Review on Polylactic Acid As Emerging Bio-Plastic

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Abstract- Polylactic acid (PLA) is a leading bioplastic in the quest for sustainable alternatives to petroleum-based plastics. From renewable feedstocks such as corn starch and sugarcane, PLA offers advantages including the potential to compost in industrial facilities, reduced greenhouse gas emissions, and high mechanical strength. In this review, PLA is compared side-by-side with conventional plastics such as HDPE to reveal both its improved environmental advantages and existing technical limitations. Brittleness, heat instability, and dependence on industrial composting facilities have rendered it increasingly more challenging to have widespread applications for PLA. Nevertheless, the improvement in polymers blending, additive technologies, heating techniques, and chemical recycling is increasingly enhancing its performance. The prospects of PLA are also highly reliant upon government subsidies in the form of composting mandates and certification standards. With increasing awareness and demand for plastic waste globally, PLA is perceived to be a material that will drive the transition towards a circular, sustainable plastic economy.

Keywords- Bio-Plastic, Future of plastic product, Green Chemistry, HPDE, Plastic, Polylactic acid (PLA)

I. INTRODUCTION

Plastics have revolutionized contemporary industries with their durability, flexibility, and cost-effectiveness in sectors like healthcare, packaging, and transportation. Yet their longevity in the environment and reliance on fossil fuels have raised pressing demands for alternatives that are sustainable. Polylactic acid (PLA), a bioplastic made from renewable feedstocks such as corn starch and sugarcane, has been touted as a likely candidate. Marrying good mechanical strength with industrial compostability and reduced carbon footprint, PLA solves a number of the most daunting challenges raised by traditional plastics like high-density polyethylene (HDPE). In order to better grasp the promise of materials like PLA, however, one needs to first appreciate the inescapable role that plastics have played in building the modern world.

Need for plastic

Global annual plastic production reached nearly 360 million tonnes in 2018, reflecting plastics' essential roles in packaging, construction, automotive, and medical sectors due to their high strength-to-weight ratio, chemical resistance, and low cost ^[1].

Since World War II, plastics have enabled unprecedented advancements—from sterile medical disposables to lightweight automotive parts—driving market growth of over 4 % annually .

Classification of Plastics

Plastics can be categorized by polymer structure and processing behavior:

- **Thermoplastics** (e.g., polyethylene, polypropylene, PET) soften upon heating and can be remolded repeatedly .
- **Thermosets** (e.g., epoxies, phenolic resins) cure irreversibly into a fixed shape .
- Engineering plastics (e.g., polycarbonate, PEEK) offer enhanced thermal/mechanical performance for demanding applications .
- **Biodegradable/biobased plastics** (e.g., PLA, PHA) derive from renewable resources and can degrade under specific conditions^[2].

Advantages

Conventional plastics excel in processability (injection molding, extrusion), durability, and barrier properties, produced predominantly via chain-growth (addition) polymerization of olefins or step-growth (condensation) polymerization of diols/diacids [2] Thermoplastics like PE polymerize from gaseous ethylene using metal catalysts, while condensation polymers like nylon require high-temperature dehydration of monomers.

Ease of Processing

Injection molding can produce high-precision, complex parts with tight tolerances (± 0.1 mm), rapid cycle times, and minimal post-machining requirements, making it the method of choice for high-volume consumer goods and automotive components ^[3].

Extrusion enables continuous production of uniform cross-section profiles—such as tubing, films, and sheets—with smooth surface finishes that require little to no post-processing; tooling costs are amortized over large runs, reducing per-unit expense ^[4].

Blow molding (extrusion or injection) produces hollow parts like bottles and tanks in a single step; its relatively low operating pressures translate into lower capital and energy costs compared to injection molding ^[5].

Thermoforming heats sheets to pliable states for vacuum/forming over molds, offering fast turnaround, low tooling costs, and excellent large-part capabilities—ideal for packaging trays, signage, and appliance panels ^{[6][7]}.

Chemical Resistance Commodity plastics resist attack by a wide variety of chemicals due to their non-polar C–C backbones and absence of reactive functional groups. For example, **polyethylene** exhibits excellent resistance to acids, bases, and alcohols, swelling only in aromatic hydrocarbons at elevated temperatures ^[8]. **Polypropylene** resists non-oxidizing acids and bases, fats, and many solvents, although it can dissolve in strong non-polar solvents like xylene at high temperature ^[9]. PVC resists alkalis, most acids, and halogenated solvents, making it suitable for pipes and chemical storage .

