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A CRITICAL REVIEW OF SUSTAINABLE APPROACHES FOR REDUCING THE ENVIRONMENTAL IMPACT OF PLASTIC PRODUCTION

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Abstract

The production of plastics in the context of global warming contributes to water pollution by microplastic particles. Consequently, a shift towards sustainable practices in the field of plastic production is crucial. This paper aims to address the main concerns related to plastic and microplastic pollution and to identify environmentally sustainable strategies applied in the production sector. A particular focus is placed on biodegradable, eco-friendly materials as alternatives to conventional plastics, with an emphasis on their environmental impact. For example, food waste has emerged as a promising alternative for plastic packaging production, offering a sustainable solution, valorization of by-products, and mitigating environmental impacts. The paper also focuses on the potential of using waste to create biodegradable materials, highlighting the importance of a zero-waste approach to enhance the economic value of by-products, while promoting a cleaner environment and waste management presented in environmental contexts. Through its comparative analysis, this study contributes to a deeper understanding of waste management and supports the advancement of a sustainable circular economy.

Key words: *biodegradable, by-products, microplastics, pollution, sustainable.*

INTRODUCTION

Conventional plastics made from petroleum have a significant impact on the environment, contributing to water pollution, global warming, resource depletion, and the spread of microplastics. This makes the search for durable and sustainable alternatives increasingly critical (Mutmainna et al., 2025; Saleem et al., 2023). Alarmingly, plastic pollution is now ubiquitous - plastic particles have been discovered in the deep sea, rainwater, and even in the human placenta and bloodstream (Stoett et al., 2024). Although the stability of conventional plastics is often cited as an advantage (Xuyang et al., 2025), it also becomes a major drawback due to their persistence and accumulation in the environment.

Globally, the average plastic consumption per person is 20.9 kg per year (Khan et al., 2025), with production projected to rise from 464 Mt in 2020 to 884 Mt by 2050 (Dokl et al., 2024). Equally concerning is that approximately 79% of plastic waste ends up either in landfills or the natural environment, while only 9% is recycled and 12% is incinerated (Kumar M. et al., 2024; Wojnowska-Baryła et al., 2022). Plastics derived from fossil fuels (crude oil, gas, and coal) are a substantial environmental threat, not only due to their long lifespan but also because they emit greenhouse gases, contributing to global temperature rise (Nicholson et al., 2021; Sharma et al., 2023).

Microplastics (MPs), defined as plastic particles smaller than 5 mm, are formed through the gradual degradation of larger plastic items, typically triggered by ultraviolet (UV) radiation (Lee et al., 2025; Niu et al., 2024; Xuyang et al., 2025). Microplastics are a complex pollutant, ubiquitous in freshwater, with negative effects that can affect the function and health of the entire ecosystem (Garfansa et al., 2025). MP can enter rivers through sources such as atmospheric deposition, surface runoff, in-stream activities, and wastewater discharge (Graham et al., 2024). Also, river receive MP from direct dumping of garbage, the confluence of small streams into the main river, effluents from the cosmetic and textile industries and fishing activities, rivers contribute about 80% of ocean pollution. Rivers also discharge 1.6- 2.3 MMT of MP into the ocean annually (Choudhary et al., 2025). Filtration methods using materials such as sand or activated carbon materials are applied in municipal wastewater treatment to remove MPs. MPs removal efficiency varies depending on particle size, adhesion to the surface of the filter medium, and filtration technique (Garfansa et al., 2025). However, these techniques are largely ineffective at removing MPs, allowing them to continue threatening aquatic environments (Lee et al., 2025; Niu et al., 2024).

In recent years, global attention has increasingly focused on the circular plastic economy and sustainable development. A truly sustainable approach seeks to meet the needs of the present without compromising the resources of future generations - one of the core objectives of of waste management and supports progress toward a sustainable circular economy.

IMPACT OF PLASTIC POLLUTION: ENVIRONMENTAL SIGNIFICANCE AND HUMAN HEALTH

Plastics pose a serious threat to ecosystems, biodiversity, and human health, while also contributing to climate change (Schmidt et al., 2024). Popa et al. (2015) observed that the anthropogenic footprint on the water quality of the Danube, was highlighted in the summer, under the action of the human, trophic factor and the impact of anthropogenic activities. MPs are considered emerging pollutants of increasing concern due to their ubiquitous presence and toxic potential in the aquatic ecosystem (Călmuc et al., 2022).

