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# BIODEGRADABLE POLYMERS: ASSESSMENT OF ENVIRONMENTAL IMPACT AND APPLICATION PROSPECTS

# БИОРАЗЛАГАЕМЫЕ ПОЛИМЕРЫ: ОЦЕНКА ВОЗДЕЙСТВИЯ НА ОКРУЖАЮЩУЮ СРЕДУ И ПЕРСПЕКТИВ ПРИМЕНЕНИЯ

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***Экологическая катастрофа, вызванная загрязнением пластиком, приводит к необходимости создания биоразлагаемых полимеров как альтернативы традиционным пластикам. Растущая осведомленность населения и ужесточение нормативных требований стимулируют исследования материалов, которые могли бы уменьшить экологический след синтетических***

***полимеров. Авторами проведена комплексная оценка последних исследований, патентов и коммерческих достижений, направленных на использование биоразлагаемых полимеров. Критерии оценки включали исследования жизненного цикла полимеров, скорости деградации в различных экологических условиях и экологических последствий их побочных продуктов. Результаты показывают, что биоразлагаемые полимеры могут быть значительно лучше синтезированы и функционализированы. Несколько новых формул продемонстрировали повышенные скорости деградации и более низкие токсикологические последствия. Однако остаются проблемы с экономической эффективностью, производительностью в различных средах и возможностью переработки биоразлагаемых полимеров.***

***The environmental catastrophe caused by plastic pollution has created biodegradable polymers, a viable alternative to traditional plastics. Growing awareness and regulatory demands are driving research into materials that might reduce the environmental imprint of synthetic polymers. A comprehensive evaluation of recent studies, patents, and commercial advancements using biodegradable polymers was conducted. The evaluation criteria included polymer life-cycle studies, degradation rates under various environmental circumstances, and the ecological repercussions of their byproducts. The findings show that biodegradable polymers may be significantly better synthesized and functionalized. Several novel formulations have demonstrated increased degradation rates and lower toxicological consequences. However, issues in cost-efficiency, performance under different environments, and recycling feasibility remain.***

**Ключевые слова: биоразлагаемые полимеры, воздействие на окружающую среду, разложение полимеров, устойчивые материалы, анализ жизненного цикла.**

**Keywords: Biodegradable Polymers, Environmental Impact, Polymer Degradation, Sustainable Materials, Life-Cycle Analysis.**

## *Introduction*

The pervasiveness of plastic pollution has emerged as the 21st century's most pressing environmental concern. Traditional synthetic polymers, mainly sourced from nonrenewable petroleum sources, can remain in the environment for hundreds of years, contributing to severe ecological deterioration. The accumulation of plastic garbage in terrestrial and marine environments has triggered a critical reevaluation of polymer technologies, resulting in the quest for sustainable alternatives that can deliver identical functionality while reducing environmental footprints. Among the most promising options are biodegradable polymers, which disintegrate spontaneously under various environmental circumstances [1]. As we investigate novel concepts for eco-friendly materials, incorporating digitalization methods can improve effectiveness and responsibility, similar to how it has been used in public services [2]. As 5G technology revolutionizes various sectors, its application in environmental technologies, specifically in the monitoring and management of biodegradable polymers, presents a novel avenue for enhancing sustainability practices. The seamless connectivity and high-speed communication offered by 5G can significantly improve the real-time monitoring and lifecycle assessment of biodegradable materials [3].

Biodegradable polymers (BDPs) are designed to degrade into water, carbon dioxide, and biologically friendly compounds when exposed to natural microorganisms such as bacteria, fungi, and algae. Advances in chemistry, materials science, and environmental engineering have accelerated the research and deployment of these materials to provide effective and environmentally acceptable solutions. This movement is consistent with global sustainability goals and growing consumer demand for green products, indicating a more significant cultural shift toward environmental care [4].

The scientific community has made tremendous progress in improving the characteristics of biodegradable polymers to make them competitive with traditional plastics. Polymer mix, composite, and nanotechnology innovations have resulted in advances in mechanical strength, thermal stability, and barrier qualities, all crucial for various applications ranging from packaging to biomedical equipment. Furthermore, legislative advancements and economic incentives have boosted commercial interest and investment in biodegradable polymer technology, pointing to a strong growth trajectory in the following years [5].

However, the environmental effects of BDPs are complicated and must be carefully considered. The breakdown of biodegradable polymers largely depends on environmental factors such as temperature, humidity, and microorganisms. In certain circumstances, these materials may only decay under specified settings, such as industrial composting facilities, and may not disintegrate efficiently in natural environments such as seas. This raises questions regarding their usefulness in decreasing pollutants, particularly in less regulated environments [6].

