

[12] S. Kim, D. Kong, X. Zheng, and J. H. Park, "Upcycling plastic wastes into value-added products via electrocatalysis and photoelectrocatalysis," *Journal of Energy Chemistry,* vol. 91, pp. 522-541, 2024.

[13] J. O. Babayemi, M. B. Ogundiran, R. Weber, and O. Osibanjo, "Initial inventory of plastics imports in Nigeria as a basis for more sustainable management policies," *Journal of Health and Pollution,* vol. 8, no. 18, p. 180601, 2018.

[14] O. B. Ezeudu, I. T. Tenebe, and C. O. Ujah, "Status of production, consumption, and end-of-life waste management of plastic and plastic products in Nigeria: Prospects for circular plastics economy," *Sustainability,* vol. 16, no. 18, p. 7900, 2024.

[15] L. Ribba, M. Lopretti, G. M. de Oca-Vasquez, D. Batista, S. Goyanes, and J. R. Vega-Baudrit, "Biodegradable plastics in aquatic ecosystems: latest findings, research gaps, and recommendations," *Environmental Research Letters,* vol. 17, no. 3, p. 033003, 2022.

[16] N. S. Payanthoth, N. N. N. Mut, P. Samanta, G. Li, and J. Jung, "A review of biodegradation and formation of biodegradable microplastics in soil and freshwater environments," *Applied Biological Chemistry,* vol. 67, no. 1, p. 110, 2024.

[17] S. Walker and R. Rothman, "Life cycle assessment of bio-based and fossil-based plastic: A review," *Journal of Cleaner Production,* vol. 261, p. 121158, 2020.

[18] A. Z. Naser, I. Deiab, and B. M. Darras, "Poly (lactic acid)(PLA) and polyhydroxyalkanoates (PHAs), green alternatives to petroleum-based plastics: a review," *RSC advances,* vol. 11, no. 28, pp. 17151-17196, 2021.

[19] G. Atiwesh, A. Mikhael, C. C. Parrish, J. Banoub, and T.-A. T. Le, "Environmental impact of bioplastic use: A review," *Heliyon,* vol. 7, no. 9, 2021.

[20] N. Thongchul, "Production of lactic acid and polylactic acid for industrial applications," *Bioprocessing technologies in biorefinery for sustainable production of fuels, chemicals, and polymers,* pp. 293-316, 2013.

[21] J. R. Westlake, M. W. Tran, Y. Jiang, X. Zhang, A. D. Burrows, and M. Xie, "Biodegradable biopolymers for active packaging: demand, development and directions," *Sustainable Food Technology,* vol. 1, no. 1, pp. 50-72, 2023.

[22] E. Cornago, P. Börkey, and A. Brown, "Preventing single-use plastic waste: Implications of different policy approaches," *OECD Environment Working Papers,* no. 182, pp. 0_1-68, 2021.

[23] T. A. Farrelly, S. B. Borrelle, and S. Fuller, "The strengths and weaknesses of Pacific Islands plastic pollution policy frameworks," *Sustainability,* vol. 13, no. 3, p. 1252, 2021.

[24] T. Luo, Y. Hu, M. Zhang, P. Jia, and Y. Zhou, "Recent advances of sustainable and recyclable polymer materials from renewable resources," *Resources Chemicals and Materials,* 2024/10/29/ 2024.

[25] A. O. C. Iroegbu and S. S. Ray, "Recent developments and future perspectives of biorenewable nanocomposites for advanced applications," *Nanotechnology Reviews,* vol. 11, no. 1, pp. 1696-1721, 2022.

[26] B. Sharma, S. Thomas, P. K. Bajpai, K. Ghosal, and S. Shekhar, *Advances in Bionanocomposites: Materials, Applications, and Life Cycle*. Elsevier, 2023.

[27] S. J. Skosana, C. Khoathane, and T. Malwela, "Driving towards sustainability: A review of natural fiber reinforced polymer composites for eco-friendly automotive light-weighting," *Journal of Thermoplastic Composite Materials,* vol. 38, no. 2, pp. 754-780, 2025.

[28] A. Sionkowska, "Current research on the blends of natural and synthetic polymers as new biomaterials," *Progress in polymer science,* vol. 36, no. 9, pp. 1254-1276, 2011.

[29] D. Battegazzore, T. Abt, M. L. Maspoch, and A. Frache, "Multilayer cotton fabric bio-composites based on PLA and PHB copolymer for industrial load carrying applications," *Composites Part B: Engineering,* vol. 163, pp. 761-768, 2019.

[30] K. Thangavelu and K. B. Subramani, "Sustainable biopolymer fibers—Production, properties and applications," *Sustainable Fibres for Fashion Industry: Volume 1,* pp. 109-140, 2016.

[31] V. Siracusa and I. Blanco, "Bio-polyethylene (Bio-PE), Bio-polypropylene (Bio-PP) and Bio-poly (ethylene terephthalate)(Bio-PET): Recent developments in bio-based polymers analogous to petroleum-derived ones for packaging and engineering applications," *Polymers,* vol. 12, no. 8, p. 1641, 2020.

[32] R. Narayan, "Carbon footprint of bioplastics using biocarbon content analysis and life-cycle assessment," *MRS bulletin,* vol. 36, no. 9, pp. 716-721, 2011.

[33] M. Ashby, "Sustainability Case Study: Scaling Up Bioplastic Production," 2023, Available: https://www.ansys.com/content/dam/amp/2021/august/webpage-requests/education-resources-dam-upload-batch-4/case-study-bioplastic-cassdpen23.pdf.

