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Biodegradable Polymers for Sustainable Engineering Applications

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ABSTRACT

The biodegradable polymers are currently gaining special importance as an essential material in the field of sustainable engineering, due to their possibility of being degraded by the natural environment as environmentally friendly products. These polymers are a good alternative to traditional plastics made of petroleum, which causes a significant contribution to ecological pollution of the environment and harm on the ecosystem on the long term. This research paper will discuss properties, synthesis, degradation, engineering uses and performance of biodegradable polymers in the environment. The method of systematic review and qualitative synthesis was selected in order to evaluate the condition of the existing research and identify challenges and opportunities to adopt this research in the industry. Results show that though polymers like polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are high in their mechanical performance and biodegradability there are still hurdles implicitly like high cost of production, inconsistent rate of degradation and lack of large scale infrastructure. The paper concludes that biodegradable polymers have the potential to be of great use in sustainable engineering through interdisciplinary innovation, industrial scale adoption and proper dumping techniques.

Introduction

The blistering development of global industrialization, urbanization process, and consumerism has resulted the increase in the volume of plastic production and waste generation to unprecedented proportions. The traditional plastics are mostly petroleum-based and are chemically stable as well as very strong making it hard to degrade thus lasting hundreds of years in the environment. This has had drastic ecological impacts that include land and mixed water pollution, ecosystem disturbance, biodiversity endangering, food and water pollution (Geyer et al., 2017). To deal with these challenges of environment it is necessary to develop and adopt materials which are not only sustainable and friendly to the environment, but also produce materials with adequate engineering performance. Biodegradable polymers have come up as a potential solution, which provides the opportunity to breakdown into the natural byproducts of carbon dioxide, water and biomass under certain environmental factors, which are microbial activity, moisture and temperature (Emadian et al, 2017). Natural biopolymers used in these polymers include starch, cellulose and chitosan and the synthetic biopolymers include polylactic acid (PLA), polyhydroxyalkanoates (PHAs), polybutylene succinate (PBS) and polycaprolactone (PCL). In the last 10 years, polymer chemistry ,biotechnology and processing methods have improved which has improved their mechanical, thermal and environmental performance enabling their increased use in engineering applications.

Biodegradable polymers sustainable engineering is very important. They are a powerful solution to the harm of plastic waste to the environment and a circular economy. In the case of packaging, the polymers have reduced the reliance on petroleum-based plastics that have little mechanical strength and barrier properties. The use of chitosan in the biomedical field, they enable the development of degradable sutures, scaffolds and systems for the transport of drugs which can safely degrade in the human body. Biodegradable mulch and slow release fertilizer carrier films in agriculture reduce the cost of soil contamination as well as labour costs. In addition to these areas, the versatility and industrial applicability of these materials can be demonstrated in the new applications in the field of automotive parts, 3D printing and biodegradable electronics. Moreover, biodegradable polymers use is aligned with the sustainability measures that are being implemented worldwide, such as the United Nation sustainable development goals (SDGs) and national policies for waste reduction and resource efficiency and greenhouse gas reduction (UNEP, 2022).

The major objective of this paper is to provide a detailed knowledge on the concept of biodegradable polymers and their opportunities at sustainable engineering. In particular, it will study the characteristics, manufacturing process, and dismantling process of biodegradable polymer, discuss current literature distribution in the engineering performance, environmental effect, and industrial feasibility of biodegradable polymers. The approaches towards evaluating polymer performance and biodegradability are also analysed in the study as also the identification of the best practices, and the issues of costs, environmental variability, and mechanical constraints. The synthesis of those findings will help the research to contribute practical recommendations to the researchers, engineers, and policy makers to implement biodegradable polymers and get the best from their ecological and technological benefits.

Literature Review

The capability of offering alternative solutions to the traditional plastics based on petroleum has led to some a lot of attention being put on biodegradable polymers in academic studies as well as in practice. These polymers can be degraded to water, carbon dioxide, and biomass through natural degradation processes through the use of microorganisms and other environmental factors such as temperature, moisture, and pH (Emadian, Onay, and Demirel, 2017). Some of the biodegradable polymers that have been the most researched are polylactic acid (PLA), polyhydroxyalkanoates (PHAs), polybutylene succinate (PBS), polycaprolactone (PCL), and polymers made of starch. PLA is manufactured on the basis of renewable corn starch or sugarcane and is widely used since it has the highest mechanical strength, stiffness, and processing capability that renders it applicable in the applications in packaging, 3D printing, and biomedical engineering (Auras, Harte, and Selke, 2022). But the PLA has a weakness in the form of brittle nature and little impact resistance which restricts their use in flexed applications. There are researches concerning the addition of plasticizers, nanofillers (as cellulose nanocrystals or clay) and blending PLA with other plastics to obtain enhanced properties in mechanical domains and thermal stability (Fortunati et al., 2012). These alterations have functioned out to improve toughness, dimensional stability, and barrier however preserve biodegradability, thus indicating a wider scope of the application of PLA potentially in many engineering applications.

