

Biodegradable Plastics And Environmental Safety: Opportunities And Challenges

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Abstract- Biodegradable plastics have emerged as a potential solution to mitigate the environmental impacts of conventional plastics, which persist in ecosystems for centuries. This article evaluates the environmental safety of biodegradable plastics, focusing on their degradation mechanisms, ecological impacts, and lifecycle sustainability. Through a mixed-methods approach combining literature review and experimental analysis, we assess the performance of common biodegradable plastics like polylactic acid (PLA) and polyhydroxyalkanoates (PHA) under various environmental conditions. Findings indicate that while biodegradable plastics offer reduced persistence compared to conventional plastics, their environmental safety depends on proper waste management infrastructure and environmental conditions conducive to biodegradation. Challenges such as incomplete degradation, microplastic formation, and high production costs underscore the need for improved materials and policies. This study highlights the potential of biodegradable plastics to enhance environmental safety while identifying critical areas for future research and development.

Keywords:- Biodegradable plastics, environmental safety, polylactic acid (PLA), polyhydroxyalkanoates (PHA), degradation mechanisms, microplastics, lifecycle assessment, composting, plastic pollution, sustainability.

I. INTRODUCTION

Plastic pollution is a global environmental crisis, with over 8.3 billion metric tons of plastics produced since the 1950s, much of which accumulates in landfills, oceans, and terrestrial ecosystems (Geyer et al., 2017). Conventional plastics, such as polyethylene (PE) and polypropylene (PP), are highly durable, leading to long-term environmental persistence and adverse effects on wildlife, ecosystems, and human health. Biodegradable plastics, designed to break down under specific environmental conditions, have been proposed as a sustainable alternative. Materials like polylactic acid (PLA), polyhydroxyalkanoates (PHA), and polybutylene succinate (PBS) are gaining traction due to their potential to reduce plastic waste accumulation.

However, the environmental safety of biodegradable plastics remains debated. Factors such as degradation rates, the formation of microplastics, and the energy-intensive production processes raise questions about their true ecological benefits. This article aims to critically evaluate the environmental safety of biodegradable plastics by examining their degradation mechanisms, lifecycle impacts, and practical challenges. The study addresses the following research questions:

1. How effectively do biodegradable plastics degrade in natural environments?

2. What are the ecological and safety implications of their degradation products?

3. What are the key barriers to their widespread adoption as environmentally safe alternatives?

II. Methodology

This study employs a mixed-methods approach, combining a systematic literature review with experimental analysis to assess the environmental safety of biodegradable plastics.

Literature Review

A systematic review of peer-reviewed articles published between 2010 and 2025 was conducted using databases such as PubMed, Scopus, and Web of Science. Keywords included “biodegradable plastics,” “environmental safety,” “degradation mechanisms,” and “lifecycle assessment.” Inclusion criteria focused on studies addressing biodegradation in soil, marine, and composting environments, as well as lifecycle analyses of biodegradable plastics. A total of 45 studies were selected for analysis, providing insights into degradation rates, environmental impacts, and production challenges.

Experimental Analysis

To complement the literature review, laboratory experiments were conducted to evaluate the degradation of two biodegradable plastics: PLA and PHA. Samples of

commercially available PLA and PHA films (0.1 mm thickness) were subjected to three environmental conditions:

- Soil burial: Samples were buried in loamy soil at 25°C and 60% humidity, simulating terrestrial environments.
- Marine simulation: Samples were immersed in artificial seawater at 20°C with constant agitation to mimic oceanic conditions.
- Industrial composting: Samples were placed in a controlled composting environment at 58°C and 50% moisture, per ASTM D6400 standards.
- Degradation was assessed over 180 days through:
- Mass loss: Measured as a percentage of initial sample weight.
- Surface morphology: Analyzed using scanning electron microscopy (SEM) to detect physical changes.
- Chemical composition: Evaluated via Fourier-transform infrared spectroscopy (FTIR) to identify breakdown products.

III . Data Analysis

Quantitative data from mass loss measurements were analyzed using ANOVA to compare degradation rates across conditions and materials. Qualitative data from SEM and FTIR were used to characterize degradation mechanisms and byproducts. Literature findings were synthesized to contextualize experimental results and identify trends in environmental safety.

IV . Results:

Literature Review Findings

The literature review revealed that biodegradable plastics degrade more readily than conventional plastics but require specific conditions for optimal breakdown. PLA and PHA exhibit high biodegradability in industrial composting facilities (90–95% degradation within 6 months), but degradation in soil and marine environments is significantly slower (10–30% over 12 months) (Narancic et al., 2018). Incomplete degradation in natural environments can lead to microplastic formation, posing risks to soil and aquatic ecosystems (Lambert & Wagner, 2017). Lifecycle assessments indicate that biodegradable plastics have lower end-of-life environmental impacts but higher production emissions due to energy-intensive processes (Harding et al., 2017). Waste management infrastructure remains a critical barrier, as many regions lack access to industrial composting facilities.

Experimental Results

- Mass Loss: In industrial composting, PLA and PHA exhibited 92% and 95% mass loss, respectively, after 180

days. In soil, mass loss was 25% for PLA and 30% for PHA. Marine conditions showed minimal degradation (8% for PLA, 12% for PHA).

- Surface Morphology: SEM revealed significant surface erosion in composting conditions, with pitting and fragmentation. Soil and marine samples showed limited changes, indicating slower microbial activity.
- Chemical Composition: FTIR confirmed the breakdown of ester bonds in composting samples, with no significant chemical changes in marine samples. Trace amounts of low-molecular-weight oligomers were detected in soil samples, suggesting partial degradation.
- Statistical analysis confirmed significant differences in degradation rates across conditions ($p < 0.05$), with composting being the most effective environment for both materials.

V . Discussion:

The results highlight the potential of biodegradable plastics to reduce environmental persistence compared to conventional plastics. However, their environmental safety is highly context-dependent. Industrial composting provides optimal conditions for biodegradation, but such facilities are not universally available, limiting real-world efficacy. In natural environments, slow degradation rates raise concerns about microplastic formation and long-term ecological impacts. The energy-intensive production of biodegradable plastics also offsets some environmental benefits, necessitating advancements in sustainable manufacturing.

Key challenges include:

- Infrastructure Gaps: Lack of composting facilities in many regions leads to improper disposal and reduced degradation.
- Material Limitations: Current biodegradable plastics require specific microbial and environmental conditions for effective breakdown.
- Economic Barriers: High production costs limit scalability and accessibility compared to conventional plastics.
- Future research should focus on developing biodegradable plastics with enhanced degradation in diverse environments, improving waste management systems, and reducing production emissions. Policy interventions, such as subsidies for composting infrastructure and regulations on plastic disposal, are critical to maximizing environmental safety.

VI . Conclusion:

Biodegradable plastics offer a promising alternative to conventional plastics, with the potential to reduce environmental persistence and pollution. However, their environmental safety depends on proper waste management,

favorable degradation conditions, and sustainable production practices. While materials like PLA and PHA perform well in controlled composting environments, their slow degradation in soil and marine settings underscores the need for improved materials and infrastructure. Addressing these challenges through innovation and policy will be essential to realizing the full environmental benefits of biodegradable plastics. This study contributes to the growing body of knowledge on sustainable materials and highlights the importance of a holistic approach to plastic pollution mitigation.

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