Recyclability

Most thermoplastics can be **mechanically recycled** via collection, sorting, shredding, washing, and re-extrusion into pellets; **HDPE** and **PET** have the highest recycling rates (~30 % globally), though average recycling across all plastics remains around 9 % ^[10].

Chemical recycling technologies (e.g., depolymerization, pyrolysis, solvent-based purification) are emerging to convert mixed or contaminated plastic waste back into monomers or feedstocks, helping to close the loop on low-value streams ^[11].

II. HIGH-DENSITY POLYETHYLENE (HDPE)

2.1 Properties

HDPE is defined by a density ≥ 0.941 g/cm³ and minimal branching, yielding high crystallinity and tensile strength of 26–33 MPa (up to 45 MPa in optimized grades) ^[12]. It melts at ~131.8 °C and crystallizes near 121.9 °C, with latent heat of fusion \approx 188.6 kJ/kg, facilitating extrusion and injection molding in packaging and piping ^[12].

2.2 Production of HDPE

HDPE is synthesized by polymerizing ethylene over Ziegler–Natta or metallocene catalysts at 1–5 MPa pressure and 70–300 °C, where catalyst choice and reaction conditions precisely control branching content ^[13]. The linear polyethylene chains pack tightly, imparting stiffness and chemical resistance but resisting biodegradation.

III. THE GENERAL DISADVANTAGE OF TRADITIONAL PLASTIC

In synthesis, conventional polymers demonstrate remarkable processability and utility but exact a profound biogeochemical and toxicological toll: they persist for centuries, disintegrate into dispersive micro- and nano plastics, bioaccumulate hydrophobic contaminants, compromise human physiology, entrench fossil-carbon dependencies, and yield hazardous byproducts during waste-management operations.

3.1 Environmental Accumulation & Ecotoxicological Impact

Annually, **19–23 million tons** of plastic waste evades waste-management infrastructures, infiltrating rivers, lakes, and oceans, thereby disrupting autochthonous biogeochemical cycles and habitat connectivity ^[14]. Microplastics act as vectors for persistent organic pollutants (PCBs, PAHs), exhibiting high absorptive capacities that exacerbate bioavailability of toxins and magnify trophic transfer, inducing oxidative stress and endocrine disruption in aquatic biota ^[15].

3.2 Human Health Implications

Cutting-edge Raman micro spectroscopy has identified microplastics in every human placenta sampled, signaling placental barrier translocation and potential fetal exposure to endocrine-disrupting additive leachates ^[16]. Moreover, a New England Journal of Medicine cohort study detected micro- and nano plastics within carotid atheroma plaques, correlating with a 4.5-fold increase in myocardial infarction, stroke, or mortality—implicating dysregulated toxicokinetic and pro-inflammatory pathways in vascular pathology ^[17].

3.3 Fossil-Fuel Dependence & Carbon Footprint

The polyolefin paradigm remains inextricably tied to naphtha and ethylene feedstocks; life-cycle assessments attribute **2.6 kg CO₂-eq per kg** to HDPE production and **2.9 kg CO₂-eq per kg** to LDPE, with steam-cracking energetics accounting for over **60** % of total GHG emissions ^[18]. This cradle-to-gate carbon intensity converges with projected tripling of plastic-related emissions by 2050, exacerbating global warming trajectories.

3.4 Recycling & Incineration Challenges

Despite advances in mechanical recycling and nascent chemical-recycling modalities (pyrolytic depolymerization), global recycling rates stagnate at **9.5** % (2022), hampered by sorting inefficiencies and polymer downcycling that degrade physicochemical properties ^[19]. Pyrolysis and solvolysis, though reducing life cycle energy use by ~50 % relative to energy- recovery incineration, demand high thermal inputs and catalytic infrastructures yet to be widely deployed ^[19]. Conversely, mass-burn incineration often releases chlorinated dioxins, furans, heavy metals (Hg, Pb), and particulate matter, imposing carcinogenic and neurotoxic burdens on adjacent communities ^[20].

IV. INTRODUCTION TO POLYLACTIC ACID

PLA's initial laboratory preparation through lactic-acid condensation traced back to the 19th century but with limited applications due to low molecular weight. Commercial feasibility arose in the 1980s when Cargill and Dow collaborated to develop Cargill Dow's PLA, which was later spun off as NatureWorks LLC in 2001, with the Blair, Nebraska factory manufacturing 140 000 t/year of IngeoTM PLA by 2002. PLA by 2010 was the second-largest bioplastic globally, implemented in textiles, packaging, and medical devices.