Water resource management is a major issue, being a very important transporter of pollutants (Pintilie et al., 2016), rivers contributing to approximately 80% of plastic pollution in the oceans, and 20% coming from marine activities sustainable development (Xuyang et al., 2025). Poor plastic waste management exacerbates environmental degradation and health hazards while also contributing to climate change (Roy & Chakraborty, 2024). The growing interest in bio-based alternatives, particularly in the food industry, reflects a shift toward sustainable, efficient, and safer packaging systems compared to those made from petroleum-derived polymers (Dorofte et al., 2023). Biodegradable plastics are now applied across various sectors, and even oil-producing nations are supporting initiatives that promote circularity within the plastic economy (Fei et al., 2024; Saxena, 2025).

The aim of this study is to provide a critical perspective on replacing petroleum-based plastics with sustainable alternatives, while promoting the circular economy and principles of sustainable development. This review offers a comprehensive synthesis of the current literature on the environmental impacts of plastics, as well as strategies for leveraging natural resources and waste to produce biodegradable materials. Emphasis is placed on the zero-waste approach, which adds economic value to by-products and fosters improved waste management. Through a comparative and critical lens, the study enhances understanding

(Kumar M. et al., 2024). MPs enter the aquatic environment through wastewater discharges, industrial operations, excessive vehicle use, and human activities (Xuyang et al., 2025). Population and distance from residential areas influence the effects of anthropogenic activity on MPs abundance, urban lakes being more affected by MPs contamination than rural lakes (Anagha et al., 2023; Pierdomenico et al., 2024). China currently records the highest level of surface water microplastic pollution globally, with a concentration of 34 MP/L detected in Lake Poyang (Tran-Nguyen et al., 2024).

In Romania, areas near the confluence of the Siret and Prut rivers with the Danube show particularly high pollutant concentrations, largely due to agricultural and industrial activity and the absence of effective water treatment systems (Iticescu et al., 2014). In marine environments, plastics reduce light and oxygen levels, diminishing biodiversity and affecting marine life through ingestion, suffocation and reduced mobility (Roy & Chakraborty, 2024). Plastics facilitate the bioaccumulation of heavy metals in aquatic systems. Heavy metals, after being released from microplastics, enter the food chain, accumulating in fish and subsequently affecting human health through biomagnification processes (Bolea et al., 2025). The ecotoxicological effects of MP depend on concentration, types, degradation process, environmental longevity and specific organisms affected (Shi et al., 2024). The presence of MPs has been reported in human saliva, feces, and blood (Saleem et al., 2023). MPs contain harmful chemicals, such as phthalates, bisphenol A (BPA), which can disrupt hormone regulation, interfere with reproductive health and increase the risk of cancer, developmental disorders, and have adverse effects on the immune, nervous, and cardiovascular system (Roy & Chakraborty, 2024; Schmidt et al., 2024). MPs generate toxicity in living organisms by disrupting the defense mechanism against oxidative stress, genotoxicity, neurotoxicity, growth and metabolic diseases, but they can also be vectors of transport in aquatic ecosystems by adsorbing potentially toxic elements (mercury, cadmium, lead and aluminum, copper, nickel, zinc, chromium or arsenic) on their surface (Kumar et al., 2024; Simionov et al., 2023). Exposure and accumulation of heavy metals in the human body has been linked to cognitive impairment, endocrine disruption, developmental abnormalities, and cancer (Simfukwe et al., 2025). As a result, bioplastics have emerged as a promising alternative, offering the potential to mitigate both health risks and environmental degradation associated with conventional plastic use (Kumar et al., 2024).

Biodegradation in soil is considered the best option due to the microorganisms present in the environment. Biodegradation in aquatic environments is usually more complex and limited due to nutrient content, temperature, pH, microbial diversity and density, which reduce the biodegradation capacity of bioplastics (Negrete-Bolagay & Guerrero, 2024).