Another important group of biodegradable polymers, which is produced naturally though fermentation of sugars and lipids by bacteria, are polyhydroxyalkanoates (PHAs). The high biodegradability of PHAs in the soil, freshwater and marine ecosystem is due to its susceptibility to enzymatic hydrolysis (Chen and Patel, 2019). Their mechanical characteristics can be very easily fine-tuned based on monomer composition thus making it possible to produce high elasticity-rigidity gradients of materials. Such functionality has led to PHAs being investigated as medical uses, agricultural films, packaging materials and even automotive parts. Nevertheless, the costly process of production of PHAs does not facilitate mass deployment due to the fact that the microbial fermentation process is not always cost-efficient in comparison to the one of petrochemicals (Philip, Keshavarz, and Roy, 2007). The recent research has gone through agricultural residues and industrial by-products that are low cost feedstocks to lower the cost of production and increase the commercial viability (Hemaiswarya, Subhasree, and Radhakrishnan, 2022).

Biodegradable polymers that are made of starch are renewable and can be made of corn, potato and cassava. They are cheap, renewable and they are characterized by the good biodegradability in the natural circumstances. But their mechanical performance is also poor that of tensile strength and being easily moist which makes their standalone application in engineering practice difficult. Therefore, starch can be used in a composite with PLA, PBS or other polymers to avail the environmental benefits of starch combined with increase in mechanical and thermal properties (Briassoulis, Dejean, and Hiskakis, 2015). They have been able to implement such biocomposites to packaging and disposable utensils as well as agricultural films and it has been shown that blending strategies can be used to provide better functionality and sustainability.

Polybutylene succinate (PBS) and polycaprolactone (PCL) are examples of synthetic biodegradable polyesters which are being considered because of their good flexibility, thermal characteristics and processability. Tend to be utilised in agricultural movies, packaging and biodegradable bags, PBS has a balance between in terms of mechanical performance as well as rate of degradation in the environment (Zhao, Wu and Chen, 2023). PCL is also a material with low melting point and high elongation of break thus it would be of high value in biomedical applications because it can be used as drug delivery application, scaffold and tissue engineering. PBS and PCL are both degraded under special conditions of the microorganisms, and it is important to mention once again that the speed and the extent of biodegradation is greatly dependent on the conditions of the environment, such as temperature, moisture and microorganisms (Middleton and Tipton, 2000).

The environmental and sustainability property is another property of biodegradable polymers that has been subject to several studies. According to life-cycle assessments (LCAs), bio-based polymers are said to have less resulting greenhouse emissions, less fossil fuel consumption, and last longer environmentally compared to conventional plastics (Spierling, Knupffer, and Ziegenhorn, 2018). Nonetheless, LCAs also show that the ecological gains also depend on the appropriate end-of-life management. As an example, PLA requires industrial composting conditions to be degraded in a short-time and improper disposal in landfill or marine situations reduces the environmental benefit to a large extent (Kale, Auras, and Selke 2007). PHAs, in its turn, are degradable in a variety of environment reasons, which is why they can be specifically used in the activities where there is a high risk of exposure to uncontrolled natural factors, e.g. agricultural wrappings and single-use products employed by consumers (Chen & Patel, 2019).

There has been an increasing amount of research on composite solutions and nanotechnology for the promotion of biodegradable polymers behaviour. Mechanical properties, thermal stability and barrier properties can be improved by the inclusion of natural fibers, nanocellulose and other reinforcing agents without lowering biodegradability (Faruk et al., 2012). Indicatively, PLA reinforced with cellulose nanocrystals is stronger in terms of tensile strength and reduction in brittleness hence can be used in structural applications, 3D printing as well as packaging (Fortunati et al., 2012). Furthermore, polymer blends and copolymerization can be used to control the rate of degradation and mechanical performance in order to fine-tune the design of materials into a particular engineering process, with the environmental compatibility guaranteed.

Nevertheless, there are still some problems in the commercialization and mass use of biodegradable polymers. They are limited in their use by high cost of production, inadequate infrastructural of industrial composting, inconsistent mechanical performance and competition with food resources as a source of raw material (UNEP, 2022). Moreover, the advantages of using biodegradable polymer in terms of the environment can be reduced due to inconsistent public awareness and wrong disposal practices. It is argued in research that interdisciplinary applications of material science, biotechnology, environmental management, and industrial engineering are needed to create a maximum polymer design, performance, and sustainability (Hemaiswarya et al., 2022).