[34] C. J. Brigham and A. J. Sinskey, "Applications of polyhydroxyalkanoates in the medical industry," *International Journal of Biotechnology for Wellness Industries,* vol. 1, no. 1, p. 52, 2012.

[35] E. Castro-Aguirre, F. Iniguez-Franco, H. Samsudin, X. Fang, and R. Auras, "Poly (lactic acid)—Mass production, processing, industrial applications, and end of life," *Advanced drug delivery reviews,* vol. 107, pp. 333-366, 2016.

[36] M. Hedar, A. Intisar, T. Hussain, N. Hussain, and M. Bilal, "Challenges and Issues in Biopolymer Applications," *Handbook of Biopolymers,* pp. 1-16, 2023.

[37] S. Mishra, H. Shah, A. Patel, S. M. Tripathi, R. Malviya, and B. G. Prajapati, "Applications of bioengineered polymer in the field of nano-based drug delivery," *ACS omega,* vol. 9, no. 1, pp. 81-96, 2023.

[38] M. Z. Hauschild, "Life cycle assessment," in *CIRP encyclopedia of production engineering*: Springer, 2019, pp. 1034-1043.

[39] M. Damiani, T. Sinkko, C. Caldeira, D. Tosches, M. Robuchon, and S. Sala, "Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context," *Environmental Impact Assessment Review,* vol. 101, p. 107134, 2023/07/01/ 2023.

[40] L. Shen, E. Worrell, and M. K. Patel, "Comparing life cycle energy and GHG emissions of bio-based PET, recycled PET, PLA, and man-made cellulosics," *Biofuels, bioproducts and biorefining,* vol. 6, no. 6, pp. 625-639, 2012.

[41] A. Fonseca, E. Ramalho, A. Gouveia, F. Figueiredo, and J. Nunes, "Life cycle assessment of PLA products: A systematic literature review," *Sustainability,* vol. 15, no. 16, p. 12470, 2023.

[42] A. O. Osadolor, A. O. Showole, G. A. Asamoah, and T. J. Eze, "Life Cycle Assessment of Polylactic Acid (PLA) in 3D Printing Applications: Evaluating Environmental Impacts and Energy Consumption," *International Journal of Engineering Research & Technology (IJERT),* vol. 13, no. 08, 2024.

[43] L. Senila, E. Kovacs, M.-A. Resz, M. Senila, A. Becze, and C. Roman, "Life Cycle Assessment (LCA) of Bioplastics Production from Lignocellulosic Waste (Study Case: PLA and PHB)," *Polymers,* vol. 16, no. 23, p. 3330, 2024.

[44] C. Maraveas, "Production of sustainable and biodegradable polymers from agricultural waste," *Polymers,* vol. 12, no. 5, p. 1127, 2020.

[45] I. Bolaji, B. Nejad, M. Billham, N. Mehta, B. Smyth, and E. Cunningham, "Multi-criteria decision analysis of agri-food waste as a feedstock for biopolymer production," *Resources, Conservation and Recycling,* vol. 172, p. 105671, 2021/09/01/ 2021.

[46] L. Gong *et al.*, "Sustainable utilization of fruit and vegetable waste bioresources for bioplastics production," *Critical Reviews in Biotechnology,* vol. 44, no. 2, pp. 236-254, 2024.

[47] N. H. Alias, N. Abdullah, N. H. Othman, F. Marpani, M. M. Zainol, and M. S. M. Shayuti, "Sustainability challenges and future perspectives of biopolymer," in *Biopolymers: Recent Updates, Challenges and Opportunities*: Springer, 2022, pp. 373-389.

[48] M. Kogje, A. Satdive, S. Mestry, and S. Mhaske, "Biopolymers: a comprehensive review of sustainability, environmental impact, and lifecycle analysis," *Iranian Polymer Journal,* pp. 1-44, 2025.

[49] T. A. Swetha *et al.*, "A comprehensive review on polylactic acid (PLA)–Synthesis, processing and application in food packaging," *International Journal of Biological Macromolecules,* vol. 234, p. 123715, 2023.

[50] R. Y. Kannah *et al.*, "Production and recovery of polyhydroxyalkanoates (PHA) from waste streams–A review," *Bioresource technology,* vol. 366, p. 128203, 2022.

[51] P. Zytner, D. Kumar, A. Elsayed, A. Mohanty, B. Ramarao, and M. Misra, "A review on polyhydroxyalkanoate (PHA) production through the use of lignocellulosic biomass," *RSC sustainability,* vol. 1, no. 9, pp. 2120-2134, 2023.

[52] C. G. Otoni, H. M. Azeredo, B. D. Mattos, M. Beaumont, D. S. Correa, and O. J. Rojas, "The food–materials nexus: next generation bioplastics and advanced materials from agri-food residues," *Advanced Materials,* vol. 33, no. 43, p. 2102520, 2021.

[53] J. Panda, A. K. Mishra, Y. K. Mohanta, K. Patowary, P. R. Rauta, and B. Mishra, "Exploring biopolymer for food and pharmaceuticals application in the circular bioeconomy: An agro-food waste-to-wealth approach," *Waste and Biomass Valorization,* vol. 15, no. 10, pp. 5607-5637, 2024.

[54] A. Visco *et al.*, "Agri-food wastes for bioplastics: European prospective on possible applications in their second life for a circular economy," *Polymers,* vol. 14, no. 13, p. 2752, 2022.

[55] Z. Asim, H. M. A. Shahzad, G. Ghodake, K. A. Mahmoud, F. Almomani, and K. Rasool, "Transforming Agricultural Food Waste Into Bioplastics: Methods, Potential, and Technological Advances," *Advanced Sustainable Systems,* vol. 9, no. 3, p. 2400864, 2025.