4.1 Methods of PLA Production

4.1.2 Direct Condensation Polymerization

Direct polycondensation of lactic acid between 130– 160 °C under reduced pressure produces PLA of moderate molecular weight, with the byproduct being water that needs to be continually removed in order to propel polymerization forward. Metal catalysts (e.g., tin(II) chloride) facilitate growth of the chains, although production of high molar mass (>100 kDa) still proves difficult with short reaction times.



Figure 1: Chemical Reaction for formation of PLA^[21].

4.1.2 Ring-Opening Polymerization (ROP) of Lactide

Industrial PLA is primarily synthesized through ROP of the cyclic dimer lactide. Lactic acid is initially transformed to lactide, which is then subjected to catalyzed ROP—preferentially using Sn(II) octoate in bulk or solution—to give high molecular weight, stereo controlled PLA (l-, d-, or meso-PLA). ROP enables strict control over polymer architecture, molecular weight (100–500 kDa), and thermal properties.



Figure 2: ROP of Lactic acid for PLA formation^[22].

V. COMPARISON OF PLA AND HDPE

5.1 Edge of PLA over Traditional HPDE in production

Polylactic acid (PLA), a bio-based thermoplastic derived from renewable resources such as corn starch, sugarcane, and cassava, has emerged as a sustainable alternative to conventional petroleum-based plastics like highdensity polyethylene (HDPE). This review evaluates the environmental benefits of PLA production and its comparative advantages over HDPE, supported by lifecycle assessments (LCAs) and empirical studies.

5.1.1 Renewable Feedstock and Reduced Carbon Footprint

PLA's production begins with fermenting plantderived sugars into lactic acid, which is polymerized into PLA. Unlike HDPE, which relies on finite fossil fuels, PLA utilizes renewable biomass annually, decoupling plastic production from petroleum dependence ^[23]. This bio-based origin enables PLA to sequester atmospheric CO₂ during crop growth, partially offsetting emissions generated during manufacturing. Studies indicate PLA production consumes **65% less energy** and emits **68% fewer greenhouse gases** (**GHGs**) than conventional plastics, including HDPE ^[24]. For instance, LCAs reveal PLA generates approximately **1.8 kg CO₂-eq/kg**, compared to **3.4 -- 6.7 kg CO₂-eq/kg** for HDPE, depending on recycling rates ^[25].

5.1.2 End-of-Life Sustainability

PLA's biodegradability under industrial composting conditions (45–90 days at 60°C) offers a critical advantage

over HDPE, which persists in landfills for centuries and contributes to microplastic pollution ^[24]. While HDPE is mechanically recyclable, only 9% of global plastic waste is effectively recycled, with the majority incinerated or discarded ^[26]. PLA, conversely, can be chemically depolymerized into its monomers for closed-loop recycling or composted to enrich soil organic matter, aligning with circular economy principles^{[27][28]}. However, PLA's composting requires specialized facilities, and current infrastructure gaps limit its efficacy, necessitating policy interventions^[27].

5.2 Properties analysis

To make a careful analysis of the potential of polylactic acid (PLA) as an eco-friendly alternative to conventional plastics, it is worth comparing its primary characteristics directly to one of the most widely used conventional plastics, high-density polyethylene (HDPE). The following table presents a clear side-by-side comparison of significant material characteristics like mechanical strength, thermal properties, capability to degrade naturally, and origin. This comparison reveals both the strengths and weaknesses of PLA versus HDPE, providing a technical foundation for evaluating its practical application.

Table 1. Comparison of HDPE and **PI** $\Delta^{[29][30][31][32]}$

Property	HDPE	PLA
Density (g/cm³)	0.94-0.97	1.24-1.30
Tensile Strength (MPa)	26–33 (up to 45)	40-62
Young's Modulus (GPa)	0.8-1.5	3.0-4.1
Elongation at Break (%)	>500	<10
Melting Temperature (°C)	120-135	130-180
Glass Transition (°C)	N/A (very low, ~- 100°C)	60-65
Biodegradability	None (persistent)	Compostable (industrial)
Feedstock	Fossil-derived (ethylene)	Renewable (corn, sugarcane)
Major Catalyst	Ziegler-Natta / Metallocene	Tin(II) Octoate (Sn(Oct) ₂)
Prime Developer	Petrochemical companies	Cargill/NatureWorks (1990s)

VI. APPLICATIONS OF PLA

Polylactic acid (PLA) has emerged as a significant material across various sectors due to its unique combination of biodegradability, biocompatibility, and processability. Its commercial and biomedical applications demonstrate the material's versatility and its increasingly important role in sustainable material development.