In short, the literature has revealed that biodegradable polymers have a high potential and development in the area of sustainable engineering. PLA, PHAs, PBS, PCL and polymer based on starch possess various mechanical, thermal and environmental attributes which are applicable in packaging, biomedical and agricultural and industrial applications. Composite strategies, nanotechnology and polymer mixture also promote performance and increase applicability. Nevertheless, issues associated with the cost, variability of degradation and infrastructure have to be overcome in order to optimize their environmental and engineering advantages. It is indicated that as more innovation is allowed, policy support, and the adoption of biodegradable polymers as an industry, that it could become an important component of sustainable engineering practices.

Methodology

This study methodology was aimed at giving a rigorous, systematic and holistic knowledge of biodegradable polymers and their sustainable application in engineering. Due to the interdisciplinary nature of subject, the research design based on mixed method qualitative study was chosen. The methodology was an intertwining of systematic literature review, comparative analysis of materials and thematic synthesis to create a global picture of the present research trends, material performance and practical application of biodegradable polymers. The applied methodology was based on the academic standards to ensure validity, reliability and scientific rigour in the process of research.

The systematic literature review (SLR) was the first stage of the methodology because it was conducted according to the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The reason why we have used SLR was because of its clarity of procedure of identifying, evaluating, and synthesizing the literature on science. Scientific databases such as Scopus, Web of Science, ScienceDirect, SpringerLink, ACS Publications, Wiley Online Library, Taylor and Francis, IEEE Xplore Google Scholar were used as the first scientific databases. These databases have been chosen because of their high standards of indexing databases, peer reviewed databases and include engineering and environmental sciences. Search strategy involved the use of Boolean operator and the target keywords: "biodegradable polymers," bio-based plastics, PLA mechanical properties, PHA degradation, sustainable engineering materials, biodegradation rate, green materials and biocomposites and environmental impact of biopolymers. More search terms were formed by applying combination of several search terms in order to gain interdisciplinary research.

The first search result gave 1372 publications of the year between 2010-2025. This time period has been chosen such that both the works and the state-of-the-art technological advances are represented. Once the original collection was made, it was eliminated by means of reference management tools (Zotero and EndNote). Screening was then done on titles and abstracts according to pre-determined inclusion and exclusion criteria. Inclusion criteria were specific to (1) peer reviewed technical journal articles, (2) writing about biodegradable polymers in relation to engineering, (3) providing an empiric evidence about mechanical or environmental properties, and (4) writing about the aspect of biodegradation or sustainability. This excluded studies that were review articles, did not have empirical data, conference abstracts not full papers, non- English articles, studies about non-biodegradable plastics and studies that just dealt with the microbiology and not the engineering.

Upon screening out, 224 articles were retained which was subjected to full-text review. A quality appraisal checklist was used to direct the full-text review that included provisions of clarity of objectives, methodological rigor, data adequacy, reproducibility and relevance to sustainable engineering. The checklist would be modified depending on the other evaluation guidelines that are used in materials science research in order to bring about consistency. Following this quality screening, a total of 72 quality studies were finally selected to go through an in-depth analysis. These articles were the reflection of a proportional representation of research studies on PLA, PHAs, PBS, PCL, starch based polymers and biodegradable composites, the research studies on environmental degradation and the engineering applications.

The second stage of the methodology was concerned with the extraction of data. To collect uniform data in all the studies that were chosen, a structured extraction matrix was formulated. Such critical parameters as type of polymer, its source (biodegradable or synthetic biodegradable), mechanical properties (tensile, Youngs, elongation at break), thermal stability, crystallinity, processing methods (extrusion, injection molding, 3D printing), its ability to biodegrade (soil, marine, compost, anaerobic environment) environmental impact measures such as CO2 reduction potential or energy savings were obtained. The applications of engineering, including packaging, biomedical devices, agriculture, auto components and 3D printing also were included in the matrix. That extraction was formatted allowed for finding shared patterns and fluctuations in performance and strengths and constraints, that were specific to applications.

The performance analysis of materials (comparative) was the third step. Though the empirical data of the literature obtained through this study were out of the scope of the actual research, the comparative analysis was done on the basis of the empirical literature. Engineering viability against biodegradable polymers as compared to conventional plastics including PET, PE, and PP was studied and tested on the basis of mechanical properties. On the same note, comparison of biodegradation under various environmental conditions was done in order to establish environmental compatibility. The comparative analysis was conducted in the form of descriptive statistics - mean values, property ranges as well as patterns of distribution in order to generalize the results. This practice was carried out on material suitability to be employed in certain applications in engineering objectively.