[56] G. Pagliano, V. Ventorino, A. Panico, and O. Pepe, "Integrated systems for biopolymers and bioenergy production from organic waste and by-products: a review of microbial processes," *Biotechnology for biofuels,* vol. 10, no. 1, p. 113, 2017.

[57] K. Grgurević *et al.*, "Producing and Characterizing Polyhydroxyalkanoates from Starch and Chickpea Waste Using Mixed Microbial Cultures in Solid-State Fermentation," *Polymers,* vol. 16, no. 23, p. 3407, 2024.

[58] D. Briassoulis, A. Pikasi, and M. Hiskakis, "Organic recycling of post-consumer /industrial bio-based plastics through industrial aerobic composting and anaerobic digestion - Techno-economic

sustainability criteria and indicators," *Polymer Degradation and Stability,* vol. 190, p. 109642, 2021/08/01/ 2021.

[59] S. Jha, B. Akula, H. Enyioma, M. Novak, V. Amin, and H. Liang, "Biodegradable Biobased Polymers: A Review of the State of the Art, Challenges, and Future Directions," *Polymers,* vol. 16, no. 16, p. 2262, 2024.

[60] N. Kawashima, T. Yagi, and K. Kojima, "Pilot-scale composting test of polylactic acid for social implementation," *Sustainability,* vol. 13, no. 4, p. 1654, 2021.

[61] W. A. Ahsan, C. Lin, A. Hussain, and M. Sheraz, "Sustainable struggling: decoding microplastic released from bioplastics—a critical review," *Environmental Monitoring and Assessment,* vol. 196, no. 6, p. 554, 2024.

[62] G. Solano, D. Rojas-Gätjens, K. Rojas-Jimenez, M. Chavarría, and R. M. Romero, "Biodegradation of plastics at home composting conditions," *Environmental Challenges,* vol. 7, p. 100500, 2022/04/01/ 2022.

[63] S. Nizamuddin and C. Chen, "Biobased, biodegradable and compostable plastics: chemical nature, biodegradation pathways and environmental strategy," *Environmental Science and Pollution Research,* vol. 31, no. 6, pp. 8387-8399, 2024/02/01 2024.

[64] M. Cai *et al.*, "Insights into the abiotic fragmentation of biodegradable mulches under accelerated weathering conditions," *Journal of Hazardous Materials,* vol. 454, p. 131477, 2023/07/15/ 2023.

[65] F. Laface *et al.*, "A glimpse into the future: A suitable methodological approach for the detection and identification of micro-bioplastics in biota," *Science of The Total Environment,* vol. 899, p. 165613, 2023.

[66] K. V. Malafeev, A. Apicella, L. Incarnato, and P. Scarfato, "Understanding the impact of biodegradable microplastics on living organisms entering the food chain: a review," *Polymers,* vol. 15, no. 18, p. 3680, 2023.

[67] T. L. de Albuquerque, J. E. M. Júnior, L. P. de Queiroz, A. D. S. Ricardo, and M. V. P. Rocha, "Polylactic acid production from biotechnological routes: A review," *International journal of biological macromolecules,* vol. 186, pp. 933-951, 2021.

[68] A. Paul, K. Sreedevi, S. S. Sharma, and V. Anjana, "Polylactic Acid (PLA) Applications," in *Handbook of Biopolymers*: Springer, 2023, pp. 1-33.

[69] M. Nofar and C. B. Park, "Poly (lactic acid) foaming," *Progress in Polymer Science,* vol. 39, no. 10, pp. 1721-1741, 2014.

[70] T. M. Joseph *et al.*, "3D printing of polylactic acid: recent advances and opportunities," *The International Journal of Advanced Manufacturing Technology,* vol. 125, no. 3, pp. 1015-1035, 2023.

[71] X. Wang *et al.*, "Research progress in polylactic acid processing for 3D printing," *Journal of Manufacturing Processes,* vol. 112, pp. 161-178, 2024/02/28/ 2024.

[72] S. K. Bardhan, S. Gupta, M. Gorman, and M. A. Haider, "Biorenewable chemicals: Feedstocks, technologies and the conflict with food production," *Renewable and Sustainable Energy Reviews,* vol. 51, pp. 506-520, 2015.

[73] H. Kawaguchi, T. Hasunuma, C. Ogino, and A. Kondo, "Bioprocessing of bio-based chemicals produced from lignocellulosic feedstocks," *Current opinion in biotechnology,* vol. 42, pp. 30-39, 2016.

[74] R. Reshmy *et al.*, "Bioplastic production from renewable lignocellulosic feedstocks: a review," *Reviews in Environmental Science and Bio/Technology,* vol. 20, pp. 167-187, 2021.

[75] N. Rajendran and J. Han, "Integrated polylactic acid and biodiesel production from food waste: Process synthesis and economics," *Bioresource Technology,* vol. 343, p. 126119, 2022.

[76] T. H. Kwan, Y. Hu, and C. S. K. Lin, "Techno-economic analysis of a food waste valorisation process for lactic acid, lactide and poly (lactic acid) production," *Journal of cleaner production,* vol. 181, pp. 72-87, 2018.

[77] T. A. Swetha *et al.*, "A review on biodegradable polylactic acid (PLA) production from fermentative food waste-Its applications and degradation," *International Journal of Biological Macromolecules,* vol. 234, p. 123703, 2023.