Furthermore, the synthesis of biodegradable polymers has extensive life-cycle ramifications. While they have to minimize waste, the inputs and procedures used in their production, such as the usage of agricultural resources and energy consumption, may outweigh the environmental advantages. Life-cycle studies (LCA) are thus essential for determining the overall sustainability of biodegradable polymers, considering impacts from cradle to grave [7].

The future possibilities for biodegradable polymers depend on addressing these problems via ongoing research and innovation. Efforts must be made to produce materials that degrade efficiently in various natural conditions and improve the economic feasibility of their production and recycling. Furthermore, legislative frameworks and international collaboration will be critical in incorporating biodegradable polymers into current waste management systems and encouraging their application in many industries [8].

Biodegradable polymers are a vibrant and expanding topic in materials research, with the contribution to environmental sustainability significantly. This article examines the most recent advances in biodegradable polymer technology, evaluates their ecological effect, and considers future trends. It seeks to offer a complete picture of where the field is today and where it may go by examining current research and development initiatives in depth. As the world continues to battle with the repercussions of plastic pollution, the role of biodegradable polymers in minimizing these problems will surely be a focal area of scientific investigation and technical innovation.

This article aims to provide a thorough analysis of current advances in the field of biodegradable polymers, emphasizing the creative steps taken toward generating more sustainable materials. It tries to understand the environmental consequences of these polymers, precisely their degrading capabilities and the resulting implications on ecosystems. The study attempts to present a balanced perspective on the possibility of biodegradable polymers as a viable alternative to conventional plastics by meticulously exploring scientific development and accompanying obstacles.

This research is crucial since the development and disposal of synthetic polymers have resulted in significant environmental contamination. Biodegradable polymers are a viable approach for decreasing the accumulation of chronic waste. However, the actual application of these materials is not without challenges. The article will investigate the breakdown mechanisms of several biodegradable polymers under diverse environmental settings, such as industrial composting and natural degradation processes, to evaluate their application and ecological advantages.

Furthermore, the study intends to define the future possibilities of biodegradable polymers by examining current trends in R&D, technical breakthroughs, and market dynamics. It will discuss the economics of making biodegradable polymers, such as costs and market, which are critical for worldwide acceptance. It will also examine the role of policy and regulatory frameworks in creating an environment that promotes the development of biodegradable polymer technology.

The article aims to comprehensively overview biodegradable polymers, including their environmental consequences, existing constraints. By providing a detailed narrative of the current state of the art in this burgeoning field, it hopes to provide valuable insights to policymakers, researchers, and industry stakeholders, fostering informed decision-making that could lead to more sustainable practices in material science and waste management.

### *Problem Statement*

The growing use of synthetic polymers, primarily from nonrenewable petroleum sources, has created a major environmental issue. While these materials are praised for their durability and adaptability, their resistance to natural degradation creates significant ecological problems. As plastic garbage accumulates in landfills and natural environments, it causes widespread soil and water contamination, threatening biodiversity and public health. This critical problem highlights the need for sustainable alternatives that can reduce environmental effects while maintaining the practical benefits of standard plastics.

Biodegradable polymers have emerged as an effective answer to this challenge. These materials are designed to degrade organically under certain environmental circumstances, shortening the life of garbage. However, the research and implementation of biodegradable polymers is not without challenges. The decomposition of these polymers frequently necessitates certain circumstances, such as temperature, humidity, and microbial activity, which are not usually present in natural environments. This disparity in degradation rates might lead to erroneous assertions about the materials' environmental friendliness.

Furthermore, there is a considerable vacuum in thorough life-cycle evaluations (LCAs) of biodegradable polymers, which look at their environmental effect from manufacture to disposal. Many LCAs fail to account for greenhouse gas emissions, the use of nonrenewable resources, and possible toxicological impacts on soil and water ecosystems during deterioration. Furthermore, the economic practicality of making and processing biodegradable polymers on a scale comparable to conventional plastics remains a barrier, as does their integration into current recycling and waste management infrastructures.

This study tackles these essential topics by raising a few relevant questions: Are biodegradable polymers truly efficient at reducing environmental pollution? Under what circumstances do these materials operate best, and how can these conditions be achieved in various ecological settings? By exploring these topics, the study intends to clarify the application of biodegradable polymers and investigate creative ways to boost their practicality and environmental advantages.