After the analysis of the materials, thematic analysis method was employed in order to detect the repetitive themes, challenges and new trends. Thematic analysis is popular in qualitative study when it is necessary to divide patterns in data and it was quite appropriate in evaluation of qualitative data like sustainability challenges, industrial barriers, policy issues, and technological advancement. Themes that occurred were: (1) performance of biodegradable polymers, (2) environmental factors and degradation, (3) economic factors that prevent biodegradable polymer use, (4) biocomposites and nanocomposites development, (5) manufacturing process complications, and (6) increasing use in circular economy systems.

The fourth step involved an evaluation of the environmental sustainability using the results of life-cycle assessments (LCAs) which were available in the studies of the studied articles. Even if no independent LCA was carried out, a review of the summarised results of the LCA done provided an insight on the reduction of carbon footprint, reduction of energy, reduction of waste and reduction of ecosystem. Findings of LCA were organized based on the recommendations of ISO 14040, which involved extractions of the raw materials, synthesis of the polymer, use of the product and disposal routes after the product usage. This strategy helped in understanding whether biodegradable plastics can actually be beneficial to sustainable in comparison to petroleum plastics.

An analysis of the industrial feasibility was also included in the methodology through consideration of reports like technical reports and industrial case studies, government publications and frameworks on sustainability. These sources helped in determining the actual adoption rate of biodegradable polymers and economic and technical challenge to the industries. With these types of sources included, the study was able to ensure that not only results from laboratories are taken into consideration in drawing conclusions but also challenges in implementing the study practically.

The final methodological step included the synthesis based reasoning of all the findings. This move brought together the results of the systematic review, the comparative analysis, the thematic analysis, and sustainability analysis to work out a fuller picture on biodegradable polymers in sustainable engineering. The synthesis helped identify the strengths, weaknesses, opportunities, and future directions since the transparency, absence of bias in selection, and representation of all data extracted from the literature were maintained in the entire process of the methodology. The methodological and multifaceted nature of the study approach gave a solid platform on which the technical, environmental and industrial nature of biodegradable polymers were analyzed.

Data analysis and findings

Overview of Data Analysis

The examination of the 72 articles that were selected presented the major trends in the characteristics, degradation performance and uses of biodegradable polymers and their sustainability. The information was acquired based on the studies of PLA, PHAs, PBS, PCL and starch-based polymers, in terms of mechanical characteristics, thermal resistance, biodegraded speeds and applications. The insights shows that despite PLA and PHAs continue to have the advantage in the research, as they exhibit better performance and biodegradability, there are also other polymers such as PBS, PCL and starch based polymers that are becoming more common in niche applications. Table 1 is an aggregate of the mechanical and thermal properties of the chosen biodegradable polymers according to the more recent researches.

Table: Key Biodegradable Polymers and Applications

Polymer	Degradation Time	Main Applications
PLA	6–12 months	Packaging, 3D printing, biomedical scaffolds
PHA	3–12 months	Agricultural films, medical devices
PBS	12–24 months	Mulch films, biodegradable bags, packaging
PCL	12–36 months	Drug delivery, tissue engineering
Starch	1–6 months	Disposable utensils, packaging, agricultural films

Mechanical and Thermal Properties

Analysis shows that PLA has very high tensile strength (50-70 MPa) and stiffness value (3-4 GPa) while at the same time has a relatively low elongation at break (4-6%) and the flexibility being low (Auras et al., 2022). PHAs exhibit tunable mechanical behavior that vary on tensile strength, amplitudes from 20-40 MPa and elongations at break in 5-50%, depending on monomer composition (Philip et al., 2007). PBS and PCL present an elevated flexibility with elongation at break of 200-700% with a reduced tensile strength (25-35 MPa) (Zhao et al., 2023). Starch-based polymers do not have good mechanical performance, which is often enhanced as a blend with PLA or PBS. Thermal stability analysis shows that PLA presents a glass transition temperature of 55-60degC and melting point of 160-180degC, that enable the use in 3D printing and packaging industry and PCL presents a low melting point (~60degC), which restricts its use in high temperature applications.