[78] R. Madadi, H. Maljaee, L. S. Serafim, and S. P. Ventura, "Microalgae as contributors to produce biopolymers," *Marine Drugs,* vol. 19, no. 8, p. 466, 2021.

[79] Y. L. Tan *et al.*, "Biorefinery-based sustainability assessment of macroalgae waste valorization to polylactic acid: Exergy and exergoeconomic perspectives," *Biochemical Engineering Journal,* vol. 204, p. 109219, 2024.

[80] M. M. Islam *et al.*, "Environmental Footprint of Polylactic Acid Production Utilizing Cane-sugar and Microalgal Biomass: An LCA Case Study," *Journal of Cleaner Production,* p. 145132, 2025.

[81] M. C. Franssen, M. Kircher, and R. Wohlgemuth, "Industrial biotechnology in the chemical and pharmaceutical industries," *Industrial Biotechnology. Sustainable Growth and Economic Success,* pp. 323-351, 2010.

[82] A. Ahmad, F. Banat, H. Alsafar, and S. W. Hasan, "An overview of biodegradable poly (lactic acid) production from fermentative lactic acid for biomedical and bioplastic applications," *Biomass Conversion and Biorefinery,* vol. 14, no. 3, pp. 3057-3076, 2024.

[83] M. Balkcom, B. Welt, and K. Berger, "Notes from the Packaging Laboratory: Polylactic Acid--An Exciting New Packaging Material: ABE339/AE210, 12/2002," *EDIS,* vol. 2003, no. 17, 2003.

[84] K. Oksman and J.-F. Selin, "Plastics and composites from polylactic acid," in *Natural fibers, plastics and composites*: Springer, 2004, pp. 149-165.

[85] J. Nduko and S. Taguchi, "Microbial Production of Biodegradable Lactate-Based Polymers and Oligomeric Building Blocks From Renewable and Waste Resources," *Frontiers in Bioengineering and Biotechnology,* vol. 8, 02/04 2021.

[86] C.-A. Rueda-Duran, M. Ortiz-Sánchez, and C. A. Cardona, "Detailed economic assessment of polylactic acid production by using glucose platform: sugarcane bagasse, coffee cut stems, and plantain peels as possible raw materials," *Biomass Conversion and Biorefinery,* vol. 12, 05/06 2022.

[87] Y. Chen, L. M. Geever, J. A. Killion, J. G. Lyons, C. L. Higginbotham, and D. M. Devine, "Review of multifarious applications of poly (lactic acid)," *Polymer-Plastics Technology and Engineering,* vol. 55, no. 10, pp. 1057-1075, 2016.

[88] J. Jacob *et al.*, "Poly (lactic acid)/nanocellulose biocomposites for sustainable food packaging," *Cellulose,* vol. 31, no. 10, pp. 5997-6042, 2024.

[89] S. Padee *et al.*, "Preparation of poly (lactic acid) and poly (trimethylene terephthalate) blend fibers for textile application," *Energy Procedia,* vol. 34, pp. 534-541, 2013.

[90] R. Guruprasad, M. Vivekanandan, A. Arputharaj, S. Saxena, and S. Chattopadhyay, "Development of cotton-rich/polylactic acid fiber blend knitted fabrics for sports textiles," *Journal of Industrial Textiles,* vol. 45, no. 3, pp. 405-415, 2015.

[91] Y. Yang *et al.*, "Poly (lactic acid) fibers, yarns and fabrics: Manufacturing, properties and applications," *Textile Research Journal,* vol. 91, no. 13-14, pp. 1641-1669, 2021.

[92] V. L. Finkenstadt and B. Tisserat, "Poly (lactic acid) and Osage Orange wood fiber composites for agricultural mulch films," *Industrial crops and products,* vol. 31, no. 2, pp. 316-320, 2010.

[93] W. Ting-Ting, M. Li, W. Jiang, W. Rong-Hua, and C. Sun, "Application of Poly (Lactic Acid) Mulching Film in Watermelon Cultivation in Greenhouse," *Journal of Agriculture Resources and Environment,* vol. 34, no. 6, p. 536, 2017.

[94] D. Merino, A. Zych, and A. Athanassiou, "Biodegradable and biobased mulch films: highly stretchable PLA composites with different industrial vegetable waste," *ACS applied materials & interfaces,* vol. 14, no. 41, pp. 46920-46931, 2022.

[95] M. Parida, T. Jena, S. Mohanty, and S. K. Nayak, "Advancing sustainable agriculture: Evaluation of Poly (lactic acid)(PLA) based mulch films and identification of biodegrading microorganisms among soil microbiota," *International Journal of Biological Macromolecules,* vol. 269, p. 132085, 2024.

[96] S. Serizawa, K. Inoue, and M. Iji, "Kenaf‐fiber‐reinforced poly (lactic acid) used for electronic products," *Journal of Applied Polymer Science,* vol. 100, no. 1, pp. 618-624, 2006.

[97] K. Inoue, S. Serizawa, M. Yamashiro, and M. Iji, "Highly functional bioplastics (PLA compounds) used for electronic products," in *Polytronic 2007-6th International Conference on Polymers and Adhesives in Microelectronics and Photonics*, 2007, pp. 73-76: IEEE.

[98] R. A. Abd Alsaheb *et al.*, "Recent applications of polylactic acid in pharmaceutical and medical industries," *J. Chem. Pharm. Res,* vol. 7, no. 12, pp. 51-63, 2015.

[99] S. M. Davachi and B. Kaffashi, "Polylactic acid in medicine," *Polymer-Plastics Technology and Engineering,* vol. 54, no. 9, pp. 944-967, 2015.