6.1 Packaging and Consumer Products

The packaging sector constitutes the largest market for PLA. PLA is utilized in the production of:

Rigid containers, such as disposable cups, clamshell packaging, and trays.

3D printing filaments (notably PLA+ variants), valued for their ease of processing and minimal warping.

Compostable single-use items, including cutlery, grocery bags, and drinking straws.

Leading companies such as **NatureWorks LLC** (IngeoTM range), **Total Corbion PLA** (LuminyTM series), and **Evonik Industries** have commercialized PLA grades optimized for these applications. The material's ability to meet compostability standards (e.g., EN 13432, ASTM D6400) further drives its adoption in environmentally conscious product lines.

6.2 Medical Applications

Owing to its proven biocompatibility and predictable degradation profile, PLA is extensively employed in the medical field for both therapeutic and structural purposes. Key applications include:

Resorbable surgical sutures, reducing the need for post-operative removal.

Orthopedic implants (e.g., screws, pins, plates) designed to degrade harmlessly as bone healing progresses.

Controlled drug delivery systems, utilizing PLA microspheres and scaffolds to release pharmaceutical agents over tailored timeframes.

For instance, the **Lupron Depot**® utilizes PLAbased microspheres for sustained hormone release in prostate cancer treatment, maintaining therapeutic plasma levels over extended durations ^{[32][33]}. PLA's tunable degradation rates, which can span from several days to many months depending on molecular weight and crystallinity, render it particularly suitable for personalized biomedical applications.

VII. CONCERNS REGARDING PLA

Brittleness: Elongation at break < 10 % restricts application in toughness requirement; development of blending with PHB or plasticizers to enhance ductility .

Hydrolytic Degradation: PLA slowly hydrolyzes in wet conditions, lowering molecular weight and mechanical stability over time .

Thermal Stability: Glass transition (~60 °C) and poor heat distortion temperature (< 55 °C) limit application in hot fill or high-temperature use without annealing or blending.

Cost: Today's PLA production costs are $\sim 25-50$ % higher than HDPE, partly owing to feedstock and processing expenses; economies of scale and process optimization will perhaps bridge this gap.

VIII. STRATEGIES FOR IMPROVING PLA PERFORMANCE

While PLA offers notable environmental benefits, its brittleness and low heat resistance restrict widespread application. Performance can be enhanced through polymer blending—such as with PBAT to improve flexibility ^[34] —and by reinforcing with natural fibers or nanofillers to strengthen mechanical properties ^[35]. Annealing techniques improve thermal resistance by increasing crystallinity ^[36]. Additionally, chemical chain extension using agents like Joncryl® raises molecular weight and melt strength, making PLA more suitable for high-performance applications without sacrificing its biodegradability.

Blending PLA with:

PBAT (polybutylene adipate terephthalate): enhances flexibility.

PHB (polyhydroxybutyrate): enhances biodegradability.

Thermoplastic starch (TPS): lowers cost and enhances moisture sensitivity.

Fillers and Nanocomposites:

Adding **cellulose**, **chitin**, or **carbon nanotubes** (**CNTs**) enhances stiffness, biodegradability, and even electrical conductivity.

Annealing and Chain Extenders:

Chemical chain extenders (e.g., Joncryl®) or thermal post-treatment can improve the crystallinity and thermal deformation resistance of PLA, allowing for high-temperature uses.

IX. CONCLUSION

Polylactic acid (PLA) is a key technology in the shift towards greener plastics. Made from renewable materials and compostable at industrial levels, PLA threatens the primacy of traditional petroplastics such as HDPE. However, its brittleness, price, and dependency on composting infrastructure limit its potential. Improvements in blending, additives, and recycling technologies hold out the promise of overcoming these obstacles. But PLA's success requires more than advances in science- it needs firm policy backing in terms of subsidies, compostable packaging requirements, standardized certificating, and investment in closed-loop systems. With innovation and regulation cooperation, PLA would be able to spearhead the development of a genuinely renewable, circular plastic economy.

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