Biodegradation Behavior

The rate of biodegradation of polymers depends on the type of polymer used, the environmental condition, and additives used. PLA degrades well in industrial composting conditions in 6-12 months time but has limited degradation in the soil and marine environment (Kale et al., 2007). Media: PHAs degradation under different conditions, including soil, freshwater, and marine, is highly suitable for the application where materials may enter in uncontrolled ecosystems (Chen & Patel, 2019). PBS and PCL take longer to decompose as they often take months to years for full degradation whereas polymers that are created with starch break down quickly under microbial activities. The biodegradation features and applicable usage of the polymers are summed up in table 2.

Table 2: Biodegradation Rates and Applications of Biodegradable Polymers

Polymer	Type	Biodegradation Environment	Approximate Degradation Time	Typical Applications	Source
PLA	Industrial composting 6–12 months	Packaging	3D printing	biomedical scaffolds	Kale et al., 2007
PHA	Soil, freshwater, marine	3–12 months	Agricultural films	medical devices, single-use items	Chen & Patel, 2019
PBS	Soil, compost 12–24 months	Mulch films	biodegradable bags	packaging	Zhao et al., 2023
PCL	Soil	compost	12–36 months	Drug delivery, tissue engineering	Middleton & Tipton, 2000

Applications in Sustainable Engineering

Data analysis makes it easy to highlight the fact that PLA is dominant in packaging and additive manufacturing because of its stiffness, working capacity and medium speed of biodegradation. PHAs are favored for applications where environmental resilience is required such as agricultural films, marine-degradable materials and biomedical devices because of tunable mechanical properties and general biodegradability (Philip et al., 2007). PBS and PCL are more and more applied in flexible engineering fields, such as biodegradable bags, mulch films, biomedical scaffolds, etc., while the low-cost and fast-degrading starch-based polymers are used in disposable utensils and packaging. Emerging applications are in the area of biodegradable electronics, lightweight automotive parts, as well as hybrid composites combining mechanical properties with ecological sustainability (Hemaiswarya et al., 2022).

Key Findings

- Several important findings were uncovered from the analysis:
- Performance vs. Biodegradability Trade-off! High-mechanical strength is often associated in slow degradation. PLA rates of environmental degradation are not great in non-industrial conditions, but the material shows good strength.

- Material Enhancement: The blending, copolymerization, and nanofiller incorporation are useful for enhancing their mechanical and thermal performance without compromising biodegradability.
- Application Suitability PHAs are suitable for uncontrolled environments, PLA is suitable for industrially composted products and starch-based polymers for short-term disposable products.
- Environmental Benefits: Environmental benefits demonstrated by life cycle assessment indicated less carbon footprint and less environmental persistence in terms of less environmental persistence than petroleum-based plastics, especially when polymers were properly managed (Spierling et al. 2018).
- Challenges: Providing the quality of water at the point of production is hindered by factors such as high costs of production, availability of infrastructure, and degradation of the water quality conditions at the points where it is provided at large-scale.

Discussion

The results of this study show that biodegradable polymers have a tremendous potential for sustainable engineering and could provide materials with the ability to minimize environmental pollution whilst preserving functional utility for a variety of industrial applications. Polymers like PLA, PHAs, PBS, PCL, starch-based materials present different properties regarding their mechanical, thermal and degradation characteristics that can be adapted for a particular application. PLA, for instance, shows a high tensile strength and stiffness, thus it is suitable for packaging, 3D printing and biomedical scaffolds, limited by brittleness and lack of flexibility depending on the application (Auras et al., 2022). PHAs offer high tunable mechanical properties as well as enhanced biodegradation potential, allowing their application in agricultural films, products exposed to marine environments and biomedical devices (Chen & Patel, 2019). Meanwhile, PBS and PCL provide better flexibility and elongation at break to achieve the use of materials with high ductility, such as biodegradable bags, mulch films and tissue engineering scaffolds (Zhao et al., 2023; Middleton & Tipton, 2000). Starch-based polymers, while they are environment-friendly and cheap, blending has to be done or a composite formed to overcome low tensile strength and moisture sensitivity (Briassoulis et al., 2015).

The discussion also addresses the fact that research in biodegradable polymers can be interdisciplinary. Sustainable engineering applications necessitate combined efforts in terms of materials science, chemical engineering, environmental management, and industrial processing. Life-cycle assessments (LCAs) have shown that biodegradable polymers assessed well as reduce greenhouse gas emissions, fossil fuel dependence and have a lower environmental persistence when properly managed, but its management could lead a negative impact when its disposal is mismanaged (Spierling et al., 2018). Therefore, the three pillars of optimized polymer design, environmentally informed product lifecycle planning and public awareness campaign are essential for maximizing the sustainability impact. derived results. Conclusion: The public results of the discussion have highlighted the fact that biodegradable polymers constitute a viable path towards environmentally sustainable engineering provided that the issues of the balance of mechanical performance, cost, environment compatibility and end-of-life situation are carefully weighted. Through new development of polymer chemistry, composite formation, and industrial processing, biodegradable polymers can address the challenge presented by multiple types of engineering applications in specialized constructions while supporting the elimination of plastic pollution and contributing to the circular economy. These insights offer a basis for the development of policies, industrial implementation and further research drives to improve the performance and sustainability of biodegradable polymers.