Biodegradation is a process that depends largely on environmental conditions, such as temperature, humidity, pH, and many other abiotic factors. Biodegradable plastics show mass losses of 23-100%, with higher degradation efficiencies than petroleum- based plastics. PLA biodegradation is complete within 1-3 months in marine environments in Hong Kong, but not all bioplastics degrade completely in these marine environments. Fragmentation of biodegradable plastics requires special attention as it can contribute to microplastic pollution, which is a challenge for in situ studies as the fragments may be too small to be recovered or further biodegraded (Cheung & Not, 2024). Microplastics generated by incomplete biodegradation of biodegradable plastics may persist in environments, affect aquatic microbial communities, plant adaptability, and animal physiology, with their toxicity increasing upon degradation, but knowledge of the effects of biodegradable microplastics, in the aquatic environment remains limited (Shi et al., 2024).

CONVENTIONAL PLASTIC

Conventional plastics, also referred to as petroleum-based, are the most widely used form of plastic. They exist in various physical forms - such as fragments, foams, films, fibers, filaments, pellets, spheres, and particles - and come in a wide range of colors, including red, green, blue, white, transparent, black, and yellow (Chen et al., 2024; de Deus et al., 2024). Depending on size, there are five distinct categories of plastics: nanoplastics (< 0.001 mm), microplastics (0.001-5 mm), mesoplastics (5-25 mm), macroplastics (> 25 mm) and megaplastics (> 1 m) (de Deus et al., 2024).

Microplastics (MPs) are further classified by origin: *primary MPs* are manufactured intentionally for industrial or domestic applications, while *secondary MPs* result from the degradation of larger plastic debris, often due to improper waste disposal or environmental breakdown (Acarer, 2023; Xuyang et al., 2025; Zhuo et al., 2024).

Packaging accounts for approximately 40% of global plastic production, with 60% of that used specifically for food and beverage applications (Ceballos-Santos et al., 2024). Conventional plastics such as polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET or PETE), low-density polyethylene (LDPE) or high-density polyethylene (HDPE) contain additives (stabilizers, plasticizers, foaming agents, colorants, etc.) which, although improving the properties of the material, are known to be endocrine disruptors and carcinogens (Rajvanshi et al., 2023). Additionally, many plastics contain environmentally harmful compounds such as flame retardants, phthalates, bisphenol A (BPA), and heavy metals (e.g., lead and cadmium), which can leach into the soil, contaminate ecosystems, and bioaccumulate in living organisms (Martínez-Narro et al., 2024).

Conventional plastics are advantageous for storage, use and transport, but not for disposal, as they degrade slowly, in approximately 500 years (Martínez-Narro et al., 2024). Currently, petroleum-based plastics are more cost-effective than those derived from renewable sources, but when external costs and future optimization are taken into account, the price of fossil-based polymers is expected to increase by 44% compared to bio-based polymers (Jiao et al., 2024).

In terms of environmental impact, conventional MPs degrade slowly and thus have a lower immediate impact on soil microorganisms; however, this same persistence increases their potential for long-term bioaccumulation and toxicity in soil fauna (Fei et al., 2024). Although petroleum-based plastics are known for their accessibility, durability, and adaptability, their widespread use continues to fuel the generation of persistent environmental pollutants and the ongoing accumulation of plastic waste (Jiao et al., 2024).

BIOPLASTIC, AN ALTERNATIVE TO CONVENTIONAL PLASTICS: SUSTAINABLE STRATEGIES

Recognizing the complexity and emerging concerns surrounding biodegradable microplastics, it is important to understand their impact on the environment (Shi et al., 2024). Bioplastics are polymers derived from natural or renewable sources that can be either *biodegradable* or *non-biodegradable* (Kumar et al., 2024). Importantly, bioplastics are not exclusively based on biological sources; they may also originate from fossil fuels. As such, there are four main categories (Jiao et al., 2024; Vigneswari et al., 2024):

- Bio-based biodegradable;
- Bio-based non-biodegradable;
- Fossil-based biodegradable;
- Fossil-based non-biodegradable.

Not all bioplastics are entirely composed of natural materials or guaranteed to be biodegradable. Therefore, understanding their classification is essential when evaluating their environmental benefits. An overview of the major classes of bioplastics is presented in Figure 1, which summarizes their source materials and degradation characteristics.

The four major bioplastic categories include:

- Bio-based biodegradable bioplastics such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB), and starch blends.
- Fossil-based biodegradable bioplastics such as poly(butylene adipate-co-terephthalate) (PBAT), polycaprolactone (PCL), poly(butylene succinate) (PBS), poly(butylene succinate-co-adipate) (PBSA), and polyvinyl alcohol (PVA).
- Bio-based non-biodegradable bioplastics including bio-based polyethylene (PE), polyethylene furanoate (PEF), polytrimethylene terephthalate (PTT), and polyethylene terephthalate (PET).