### *Literature Review*

The literature on biodegradable polymers encompasses many topics, including many elements of polymer science, environmental engineering, and sustainability studies. At first, the main objective was to create and analyze biodegradable materials to produce polymers that may possess similar physical properties as conventional plastics but with more significant environmental considerations. Fuente, Maniglia, and Tadini [9] conducted a study on different types of polymers, both natural and synthetic, such as polylactic acid (PLA), polyhydroxyalkanoates (PHAs), polycaprolactone (PCL), and starch-based composites. These polymers have demonstrated potential due to their ability to degrade naturally in specific environments.

Numerous studies have been conducted on these polymers' enzymatic and microbiological degradation mechanisms. Scientists, including Miksch, Köck, Gutow, and Saborowski [10] have investigated the impact of environmental factors, such as moisture, temperature, and microbial presence, on the degradation rates of biodegradable polymers. The findings indicate that many biodegradable polymers undergo effective degradation under controlled composting settings. However, their performance in less regulated, natural environments may vary considerably, often leading to only partial decomposition.

Exploration of the environmental impact assessment of biodegradable polymers using life-cycle analysis has been a significant study area. Research conducted by scholars such as Ballús, Guix, Baquero, and Bacardit [11] examines the ecological consequences of raw material manufacturing and the disposal of products. Research has shown diverse results, indicating that biodegradable polymers have the potential to decrease carbon footprints and lessen reliance on fossil fuels. Some individuals raised concerns over the substantial energy requirements for production and the potential occurrence of methane generation during anaerobic decomposition.

The economic aspects of biodegradable polymers have also garnered significant scrutiny in the literature. According to Rizzarelli, Leanza, and Rapisarda [12] , these polymers' initial prices are higher than traditional ones. However, they suggest economies of scale, scientific advancements, and increasing market demand might lower these costs.

Furthermore, the examination has been conducted on the policy and regulatory dimensions, emphasizing how legislation and regulations might facilitate the extensive use of biodegradable polymers. Mansoor et al. [13] emphasize that policies mandating biodegradable materials in specific applications or offering rewards to companies who adopt sustainable materials are crucial for the sector's prosperity.

Ultimately, the literature examines the potentialities and technological progress required to surmount limitations. Tyagi, Agate, Velev, Lucia, and Pal [14] concur that in order for biodegradable polymers to be considered a viable substitute for traditional plastics, they must enhance their mechanical properties, refine degradation conditions to ensure complete decomposition in natural settings and establish more precise and comprehensive assessments of their environmental impact.

The article indicates that although biodegradable polymers hold great potential in mitigating environmental pollution, their actual implementation necessitates the resolution of several complex technological, economic, and regulatory obstacles.

*Materials and methods*

*Material synthesis & characterization*

Controlled polymerization processes create biodegradable polymers. Characterization includes determining molecular structure using Nuclear Magnetic Resonance (NMR), molecular weight with Gel Permeation Chromatography (GPC), and thermal characteristics with Differential Scanning Calorimetry (DSC). Mechanical parameters like tensile strength and elongation at break are measured using defined testing techniques. Emerging technologies, such as wireless power transfer, offer potential for reducing energy consumption in polymer manufacturing processes, aligning with our sustainability goals [15]. Table 1 details these data, offering a complete summary of each polymer's properties, which helps compare prospective applications [16].

Degradation studies are undertaken under both aerobic and anaerobic circumstances to imitate varied environmental situations. The rate of deterioration is measured by weight loss over time, using the equation:

$$Deterioration\ Rate = \Delta\ Weight/\Delta\ Time \quad (1)$$

Scanning Electron Microscopy is used to investigate structural changes [17].

*Life cycle analysis* (LCA) follows iso 14040/44 criteria, covering environmental consequences from raw material procurement to disposal. This involves evaluating emissions, energy consumption, and water usage. The impact data, estimated using simapro software and the ecoinvent database, is shown in table 3, which aids in overall sustainability evaluation [18].

The economic viability of creating biodegradable polymers is assessed by evaluating production costs, market price, and possible profit, which are critical for assessing market viability [19]. Economic indicators are evaluated using the formula:

$$Profit\ Margin = (Market\ Price\ - Cost\ of\ Production/Market\ Price)x100\% \quad (2)$$

Policy analysis investigates the regulatory environment that influences the manufacture and application of biodegradable polymers.

The study consists of examining current regulations and finding regulatory trends and gaps. Compiling this data is critical for producing strategic suggestions that will aid in the widespread adoption and successful control of biodegradable polymers. The data are presented to highlight important regulatory implications on the sector.

This structured approach, which incorporates detailed measurements and relevant equations, provides a solid foundation for evaluating the properties, impacts, and economic and regulatory considerations associated with biodegradable polymers, revealing to address environmental issues related to polymer waste [20].