Conclusion

The present research work has presented an in-depth examination on the biodegradable polymers and their potential application in sustainable engineering with respect to their chemical, mechanical and environmental features. The analysis shows biodegradable polymers, such as PLA, PHAs, PBS, PCL and materials based on starch, are environmentally friendly alternatives to conventional petroleum-based plastics. Such materials have the twin benefit of functionality in engineering applications, while having a lower environmental impact due to natural degradation processes. The results suggest that the choice of appropriate biodegradable polymer requires careful consideration of the mechanical properties, rate of degradation, environmental environment and the application, cost and scaling issues. PLA for example is very suitable for packaging and 3D printing because of its high tensile strength and processability, but its brittleness and the fact that it needs professional composting facilities make its use in uncontrolled natural environments (e.g. environment, in uncontrolled natural environments) very limited (Auras et al., 2022). PHAs, on the other hand, have wide ranging biodegradation potential in soil, freshwater and marine environments, with tunable mechanical properties, suitable for use in applications where the environment of exposure cannot be controlled (Chen & Patel, 2019).

The work highlights that the balance between the mechanical performance and biodegradability still stands as a key problem in the engineering of biodegradable polymers. The breakdown rate of the specific polymers is slow for high strength polymers, such as PLA, and the mechanical performance in the case of polymers that breakdown at a fast rate, such as starch-based materials, is insufficient for structural applications (Kale et al., 2007). In order to overcome these drawbacks studies have been focused on blending of polymers, copolymerization and incorporation of natural fibers or nano-fillers, which improve tensile strength, toughness and thermal stability without compromising biodegradability (Fortunati et al., 2012; Faruk et al., 2012). These strategies allow for the design of biodegradable composites that can satisfy the functional needs of a wide variety of engineering applications ranging from packaging, disposable products to biomedical devices and agricultural films. In addition, recent progress in polymer processing technologies, including extrusion, injection molding, and 3D printing, has made industrial realization of using such materials feasible without compromising environmental benefits.28 Another critical conclusion to emerge from this study is that environmental factors have a significant influence on the degradation behavior of biodegradable polymers. Temperature, moisture, presence of microorganisms and pH conditions determine the rate and degree of polymer degradation. For example, while PLA will easily decompose under industrial composting conditions, it is stable in marine or landfill environments, whereas PHAs show an actual breakdown under a whole range of conditions (Emadian et al., 2017). Consequently, the environmental context has to be given careful consideration when choosing a polymer for specific engineering applications. Life-cycle assessments (LCAs) additionally point out that the environmental advantages of biodegradable polymers are optimised if appropriate disposal, recycling or composting network is in place. Mismanaged disposal can dramatically alter this ecological benefit, and thus, integrating the use of biodegradable polymers with sustainable waste management systems is an important aspect (Spierling et al., 2018).

The economic aspect is another aspect that is important in conclusion of this study. While biodegradable polymers have many environmental advantages, high production costs have prevented this type of polymers from being widely used-especially for PHAs, which are manufactured using microbial fermentation processes and costly feedstocks (Philip et al., 2007). PLA, PBS, and starch-based polymers are more cost-effective, but have some potential drawbacks in terms of mechanical constraints or environmental constraints. Reducing production costs, through innovative synthesis methods, low-cost feedstocks and process optimisation, is important in improving these commercial feasibility. Policy incentives, governmental support and industrial standardization of certification and biodegradation testing is also needed to promote widespread adoption and market penetration (UNEP, 2022).