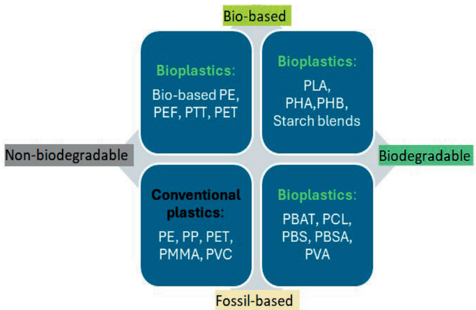

Figure 1. Classification of plastics based on their origin and degradability. Adapted from Shi et al. (2024) and Vigneswari et al. (2024)

In line with current trends, the development of eco-friendly plastics increasingly focuses on low-cost and renewable raw materials as a sustainable alternative to conventional petroleum-based plastics. These bio-based materials show great potential for application across multiple sectors, including packaging, agriculture, and biomedical industries (Rajvanshi et al., 2023).

Table 1 summarizes various biodegradable alternatives to conventional plastics, outlining their applications, key advantages, and limitations.

The primary advantages of bio-based polymers stem from their renewable and low-cost sources. However, cost feasibility is a challenge for the commercial viability of bioplastics. For example, the use of PHA in various applications remains limited due to the high production costs and the high cost of substrates for PHA production (refined carbon origins, sugars, oils, organic acids and fatty acids). Current studies present methods to reduce the cost of PHA production such as the use of renewable substrates, the use of cheaper carbon sources from industries (biodiesel, agriculture, dairy and animal processing). Less expensive substrates for PHA synthesis must be accessible, available in sufficient quantities, stable and resistant to microbial spoilage, and easy to store (Hadri et al., 2025).

Bioplastics derived from biological materials—such as starch, cellulose, vegetable oils, fats, and microorganisms—are generally non-toxic, easier to recycle, and faster to degrade than conventional plastics. They contribute to energy savings, reduce waste volume and landfill space requirements, and help lower greenhouse gas emissions, making them promising solutions due to their abundance and biodegradability (Khan et al., 2025; Mutmainna et al., 2025; Vigneswari et al., 2024).

Table 1. Alternative bio-based for conventional plastics

Biodegradable materials	Advantages	Disadvantages	Applications	References
PLA	Biocompatibility, resistance to fragmentation and good processability, good mechanical properties, simple and rapid degradation mechanism, gas barrier comparable to that of polystyrene and low-density polyethylene (LDPE).	Low degradability in water. Can increase oxidative stress of organisms, cause metabolic disorders, growth limitations; can adsorb heavy metals; higher gas barrier than PET. The cytotoxicity in human cell lines remains limited.	Packaging materials, tissue engineering, drug delivery, 3D printing, face masks.	(Burada et al., 2015; Fei et al., 2024; Hadri et al., 2025; Jiao et al., 2024; Kumar S. et al., 2024; Niu et al., 2024; Rajvanshi et al., 2023; Wen et al., 2025)
PBS	Crystallinity, mechanical performance equivalent to PP/PE, good processability, thermal stability, simple and rapid degradation mechanism.	Requires specific conditions for biodegradation. Weaker mechanical and physical properties. The cytotoxicity in human cell lines remains limited.	Packaging materials, compost bags, biomedical materials and hygiene products.	(Fei et al., 2024; Hadri et al., 2025; Kaur et al., 2025)
PCL	Elastomeric, relatively crystalline and suitable for modification, mechanical properties comparable to other basic plastics.	Requires specific conditions for biodegradation.	Mulch films, tissue engineering, dressings, drug delivery.	(Fei et al., 2024; Hadri et al., 2025; Kaur et al., 2025)
PBAT	High flexibility and toughness, biocompatibility, good processability.	Requires specific conditions for biodegradation. The cytotoxicity in human cell lines remains limited.	Mulch sheets, packaging materials and shopping bags.	(Fei et al., 2024; Mutmainna et al., 2025; Wen et al., 2025)
PHA	Eco-friendly, biocompatible, biodegradable, moisture and heat resistant, good gas barrier properties, rigid.	Requires specific conditions for biodegradation.	Packaging, bags, containers, drug delivery, pens and hygiene products.	(Mutmainna et al., 2025; Vigneswari et al., 2024)
PGA (Polyglycolic acid)	Crystalline, thermal stability, good degradability and biocompatibility.	The cytotoxicity of new degradable polymers in human cell lines remains limited.	Materials for drug delivery and packaging.	(Chia et al., 2020; Hadri et al., 2025; Mogany et al., 2024)