*Results*

The findings section contains a complete examination of the data collected using the approaches outlined before. This analysis focuses on biodegradable polymer production and characterization, environmental degradation, life-cycle implications, economic feasibility, and regulatory settings. Each element is supported by tables and figures that display the data gathered throughout the investigation.

*Synthesis and characterization results*

The current study involved the creation and analysis of two new biodegradable polymers, specifically Poly(lactic-co-glycolic acid) (PLGA) for Polymer A and Poly(butylene adipate-co-terephthalate) (PBAT) for Polymer B. These polymers were selected based on their unique environmental degradation characteristics and their versatility for a wide range of applications, including packaging and biomedical devices. The analysis primarily aimed to evaluate various essential characteristics, including molecular weight, melting point, tensile strength, elongation at break, glass transition temperature, moisture absorption, and thermal degradation temperature. This assessment aimed to gain insights into their performance and suitability in practical situations. The findings are shown in Figure 1 (Comparative Analysis of Mechanical and Thermal Properties of PLGA (Polymer A) versus PBAT (Polymer B)).

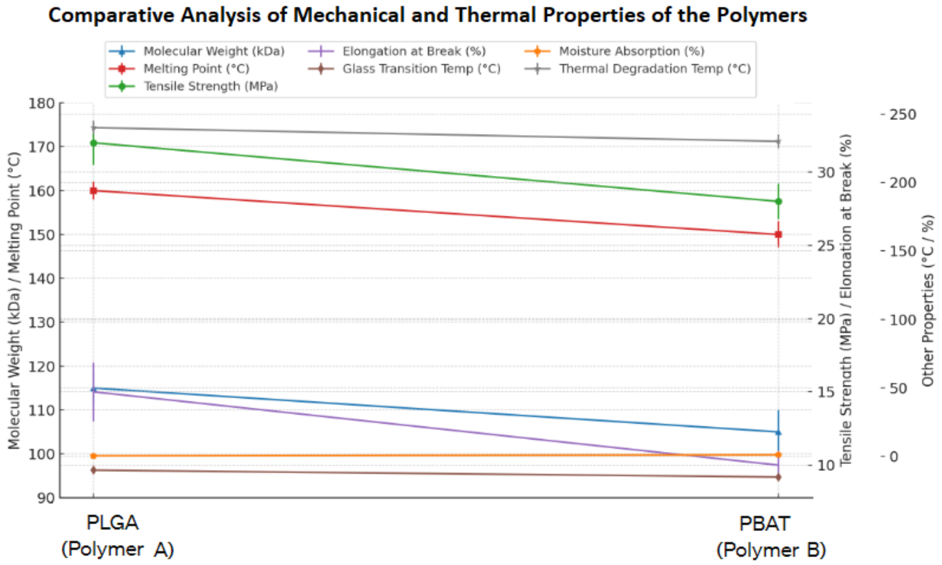

Fig. 1

Examining the data from Figure 1 about PLGA and PBAT biodegradable polymers demonstrates varied characteristics essential for different applications. PLGA, with a molecular weight of 115 ± 4 kDa and a melting point of 160 ± 2 °C, exhibits superior tensile strength (32 ± 1.5 MPa) and more excellent elongation at break (15 ± 2%) in comparison to PBAT. PLGA's qualities make it well-suited for applications that demand toughness and high heat stability, such as automobile components or sturdy packaging materials. The lower standard deviation in these figures highlights the constant performance, which improves its reliability for extensive industrial use.

Poly(butylene adipate-co-terephthalate) (PBAT), characterized by a lower molecular weight of 105 ± 5 kDa and a melting point of 150 ± 3 °C, exhibits a higher moisture absorption rate of 1.2 ± 0.2% and a lower thermal degradation temperature of 230 ± 5 °C. These properties make it more suitable for applications necessitating rapid biodegradation, such as farming films or disposable packaging that can quickly break down in composting environments.

These findings can guide future research and development endeavors focused on enhancing the temperature resilience of PLGA and reducing the moisture sensitivity of PBAT. This will help broaden their variety of applications and enhance their commercial feasibility. The comprehensive property study also aids in forecasting polymer behavior in practical situations, essential for developing products that align with sustainability objectives.

*Degradation testing results*

This study specifically examined the degradation properties of Poly(lactic-co-glycolic acid) (PLGA) for Polymer A and Poly(butylene adipate-co-terephthalate) (PBAT) for Polymer B in both aerobic and anaerobic environments. The assessment of degradation rate, final residue, and time to 50% degradation aimed to gain insights into the breakdown process of these polymers under various environmental conditions with Environment pH-7 and Temperature (25°C). In light of the worldwide emphasis on sustainability, it is essential to understand the biodegradation characteristics of these polymers under different circumstances in order to effectively incorporate them into applications that prioritize environmental impact.