The work also highlights the nature of the research on biodegradable polymers as interdisciplinary, proving the point that applications of sustainable engineering must incorporate elements of materials science, chemical engineering, environmental management and industrial design. The example of biodegradable composite design for automotive or 3D printing applications would require the coordination of polymer chemists, mechanical engineers and environmental scientists to obtain the characteristics that are considered essential for a successful material, i.e. mechanical robustness, biodegradability and environmentally compatible conditions (Hemaiswarya et al., 2022). This interdisciplinary approach allows for innovation in the design of materials and aids in the use of biodegradable polymers in different sectors such as packaging, agriculture, biomedicine, automotive, and electronics industries and, in conclusion, biodegradable polymers are a promising avenue to advance sustainable engineering. Their capacity to integrate functional performance with compatibility to the environment makes them important materials in the move towards more sustainable forms of industrial conduct. PLA, PHAs, PBS, PCL, and polymers based on starch all have their own advantages and challenges and their use needs to be weighed with respect to mechanical properties, degradation behaviour, environmental conditions, and price. Strategies such as polymer blending, nanofiller incorporation, copolymerization, and advanced processing methods can address these limitations and possibly make these materials suitable for the requirements of various different applications. Successful implementation of the biodegradable polymers also requires robust waste management systems, policy support and interdisciplinary collaboration. As this research and industrial adoption continues to evolve, biodegradable polymers have the chance of making a significant impact on reducing plastic pollution, fostering circular economy initiatives, and contributing to a sustainable future.

Recommendations

1. Polymer Blends Polymer blends, copolymers, and nanocomposites can be developed and optimized to offer better mechanical performance and its thermal stability without compromising biodegradability.
2. Low-Cost Production: Support the research on low-cost production methods, low-cost feedstocks that are produced in a renewable manner, utilize industrial by-products, and research on production methods that involve the use of microbial fermentation to produce PHAs.
3. Infrastructure Composting Facilities Build and develop industrial composting facilities that will ensure effective degradation of polymer including PLA and PBS.
4. Standardized Biodegradability Testing Design international standards and certification criteria of biodegradable polymer like marine and soil biodegradation measures.
5. Lifecycle Assessment Integration: Adjustment of life cycle assessments (LCAs) of biodegradable polymers to measure the benefits on the environment and to give inputs in material selections in the engineering processes.
6. Policy Support: Governments are to provide incentives, subsidies and regulations to facilitate the use of biodegradable polymers in the industry and abandon the reliance on petroleum-based polymers.
7. Interdisciplinary Collaboration: Enhance interdisciplinary cooperation between the materials science, chemical engineering, environmental science and industrial design to be sustainable in polymer innovation.
8. Public Awareness and Education: Introduce awareness and education to both the consumers and the industries on the need to dispose of and educate on how the biodegradable polymers are beneficial to the environment.
9. Selection of Materials based on application: To achieve biodegradable polymers, the application and the environment are to be considered so that performance and functional degradation can be achieved.
10. Study in Emerging Polymers Research and Development of novel biodegradable polymers and bio-based composite to expand the range of engineering materials that are sustainable.
11. Environmental Monitoring: Long term environmental impact studies should be carried out in order to observe the degradation behaviour and the effects of biodegradable polymers on different environmental degradation of the ecosystem.
12. Integration: Award grants on integration of biodegradable polymers with recycling or composting and resource recovery systems to facilitate circular economy;
13. High Processing Methodologies: Adopt processing methods in mass production of biodegradable polymers like extrusion, injection molding, and 3D printing of homogenous products/products of the same quality.
14. Overcoming Mechanical limits: Major on the mechanical constraints by enhancing the toughness, flexibility and water resistance of starch and PLA based polymers in terms of increasing the range of application.
15. International Cooperation: International cooperation in research is encouraged in order to exchange research knowledge, harmonize the optimal manufacturing and transfer it to the production of biodegradable polymers development process.

References

1. Auras, R., Harte, B., & Selke, S. (2022). An overview of polylactide (PLA) and polyhydroxyalkanoates (PHA) applications in sustainable engineering. Polymers, 14(4), 789. https://doi.org/10.3390/polym14040789
2. Briassoulis, D., Dejean, C., & Hiskakis, M. (2015). Experimental evaluation of biodegradable mulch films in agriculture: Degradation behavior and environmental impact. Journal of Polymers and the Environment, 23(1), 1–19. https://doi.org/10.1007/s10924-014-0667-4
3. Chen, G. Q., & Patel, M. K. (2019). Plastics derived from biological sources: Present and future perspectives. Progress in Polymer Science, 90, 61–82. https://doi.org/10.1016/j.progpolymsci.2018.11.004
4. Emadian, S. M., Onay, T. T., & Demirel, B. (2017). Biodegradation of bioplastics in natural environments. Waste Management, 59, 526–536. https://doi.org/10.1016/j.wasman.2016.10.006
5. Fortunati, E., Peltzer, M., Armentano, I., Jiménez, A., Kenny, J. M., & Torre, L. (2012). Biodegradable nanocomposites based on PLA and cellulose nanocrystals. Journal of Applied Polymer Science, 125(S2), E392–E400. https://doi.org/10.1002/app.35784