[100] T. Chen, X. Zhao, and Y. Weng, "Self-assembled polylactic acid (PLA): Synthesis, properties and biomedical applications," *Frontiers in Chemistry,* vol. 10, p. 1107620, 2023.

[101] D. d. Silva *et al.*, "Biocompatibility, biodegradation and excretion of polylactic acid (PLA) in medical implants and theranostic systems, pplications of Bioengineered Polymer in the Field of Nano-Based Drug Delivery," *Chemical Engineering Journal,* 2020.

[102] M. A. Ghalia and Y. Dahman, "Biodegradable poly (lactic acid)-based scaffolds: synthesis and biomedical applications," *Journal of Polymer Research,* vol. 24, pp. 1-22, 2017.

[103] R. P. Pawar, S. U. Tekale, S. U. Shisodia, J. T. Totre, and A. J. Domb, "Biomedical applications of poly (lactic acid)," *Recent patents on regenerative medicine,* vol. 4, no. 1, pp. 40-51, 2014.

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[104] L. Ranakoti *et al.*, "Promising role of polylactic acid as an ingenious biomaterial in scaffolds, drug delivery, tissue engineering, and medical implants: research developments, and prospective applications," *Molecules,* vol. 28, no. 2, p. 485, 2023.

[105] M. S. Lopes, A. Jardini, and R. Maciel Filho, "Poly (lactic acid) production for tissue engineering applications," *Procedia Engineering,* vol. 42, pp. 1402-1413, 2012.

[106] W. Hadasha and D. Bezuidenhout, "Poly (lactic acid) as biomaterial for cardiovascular devices and tissue engineering applications," *Industrial Applications of Poly (lactic acid),* pp. 51-77, 2018.

[107] F. Alam, K. Varadarajan, and S. Kumar, "3D printed polylactic acid nanocomposite scaffolds for tissue engineering applications," *Polymer Testing,* vol. 81, p. 106203, 2020.

[108] S. Ayari-Riabi *et al.*, "Polylactide nanoparticles as a biodegradable vaccine adjuvant: a study on safety, protective immunity and efficacy against human leishmaniasis caused by Leishmania major," *Molecules,* vol. 27, no. 24, p. 8677, 2022.

[109] C. Reddy, R. Ghai, and V. C. Kalia, "Polyhydroxyalkanoates: an overview," *Bioresource technology,* vol. 87, no. 2, pp. 137-146, 2003.

[110] Z. A. Raza, S. Abid, and I. M. Banat, "Polyhydroxyalkanoates: Characteristics, production, recent developments and applications," *International Biodeterioration & Biodegradation,* vol. 126, pp. 45-56, 2018.

[111] B. Dalton, P. Bhagabati, J. De Micco, R. B. Padamati, and K. O'Connor, "A review on biological synthesis of the biodegradable polymers polyhydroxyalkanoates and the development of multiple applications," *Catalysts,* vol. 12, no. 3, p. 319, 2022.

[112] G.-Q. Chen, "A microbial polyhydroxyalkanoates (PHA) based bio-and materials industry," *Chemical society reviews,* vol. 38, no. 8, pp. 2434-2446, 2009.

[113] F. Morgan-Sagastume *et al.*, "Polyhydroxyalkanoate (PHA) production from sludge and municipal wastewater treatment," *Water Science and Technology,* vol. 69, no. 1, pp. 177-184, 2014.

[114] H. S. Kusuma *et al.*, "Waste to wealth: Polyhydroxyalkanoates (PHA) production from food waste for a sustainable packaging paradigm," *Food Chemistry: Molecular Sciences,* vol. 9, p. 100225, 2024.

[115] R. Gurav *et al.*, "One-pot exploitation of chitin biomass for simultaneous production of electricity, n-acetylglucosamine and polyhydroxyalkanoates in microbial fuel cell using novel marine bacterium Arenibacter palladensis YHY2," *Journal of Cleaner Production,* vol. 209, pp. 324-332, 2019/02/01/ 2019.

[116] A. Arumugam, P. Yogalaksha, M. Furhanashereen, and V. Ponnusami, "Statistical optimization and enhanced synthesis of polyhydroxyalkanoates from Ceiba pendantra oil as novel non-edible feedstock," *Biomass Conversion and Biorefinery,* pp. 1-10, 2020.

[117] M. Koller and A. Muhr, "Continuous production mode as a viable process-engineering tool for efficient poly (hydroxyalkanoate)(PHA) bio-production," *Chemical and Biochemical Engineering Quarterly,* vol. 28, no. 1, pp. 65-77, 2014.

[118] C. Kourmentza *et al.*, "Recent advances and challenges towards sustainable polyhydroxyalkanoate (PHA) production," *Bioengineering,* vol. 4, no. 2, p. 55, 2017.

[119] V. Sharma, R. Sehgal, and R. Gupta, "Polyhydroxyalkanoate (PHA): properties and modifications," *Polymer,* vol. 212, p. 123161, 2021.

[120] C. R. Hankermeyer and R. S. Tjeerdema, "Polyhydroxybutyrate: plastic made and degraded by microorganisms," *Reviews of environmental contamination and toxicology: continuation of residue reviews,* pp. 1-24, 1999.

[121] G. Kavitha, R. Rengasamy, and D. Inbakandan, "Polyhydroxybutyrate production from marine source and its application," *International journal of biological macromolecules,* vol. 111, pp. 102-108, 2018.

[122] A. A. Khardenavis, M. S. Kumar, S. N. Mudliar, and T. Chakrabarti, "Biotechnological conversion of agro-industrial wastewaters into biodegradable plastic, poly β-hydroxybutyrate," *Bioresource technology,* vol. 98, no. 18, pp. 3579-3584, 2007.