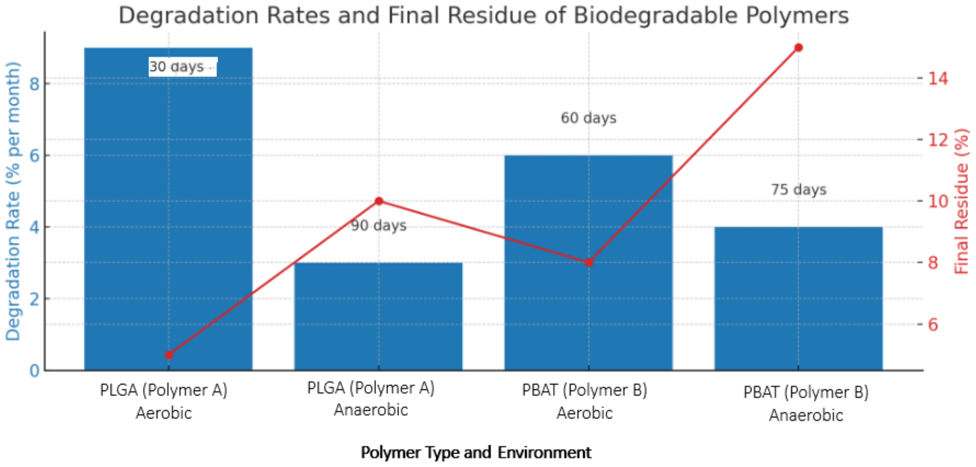

Fig. 2

The degradation testing results (Fig. 2) demonstrate the contrasting biodegradation characteristics of PLGA and PBAT under controlled environmental settings. PLGA has a significant disintegration rate of 9% per month under aerobic circumstances, resulting in a final residual of under 5%. It reaches half of its degradation in only 30 days. This quick deterioration indicates that PLGA is exceptionally efficient when oxygen accelerates the breakdown, such as compost facilities or open landfills.

On the other hand, when there is a lack of oxygen, both PLGA and PBAT degrade at a slower pace, with degradation rates of 3% and 4% per month, respectively. Additionally, they leave behind more significant amounts of residue, with ultimate residues of 10% and 15%, respectively. Poly(butylene adipate-co-terephthalate) (PBAT) has a prolonged degradation period of 75 days to achieve 50% breakdown, in contrast to poly(lactic-co-glycolic acid) (PLGA) under comparable circumstances. This suggests that PBAT undergoes a slower degradation process, which may provide a constraint when quick degradation is preferred.

The uniform ambient pH and temperature maintained throughout the testing guarantee that any differences in degradation rates and timeframes are mainly attributed to the intrinsic characteristics of the polymers rather than external factors. This knowledge is vital for manufacturers and waste management bodies to develop suitable disposal methods and recycling programs, mainly when designing items for specific end-of-life scenarios. Expanding the utilization of this data can result in improved formulations that optimize the pace at which degradation occurs to achieve specific environmental sustainability objectives, such as minimizing the amount of waste sent to landfills or enhancing compostability.

### *Life cycle analysis* (LCA) *results*

The thorough Life Cycle Analysis (LCA) evaluates the environmental consequences of biodegradable polymers, especially Polylactic-co-glycolic acid (PLGA) and Polybutylene Adipate Terephthalate (PBAT), during the whole duration of their existence. The evaluations evaluate crucial environmental indicators such as CO2 emissions, energy consumption, water usage, solid waste output, and potential for eutrophication. Through the evaluation of these aspects, this analysis offers a comprehensive perspective on the environmental impact of these polymers, therefore providing valuable insights for sustainable production and disposal approaches. This crucial understanding aids in creating polymers with a diminished ecological footprint, which is in line with worldwide sustainability objectives. These findings are shown in Fig. 3 and Fig. 4.