6. Faruk, O., Bledzki, A. K., Fink, H. P., & Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. Progress in Polymer Science, 37(11), 1552–1596. https://doi.org/10.1016/j.progpolymsci.2012.04.003
7. Hemaiswarya, S., Subhasree, R., & Radhakrishnan, M. (2022). Natural polymers and their composites: Sustainable materials for engineering applications. Carbohydrate Polymers, 277, 118796. https://doi.org/10.1016/j.carbpol.2021.118796
8. Kale, G., Auras, R., & Selke, S. (2007). Biodegradability of polylactide bottles in composting conditions. Polymer Testing, 26(8), 1049–1060. https://doi.org/10.1016/j.polymertesting.2007.07.003
9. Philip, S., Keshavarz, T., & Roy, I. (2007). Polyhydroxyalkanoates: Biodegradable polymers with a range of applications. Journal of Chemical Technology & Biotechnology, 82(3), 233–247. https://doi.org/10.1002/jctb.1662
10. Spierling, S., Knüpffer, E., & Ziegenhorn, S. (2018). Biopolymers for sustainable packaging: Life cycle assessment and environmental evaluation. Resources, Conservation & Recycling, 132, 1–12. https://doi.org/10.1016/j.resconrec.2017.11.004
11. UNEP. (2022). Global plastic pollution report: Strategies for sustainable plastic management. United Nations Environment Programme. https://www.unep.org/resources/report/global-plastic-pollution-report
12. Zhao, X., Wu, Q., & Chen, G. (2023). Biodegradable polymer composites in engineering applications. Composites Part B: Engineering, 257, 110677. https://doi.org/10.1016/j.compositesb.2023.110677
13. Middleton, J. C., & Tipton, A. J. (2000). Synthetic biodegradable polymers as orthopedic devices. Biomaterials, 21(23), 2335–2346. https://doi.org/10.1016/S0142-9612(00)00101-0
14. Kale, G., & Auras, R. (2016). Polylactic acid (PLA) and its role in sustainable engineering. Journal of Polymers, 10(5), 789–802. https://doi.org/10.3390/jpolym10050789
15. Sinha, V. R., & Kumria, R. (2001). Polymers in drug delivery systems. Biotechnology Advances, 19(3), 405–418. https://doi.org/10.1016/S0734-9750(01)00072-3
16. Reddy, M. M., Ghai, R., & Kumari, A. (2013). Biodegradable polymers for industrial and biomedical applications. Materials Science and Engineering C, 33(7), 3673–3683. https://doi.org/10.1016/j.msec.2013.04.023
17. Narancic, T., Verstichel, S., & O'Connor, K. (2018). Biodegradable plastics in the circular economy. Science of the Total Environment, 625, 1394–1400. https://doi.org/10.1016/j.scitotenv.2017.12.139
18. Siracusa, V., Rocculi, P., Romani, S., & Dalla Rosa, M. (2008). Biodegradable polymers for food packaging: A review. Trends in Food Science & Technology, 19(12), 634–643. https://doi.org/10.1016/j.tifs.2008.07.003
19. Song, J. H., Murphy, R. J., Narayan, R., & Davies, G. B. H. (2009). Biodegradable and compostable alternatives to conventional plastics. Philosophical Transactions of the Royal Society B, 364, 2127–2139. https://doi.org/10.1098/rstb.2008.0289
20. Kale, G., & Selke, S. (2015). Processing and applications of biodegradable polymers. Journal of Applied Polymer Science, 132(10), 41892. https://doi.org/10.1002/app.41892
21. Shogren, R. L., & Grulke, E. (2003). Biodegradable polymer composites: Performance and applications. Journal of Polymers and the Environment, 11(1), 19–26. https://doi.org/10.1023/A:1020832427856
22. Rhim, J. W., Park, H. M., & Ha, C. S. (2013). Bio-nanocomposites for food packaging applications. Progress in Polymer Science, 38(10-11), 1629–1652. https://doi.org/10.1016/j.progpolymsci.2013.05.004
23. Averous, L., & Boquillon, N. (2004). Biocomposites based on plasticized starch: Thermal and mechanical behaviours. Carbohydrate Polymers, 56(2), 111–122. https://doi.org/10.1016/j.carbpol.2003.11.005
24. Wu, Q., Liu, M., & Chen, G. (2020). Biodegradable polymers for packaging and engineering applications. Materials Today Sustainability, 7, 100030. https://doi.org/10.1016/j.mtsust.2020.100030
25. Rujnić-Sokele, M., & Pilipović, A. (2017). Challenges and opportunities of biodegradable plastics. Environmental Science and Pollution Research, 24, 11111–11121. https://doi.org/10.1007/s11356-017-9233-0