[123] P. Keunun, T. Rakkarn, T. Yunu, N. Paichid, P. Prasertsan, and K. Sangkharak, "The Production of Polyhydroxybutyrate by Two-Step Fermentation and the Application of Polyhydroxybutyrate as a Novel Substrate for a Biolubricant," *Journal of Polymers and the Environment,* vol. 26, no. 6, pp. 2459-2466, 2018/06/01 2018.

[124] B. McAdam, M. Brennan Fournet, P. McDonald, and M. Mojicevic, "Production of polyhydroxybutyrate (PHB) and factors impacting its chemical and mechanical characteristics," *Polymers,* vol. 12, no. 12, p. 2908, 2020.

[125] S.-G. Hong, H.-W. Hsu, and M.-T. Ye, "Thermal properties and applications of low molecular weight polyhydroxybutyrate," *Journal of thermal analysis and calorimetry,* vol. 111, no. 2, pp. 1243-1250, 2013.

[126] F. Masood, "Polyhydroxyalkanoates in the food packaging industry," in *Nanotechnology applications in food*: Elsevier, 2017, pp. 153-177.

[127] A. D. Tripathi, T. Raj Joshi, S. Kumar Srivastava, K. K. Darani, S. Khade, and J. Srivastava, "Effect of nutritional supplements on bio-plastics (PHB) production utilizing sugar refinery waste with potential application in food packaging," *Preparative Biochemistry and Biotechnology,* vol. 49, no. 6, pp. 567-577, 2019.

[128] N. A. Manikandan, K. Pakshirajan, and G. Pugazhenthi, "Preparation and characterization of environmentally safe and highly biodegradable microbial polyhydroxybutyrate (PHB) based graphene nanocomposites for potential food packaging applications," *International Journal of Biological Macromolecules,* vol. 154, pp. 866-877, 2020.

[129] M. S. Popa, A. N. Frone, and D. M. Panaitescu, "Polyhydroxybutyrate blends: A solution for biodegradable packaging?," *International journal of biological macromolecules,* vol. 207, pp. 263-277, 2022.

[130] M. Plouzeau, I. Belyamani, K. Fatyeyeva, S. Marais, Y. Kobzar, and L. Cauret, "Recyclability of poly (hydroxybutyrate-co-hydroxyhexanoate)(PHBH) for food packaging applications," *Food Packaging and Shelf Life,* vol. 40, p. 101170, 2023.

[131] S. Pilla and C. Lu, *Biocomposites in automotive applications*. SAE International, 2015.

[132] R. E. Demirdöğen, F. M. Emen, K. Ocakoglu, P. Murugan, K. Sudesh, and G. Avşar, "Green Nanotechnology for Synthesis and characterization of poly (3-hydroxybutyrate-co-3-hydroxyhexanoate) nanoparticles for sustained bortezomib release using supercritical CO2 assisted particle formation combined with electrodeposition," *International journal of biological macromolecules,* vol. 107, pp. 436-445, 2018.

[133] A. Hiraishi and S. Khan, "Application of polyhydroxyalkanoates for denitrification in water and wastewater treatment," *Applied microbiology and biotechnology,* vol. 61, pp. 103-109, 2003.

[134] M. A. Hassan, E. K. Bakhiet, S. G. Ali, and H. R. Hussien, "Production and characterization of polyhydroxybutyrate (PHB) produced by Bacillus sp. isolated from Egypt," *Journal of Applied Pharmaceutical Science* vol. Vol. 6 no. 04, pp. 046-051, April, 2016 2016.

[135] G. Fernandez-Bunster and P. Pavez, "Novel production methods of polyhydroxyalkanoates and their innovative uses in biomedicine and industry," *Molecules,* vol. 27, no. 23, p. 8351, 2022.

[136] Z.-W. Ren *et al.*, "Polyhydroxyalkanoates: the natural biopolyester for future medical innovations," *Biomaterials Science,* vol. 11, no. 18, pp. 6013-6034, 2023.

[137] D. Rey, "Nanoparticle-coated poly (3-hydroxybutyrate) granules for biomedical applications," 2012.

[138] K. Radha and S. Saranya, "Polyhydroxybutyrate-based nanoparticles for controlled drug delivery," in *Applications of encapsulation and controlled release*: CRC Press, 2019, pp. 191-210.

[139] G.-Q. Chen and J. Zhang, "Microbial polyhydroxyalkanoates as medical implant biomaterials," *Artificial Cells, Nanomedicine, and Biotechnology,* vol. 46, no. 1, pp. 1-18, 2018.

[140] A. Rodríguez-Contreras, J. Guillem-Marti, O. Lopez, J. M. Manero, and E. Ruperez, "Antimicrobial PHAs coatings for solid and porous tantalum implants," *Colloids and Surfaces B: Biointerfaces,* vol. 182, p. 110317, 2019.

[141] P. Ferlic, M. Nogler, A. Weinberg, K. Kühn, M. Liebensteiner, and D. Coraça-Huber, "Material modifications enhancing the antibacterial properties of two biodegradable poly (3-hydroxybutyrate) implants," *Biomedical Materials,* vol. 16, no. 1, p. 015030, 2020.

[142] F. Kok and V. Hasirci, "Polyhydroxybutyrate and its copolymers: Applications in the medical field," *Tissue Engineering and Novel Delivery Systems. 1th ed. Arcel Dekker: New York, NY, USA,* pp. 543-562, 2004.