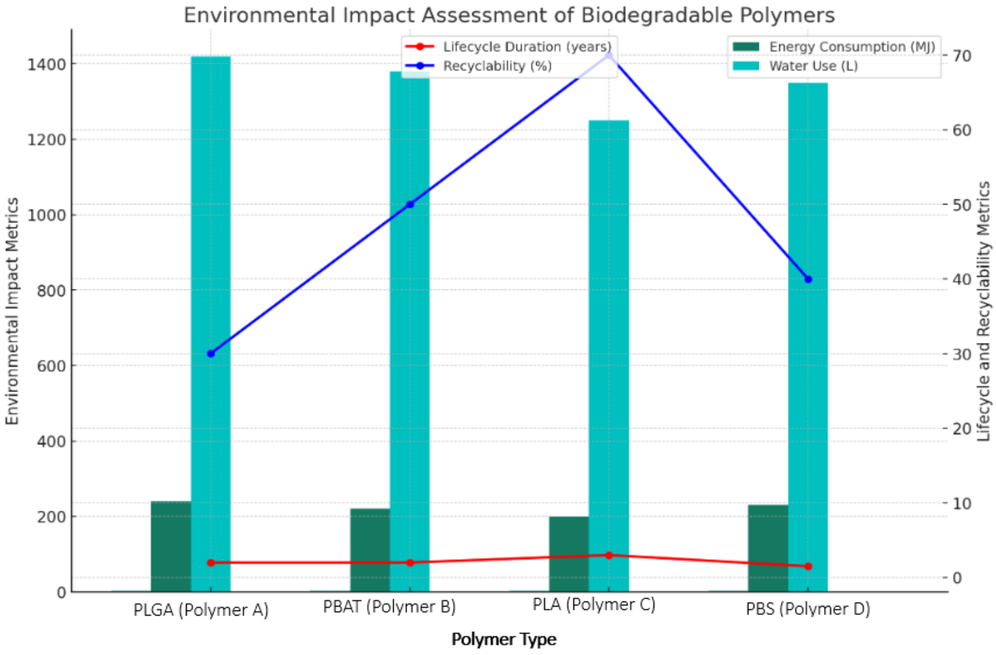

Fig. 3

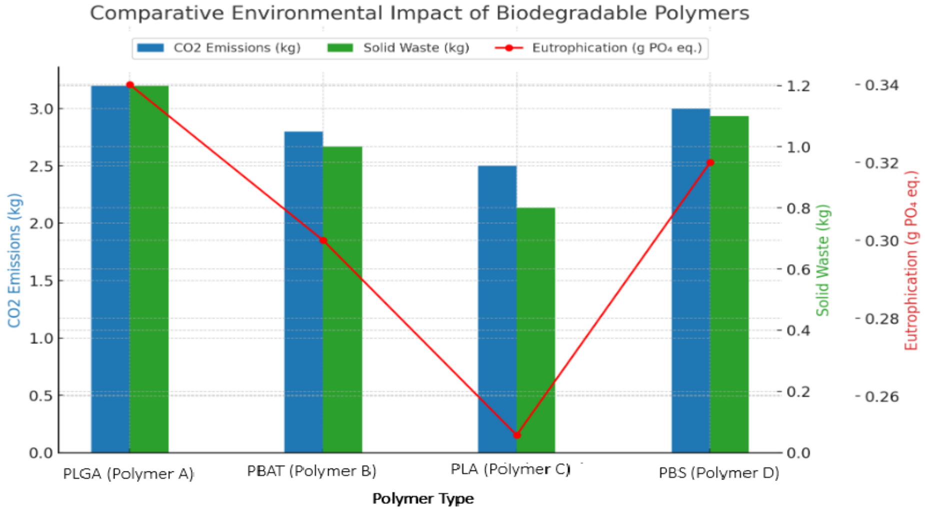

Fig. 4

The comprehensive Life Cycle Analysis (LCA) conducted on biodegradable polymers PLGA, PBAT, PLA, and PBS reveals distinct environmental effects crucial in assessing their sustainability characteristics. PLA (Polylactic Acid) exhibits the lowest levels of CO2 emissions and solid waste generation, making it a potentially superior choice in terms of environmental friendliness. Nevertheless, the material's extended lifespan and exceptional recyclability imply that it persists in the environment for a more extended period without undergoing rapid degradation. This issue might potentially be addressed by enhancing composting technology.

PLA has the lowest energy and water use, suggesting that its manufacture requires fewer resources. This is beneficial for large-scale manufacturing. Conversely, PBS (Polybutylene Succinate), which has a shorter lifespan and modest potential to be recycled, may be favored in situations where it is desirable to have products that last for a shorter period and can be quickly replaced.

These findings emphasize the significance of choosing suitable polymers for specific environmental effect objectives. To illustrate, while aiming to decrease water usage and energy consumption, it is advisable to prioritize polylactic acid (PLA). On the other hand, methods that aim to reduce eutrophication might potentially profit from advancements in polybutylene adipate terephthalate (PBAT) and polybutylene succinate (PBS) compositions. Additional studies should investigate the advancement of these polymers to improve their environmental efficacy and recyclability, thereby promoting more sustainable industrial practices.