One of the disadvantages of biodegradable MPs is that they can accumulate cadmium, could support certain microbial communities or could inhibit microbial activity, could negatively affect plant adaptability and animal physiology, and their toxicity may increase with their degradation (Shi et al., 2024). In addition, biodegradable plastics require specific conditions for their mineralization (humidity, temperature, pH, oxygen, light and the presence of functional microorganisms) (Rajvanshi et al., 2023), and failure to meet the conditions turns bioplastics into a source of pollution (Shi et al., 2024), with prolonged periods being required for the biodegradation process (Fei et al., 2024). Biodegradable MPs have a higher adsorption capacity and exhibit greater mobility than conventional MPs, thus they promote the transport of contaminants, affecting ecosystems (Fei et al., 2024). Compared to conventional plastics, bioplastics have poorer mechanical and barrier properties, which limits their commercial use (Dorofte et al., 2025; Kumar et al., 2024).

Recent studies also challenge the notion that all bioplastics are inherently biodegradable. They emphasize limitations such as the need for equivalence in production volumes relative to conventional plastics and the requirement of specific conditions for effective degradation. Nevertheless, microbial degradation technologies offer promising, environmentally friendly avenues for managing bioplastic waste sustainably (Roy & Chakraborty, 2024).

WASTE MANAGEMENT AND FOOD PACKAGING INNOVATION FOR SUSTAINABILITY

Urbanization has led to a significant increase in food waste generation from various sources. In this context, biomaterials derived from food waste have emerged as promising alternatives for plastic production due to their biodegradability, biocompatibility, bio-stability, and biofunctionality. Adopting a zero-waste approach enhances both the sustainability and the economic value of these by-products, while contributing to a cleaner environment through more effective food waste management (Mutmainna et al., 2025).

One such example is vegetable starch, a biodegradable biopolymer presents in various food waste streams, which can be processed into functional, environmentally friendly bioplastics such as PLA (Hadri et al., 2025; Li & Chen, 2024; Mutmainna et al., 2025). Similarly, whey proteins, a by-product of the cheese manufacturing industry, are being utilized to develop biodegradable packaging materials. Their low cost, high biodegradability, flexibility, and neutral taste and aroma make them ideal for food applications (Dorofte et al., 2025).

Waste from the meat and poultry processing industry (bones, blood, eggshells, skin, tendons, etc.) is used to produce polymers such as collagen, chitin, PHA and gelatin, and waste generated from dairy processing, grain processing and fruit and vegetable processing industries are also widely used for PHA production (Rajvanshi et al., 2023). Also, food waste from agriculture, fruits, vegetables and plant by-products (banana peels, pineapple peels, avocado seeds and durian seeds) offer a sustainable solution to reduce plastic pollution (Mutmainna et al., 2025). Other industrial by-products such as glycerol, cellulosic materials, molasses and waste oil are also used as alternative raw materials for bioplastic production (Rajvanshi et al., 2023).

The research trajectory is moving towards new biodegradable and sustainable food packaging solutions as alternatives to conventional packaging, which can provide safe and quality food, so mixing essential oils with bioplastics, alternative to chemical preservatives, is a growing trend for creating antimicrobial films to conventional plastic used as packaging in the food industry (Dorofte et al., 2024; Kumar et al., 2024). Whey films functionalized with essential oils have high potential for use on various foods due to their antimicrobial and antioxidant activities (Lanciu Dorofte et al., 2023). Microbial polymers such as yeast and fungal biomass, exopolymers such as kefiran from kefir culture, bacterial cellulose, gellan and levan, are capable of forming films, being used as packaging materials (Bleoanca et al., 2025).