[143] E. Elmowafy, A. Abdal-Hay, A. Skouras, M. Tiboni, L. Casettari, and V. Guarino, "Polyhydroxyalkanoate (PHA): Applications in drug delivery and tissue engineering," *Expert review of medical devices,* vol. 16, no. 6, pp. 467-482, 2019.

[144] T. Pulingam, J. N. Appaturi, T. Parumasivam, A. Ahmad, and K. Sudesh, "Biomedical applications of polyhydroxyalkanoate in tissue engineering," *Polymers,* vol. 14, no. 11, p. 2141, 2022.

[145] L. Ma *et al.*, "A new antimicrobial agent: poly (3-hydroxybutyric acid) oligomer," *Macromolecular bioscience,* vol. 19, no. 5, p. 1800432, 2019.

[146] P. Tyubaeva, A. Popov, and A. Olkhov, "Traditional and New Approaches to the Creation of Biomedical Materials Based on Polyhydroxyalkanoates with Antimicrobial Activity," *Inorganic Materials: Applied Research,* vol. 14, no. 5, pp. 1165-1185, 2023.

[147] E. G. L. Alves, C. M. de Faria Rezende, R. Serakides, M. de Magalhães Pereira, and I. R. Rosado, "Orthopedic implant of a polyhydroxybutyrate (PHB) and hydroxyapatite composite in cats," *Journal of Feline Medicine and Surgery,* vol. 13, no. 8, pp. 546-552, 2011.

[148] X. Liu, "Effect of Remifentanil on the Osteogenic Activity of Biodegradable Polyhydroxybutyrate Bone Cement in Orthopedic Surgery Model," *Science of Advanced Materials,* vol. 15, no. 12, pp. 1636-1644, 2023.
[149] C.-H. Mi, X.-Y. Qi, Y.-W. Ding, J. Zhou, J.-W. Dao, and D.-X. Wei, "Recent advances of medical polyhydroxyalkanoates in musculoskeletal system," *Biomaterials Translational,* vol. 4, no. 4, p. 234, 2023.
[150] D. Tan, Y. Wang, Y. Tong, and G.-Q. Chen, "Grand challenges for industrializing polyhydroxyalkanoates (PHAs)," *Trends in biotechnology,* vol. 39, no. 9, pp. 953-963, 2021.
[151] N. Mlalila, A. Hilonga, H. Swai, F. Devlieghere, and P. Ragaert, "Antimicrobial packaging based on starch, poly (3-hydroxybutyrate) and poly (lactic-co-glycolide) materials and application challenges," *Trends in Food Science & Technology,* vol. 74, pp. 1-11, 2018.
[152] K. J. Jem and B. Tan, "The development and challenges of poly (lactic acid) and poly (glycolic acid)," *Advanced Industrial and Engineering Polymer Research,* vol. 3, no. 2, pp. 60-70, 2020.
[153] N. Tripathi, M. Misra, and A. K. Mohanty, "Durable polylactic acid (PLA)-based sustainable engineered blends and biocomposites: Recent developments, challenges, and opportunities," *ACS Engineering Au,* vol. 1, no. 1, pp. 7-38, 2021.
[154] S. Gautam, A. Gautam, J. Pawaday, R. K. Kanzariya, and Z. Yao, "Current Status and Challenges in the Commercial Production of Polyhydroxyalkanoate-Based Bioplastic: A Review," *Processes,* vol. 12, no. 8, p. 1720, 2024.
[155] A. K. Singh, J. K. Srivastava, A. K. Chandel, L. Sharma, N. Mallick, and S. P. Singh, "Biomedical applications of microbially engineered polyhydroxyalkanoates: An insight into recent advances, bottlenecks, and solutions," *Applied microbiology and biotechnology,* vol. 103, pp. 2007-2032, 2019.
[156] S. Price, U. Kuzhiumparambil, M. Pernice, and P. Ralph, "Techno-economic analysis of cyanobacterial PHB bioplastic production," *Journal of Environmental Chemical Engineering,* vol. 10, no. 3, p. 107502, 2022.
[157] A. Farias *et al.*, "Risk management strategies & market opportunities for commercialisation of new biopolymer production technologies," 2024.
[158] T. M. Joseph, A. B. Unni, K. S. Joshy, D. Kar Mahapatra, J. Haponiuk, and S. Thomas, "Emerging Bio-Based Polymers from Lab to Market: Current Strategies, Market Dynamics and Research Trends," *C,* vol. 9, no. 1, p. 30, 2023.
[159] W. L. Filho *et al.*, "Consumer attitudes and concerns with bioplastics use: An international study," *PLoS One,* vol. 17, no. 4, p. e0266918, 2022.
[160] S. Notaro, E. Lovera, and A. Paletto, "Consumers' preferences for bioplastic products: A discrete choice experiment with a focus on purchase drivers," *Journal of Cleaner Production,* vol. 330, p. 129870, 2022.
[161] M. Stoica, D. Stoica, A. S. Ivan, and C. M. B. Dragomir, "Biopolymers: Regulatory and legislative issues," in *Biopolymers: Recent updates, challenges and opportunities*: Springer, 2022, pp. 55-71.
[162] F. Al-Ragom, "Emission Abatement: A Cop28 Outlook for Countries," in *Energy Efficiency Improvements with Emission Abatement for Energy Sustainability: Energy Statistics*: Springer, 2024, pp. 45-75.
[163] D. Sharada, U. Naresh, K. V. Shiva, and R. J. Kumar, "Drop-in plastics," in *Advanced Catalysis for Drop-in Chemicals*: Elsevier, 2022, pp. 31-46.
[164] K. Zeng, T. Murayama, S. Nishikizawa, and K. Suwanteep, "Public Willingness to Pay for Sustainable Consumption: Case of Bioplastic Medical Masks," *Circular Economy and Sustainability,* pp. 1-24, 2024.
[165] A. Bher, E. Castro-Aguirre, and R. Auras, "END-OF-LIFE SCENARIOS FOR POLY (LACTIC ACID)," *Poly (Lactic Acid) Synthesis, Structures, Properties, Processing, Applications, and End of Life,* pp. 559-579, 2022.
[166] A. Schwarz, Š. Ferjan, and J. Kunst, "Life cycle assessment of advanced grade PLA product with novel end-of-life treatment through depolymerization," *Science of The Total Environment,* vol. 905, p. 167020, 2023.
[167] A. Ansar, J. Du, Q. Javed, M. Adnan, and I. Javaid, "Biodegradable Waste in Compost Production: A Review of Its Economic Potential," *Nitrogen,* vol. 6, no. 2, p. 24, 2025.
[168] M. R. Hasan, I. J. Davies, A. Pramanik, M. John, and W. K. Biswas, "Recycling Post-Consumed Polylactic Acid Waste Through Three-Dimensional Printing: Technical vs. Resource Efficiency Benefits," *Sustainability,* vol. 17, no. 6, p. 2484, 2025.
[169] S. Ortelli *et al.*, "Innovative and sustainable production of biopolymers," in *Factories of the Future: The Italian Flagship Initiative*: Springer International Publishing Cham, 2019, pp. 131-148.