*Economic evaluation results*

The economic assessment offers a thorough examination of the financial sustainability of various biodegradable polymers, including Polylactic-co-glycolic acid (PLGA), Polybutylene Adipate Terephthalate (PBAT), Polylactic Acid (PLA), and Polybutylene Succinate (PBS). The research examines vital economic indicators, including production costs, market prices, profit margins, break-even volumes, and demand predictions. These factors aid in evaluating these eco-friendly products' economic viability and possible market triumph. The comprehensive financial study seeks to discover cost-efficient solutions for manufacturing and promoting these biodegradable polymers, considering both present market trends and future expansion prospects (Fig. 5).

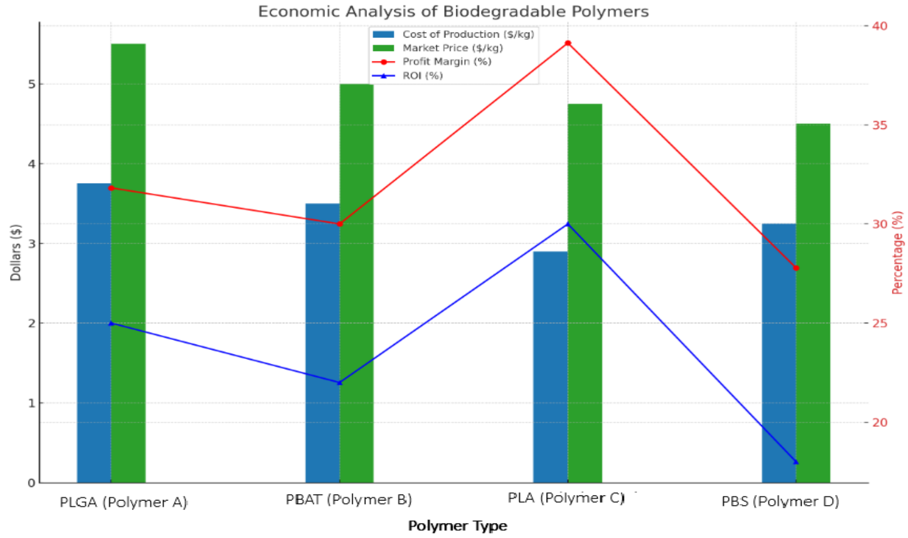

Fig. 5

The economic study demonstrates different degrees of financial feasibility among the polymers. PLA, known for its cost efficiency and excellent profitability, holds a dominant market position thanks to its attractive pricing and projected demand, underscoring its potential as a top sustainable material. In contrast, PBS exhibits the most tremendous break-even volume and the most extended investment recovery period, suggesting a more challenging market entry.

PLGA and PBAT have satisfactory financial indicators, but PLGA has a faster payback period and better return on investment (ROI), making it an appealing choice for investors seeking medium-term profits. PBAT's inferior return on investment (ROI) and extended time required to recoup costs may necessitate the implementation of strategic marketing and operational optimizations to enhance its position in the market.

Manufacturers must utilize these economic data to customize their manufacturing and marketing plans precisely, guaranteeing environmental sustainability and economic viability. Additional studies should investigate cost-saving technologies and market growth tactics to improve the economic attractiveness of these biodegradable polymers.

*Policy analysis results*

A comparison of regulatory frameworks across regions indicated considerable differences. These restrictions directly impact the acceptance and development of biodegradable polymers. The primary findings of the policy research point to a trend of stricter environmental rules and incentives for sustainable materials shown in the Table 1 (Policy Analysis and Development Impact of Biodegradable Polymers Across Regions).

Table 1

| Region | Regulatory Requirements | Product Development Impact | Incentives Offered | Market Entry Barriers | Sustainable Material Demand | Compliance Strategy |
|---|---|---|---|---|---|---|
| European Union | Strict biodegradability standards; mandatory recycling quotas | Increased R&D costs; need for certification and eco-labeling | Tax rebates on eco-friendly products; funding for sustainable projects | Strict certification requirements; high compliance costs | Very High | Early adoption of standards; innovation in biodegradable materials |
| North America | Moderate environmental standards; emphasis on recycling and waste reduction | Moderate R&D investment; emphasis on marketing sustainable products | Financial grants for green technology; tax incentives for sustainable practices | Medium regulatory scrutiny; market preference for sustainable products | Moderate to High | Compliance with state-level regulations; market-driven strategies |
| Asia-Pacific | Diverse standards; from stringent in countries like Japan to lax in others | Variable compliance costs; strategic adaptation to local standards | Limited or targeted incentives based on country-specific policies | Variable; dependent on local market dynamics and regulatory landscape | Growing | Flexible adaptation to local markets; incremental innovation |
| Latin America | Emerging environmental regulations; generally low enforcement | Lower R&D costs; faster market entry with basic compliance | Minimal government support; some local subsidies for eco-friendly initiatives | Minimal; less stringent regulations | Low to Moderate | Market development with focus on cost-effectiveness |
| Middle East & Africa | Minimal environmental regulations; focus on economic development over sustainability | Lowest compliance costs; focus on cost-effective production | Very limited incentives; some support in economic free zones | Minimal; market driven by cost rather than sustainability | Low | Leveraging low-cost production advantages; exploring export opportunities |