Despite their benefits, bioplastics derived from plant waste often exhibit inferior mechanical properties compared to conventional plastics. However, these limitations can be mitigated through innovative enhancements, such as the incorporation of materials like chitosan, polyvinyl alcohol (PVA), nanoparticles, or the application of ultrasound treatments, which significantly improve the structural and functional performance of bioplastics (Mutmainna et al., 2025).

CIRCULAR ECONOMY, SUSTAINABILITY AND PLASTIC POLLUTION MANAGEMENT STRATEGIES

Plastic waste management is one of the imperative components of the circular economy concept. This model seeks to transform the traditional linear plastic economy - characterized by a "take, make, dispose" approach - into a more sustainable system by eliminating unnecessary plastic use, fostering innovation, and promoting material recirculation. This transformation aims to reduce plastic leakage into the environment while enhancing long-term sustainability (Mehta et al., 2025).

The efficiency of the circular economy is supported by the integration of recyclable materials and the transition to a circular economy is a central pillar of European sustainable development to achieve successful European goals (Georgescu et al., 2025). Among its key objectives is tackling plastic pollution by promoting recycling and reducing waste generation (Buruiana et al., 2023).

The linear economy model is one in which products are manufactured, used and disposed of as waste, but the circular approach emphasizes the importance of closing the loop by recycling and reusing at every stage, to create a sustainable system that maximizes resource efficiency and minimizes environmental pollution (Saxena, 2025).

Currently, mechanical recycling is still the main plastic recycling process in Europe (Hsu et al., 2022). Although waste-to-energy processes (pyrolysis and gasification) convert plastic waste into fuels or chemicals, promoting a circular economy, the disadvantage is that they generate carbon, a solid residue often deposited (Khan et al., 2025). Compared to conventional plastics, bioplastics can be completely degraded under controlled conditions, reducing CO_2 emissions. Recycling helps conserve resources, reduce energy consumption and minimize the carbon footprint associated with plastic production (Fayshal, 2024).

However, several barriers hinder the widespread adoption of recycling and circular strategies. These include techno-economic challenges such as the high cost and reduced quality of recycled plastics, as well as legislative, social, and cultural obstacles (Xuyang et al., 2025). An emerging solution is the biodegradation of plastics using microorganisms isolated from landfills, which can break down plastics into carbon dioxide, water, and biomass in an environmentally friendly manner (Hsu et al., 2022; Roy & Chakraborty, 2024).

Although recycling recovers valuable petrochemicals, recycled plastics have disadvantages, such as significant emissions that could be produced during transportation, lower quality compared to new products, and energy consumption. By using bioplastics, reducing the use of unnecessary packaging, and adopting environmentally friendly materials, the negative environmental impact caused by plastics can be effectively mitigated (Jiao et al., 2024).

Circular approach measures such as using reusable products, transforming plastic waste into value-added products to improve socio-economic conditions, or adopting a "zero waste" lifestyle contribute to the transition towards adopting sustainable practices, which is a complex but necessary one (Bertolazzi et al., 2024; Kaplan Sarısaltık et al., 2025; Roy & Chakraborty, 2024).

CONCLUSIONS

Plastic and microplastic pollution in the aquatic environment are one of the most urgent global challenges, as it represents an undeniable threat to marine ecosystems and human health. This study presents an overview of the use of sustainable bioplastics over conventional plastics, with the aim of reducing the total consumption of fossil-based plastics and their waste, minimizing the devastating impact on the environment and mitigating the harmful effects of microplastic pollution.

Implementing sustainable strategies for the use and disposal of synthetic polymers is essential, as these materials are major contributors to environmental contamination through the continuous release of microplastics. While bio-based materials offer a promising solution - being more sustainable, durable, and aligned with the zero-waste approach - their widespread adoption still faces significant hurdles.

Addressing the challenges related to the properties of bioplastics, their costs and their biodegradability are essential for their widespread adoption.

This review highlights both the advantages and limitations of conventional plastics and bio-based alternatives. Future research and innovation in the field of bioplastic development, biodegradation technologies, and circular economy practices will be critical for improving bioplastics' market performance and environmental impact. These efforts will play a pivotal role in tackling the global plastic pollution crisis and in advancing the broader goals of sustainability and circular economy adoption. Based on this review work, the following ideas for future work are recommended: exploring the development of biodegradable plastic formulations with better degradation efficiency in various environments, streamlining the production costs of bio-based

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materials, and improving waste management systems.

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