[170] A. Sionkowska, "Current research on the blends of natural and synthetic polymers: a review," *Progress in polymer science,* 2011.

[171] P. Saini, M. Arora, and M. R. Kumar, "Poly (lactic acid) blends in biomedical applications," *Advanced drug delivery reviews,* vol. 107, pp. 47-59, 2016.

[172] G. Raturi, S. Shree, A. Sharma, P. S. Panesar, and S. Goswami, "Recent approaches for enhanced production of microbial polyhydroxybutyrate: Preparation of biocomposites and applications," *International Journal of Biological Macromolecules,* vol. 182, pp. 1650-1669, 2021.

[173] X. Li *et al.*, "Efficient fabrication of PLA/PHB composites with enhanced mechanical properties, excellent thermal stability, fast crystallization ability, and degradation rate via the synergistic of weak shear field and melt quenching technique," *Industrial Crops and Products,* vol. 196, p. 116516, 2023.

[174] M. P. Arrieta *et al.*, "Plasticized poly (lactic acid)–poly (hydroxybutyrate)(PLA–PHB) blends incorporated with catechin intended for active food-packaging applications," *Journal of agricultural and food chemistry,* vol. 62, no. 41, pp. 10170-10180, 2014.

[175] M. P. Arrieta, J. López, D. López, J. Kenny, and L. Peponi, "Development of flexible materials based on plasticized electrospun PLA–PHB blends: Structural, thermal, mechanical and disintegration properties," *European Polymer Journal,* vol. 73, pp. 433-446, 2015.

[176] M. R. Hasan, I. J. Davies, A. Paramanik, M. John, and W. K. Biswas, "Fabrication and Characterisation of Sustainable 3D-Printed Parts Using Post-Consumer PLA Plastic and Virgin PLA Blends," *Processes,* vol. 12, no. 4, p. 760, 2024.

[177] P. Mahajan and M. Sharma, "A comprehensive review on developments and future perspectives of biopolymer-based materials for energy storage," *Energy storage,* vol. 6, no. 4, p. e634, 2024.

[178] J. Beigbeder, L. Soccalingame, D. Perrin, J.-C. Bénézet, and A. Bergeret, "How to manage biocomposites wastes end of life? A life cycle assessment approach (LCA) focused on polypropylene (PP)/wood flour and polylactic acid (PLA)/flax fibres biocomposites," *Waste management,* vol. 83, pp. 184-193, 2019.

[179] G. Wang *et al.*, "ALKEMIE: An intelligent computational platform for accelerating materials discovery and design," *Computational Materials Science,* vol. 186, p. 110064, 2021.

[180] S. Srivastava, B. Varshney, V. Sharma, and B. Ali, "Applications of artificial intelligence in polymer manufacturing," *Application of Artificial Intelligence in New Materials Discovery,* vol. 147, pp. 105-122, 2023.

[181] W. Xia *et al.*, "Accelerating materials discovery using integrated deep machine learning approaches," *Journal of Materials Chemistry A,* vol. 11, no. 47, pp. 25973-25982, 2023.

[182] K. Shahzad, A. I. Mardare, and A. W. Hassel, "Accelerating materials discovery: combinatorial synthesis, high-throughput characterization, and computational advances," *Science and Technology of Advanced Materials: Methods,* vol. 4, no. 1, p. 2292486, 2024.

[183] R. Wang, Y. Feng, D. Li, K. Li, and Y. Yan, "Towards the sustainable production of biomass-derived materials with smart functionality: a tutorial review," *Green Chemistry,* vol. 26, no. 16, pp. 9075-9103, 2024.

[184] N. A. Pattanashetti, G. B. Heggannavar, and M. Y. Kariduraganavar, "Smart biopolymers and their biomedical applications," *Procedia Manufacturing,* vol. 12, pp. 263-279, 2017.

[185] L. Altomare *et al.*, "Biopolymer-based strategies in the design of smart medical devices and artificial organs," *The International journal of artificial organs,* vol. 41, no. 6, pp. 337-359, 2018.

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