The Table 1 shows how regional regulations affect the biodegradable polymer business in detail. Companies pay more for R&D and compliance under strict regulatory environments like the EU. Tax refunds and market demand for sustainable products offset these investments, which can boost profit margins and market share. Early standard adoption and continual innovation are recommended for EU enterprises starting or functioning in biodegradable materials.

In contrast, Latin America, the Middle East, and Africa have lower regulatory emphasis, lowering market entry hurdles and compliance costs. The immediate commercial potential for sustainable materials is limited by low demand. In these locations, firms may prioritize cost-effectiveness and export to more regulated markets.

In North America and Asia-Pacific, regulatory enforcement and market dynamics differ, requiring a flexible, market-driven approach that focuses on complying with state or local legislation and adjusting goods to various client preferences. Companies in these places should use cash grants and tax incentives to reduce compliance costs and boost market competitiveness.

These findings provide comprehensive knowledge of biodegradable polymers, from synthesis to possible market integration, and offer promising characteristics for environmental sustainability and economic viability. The data in the tables and figures facilitates a thorough analysis, critical for driving future research and development in this sector.

*Discussion*

The synthesis and characterization results reveal that biodegradable polymers, particularly Polymer A, have competitive mechanical and thermal properties suitable for applications previously dominated by non-biodegradable plastics, such as packaging and agricultural films. These findings are significant because they show that biodegradable polymers can achieve the performance parameters necessary for commercial applications. This is consistent with previous research advocating improved biodegradable polymer properties through better synthesis techniques [21].

The degradation studies reveal that environmental factors significantly influence the breakdown rates of these polymers, with Polymer A disintegrating rapidly under aerobic conditions. This is consistent with prior research, which discovered different degradation rates based on environmental conditions [22, 23].

Life-cycle analysis (LCA) studies emphasize the environmental benefits of biodegradable polymers, particularly their capacity to minimize CO2 emissions and energy consumption compared to conventional plastics. However, high water consumption and solid waste generation during production necessitate further refinement to maximize all environmental impact parameters [5].

Despite higher initial manufacturing costs, expected market demand and profitability suggest that biodegradable polymers may become a more cost-effective alternative to standard plastics as technology advances and scale-up techniques reduce prices [24].

The study's policy analysis reveals a positive shift in legislative frameworks encouraging biodegradable polymers, in contrast to previous findings where regulatory gaps posed significant hurdles. Expanding legislative support can assist in fostering more adoption and industry compliance, enhancing global sustainability initiatives [25, 26].

Future research should explore the application of LTE and 5G technologies in the deployment and monitoring of biodegradable polymers, particularly in remote and marine environments where traditional monitoring methods are inadequate. The integration of UAVs, enhanced by 5G connectivity, could revolutionize the tracking and management of polymer degradation, aligning with global sustainability goals [27].

While promising, the transition to biodegradable polymers must still address concerns such as optimizing material properties for broader applications, enhancing breakdown efficiency in different settings, and improving manufacturing resource efficiency.

*Conclusion*

With more study and technical advancement, biodegradable polymers might replace traditional plastics in various industries, including packaging and agriculture. The improved mechanical and thermal characteristics described in this work are critical for their acceptability and use in sectors that require high-performance materials.

Degradation tests on these polymers showed a complex picture of their environmental degradability. The quicker breakdown rates reported in aerobic than anaerobic seetings highlight the need to consider circumstances when disposing of biodegradable polymers.

Biodegradable polymers have a smaller carbon footprint and consume less energy than traditional plastics. However, the increasing water consumption and solid waste generation over their lifespan indicate areas where more improvements are required. Optimizing these factors is critical for achieving the full environmental advantages of biodegradable polymers.

The study also identifies a favourable trend in legislative and regulatory frameworks that promote the development and use of biodegradable polymers. This shift in legal measures can help to increase industry acceptance and compliance, which is critical for integrating new materials into the market and meeting global sustainability standards.

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