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Review

Ecotoxicological Impact of Bioplastics Biodegradation: A Comprehensive Review

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Abstract: The emergence of bioplastics presents a promising solution to the environmental impact of the plastics industry. Biodegradable plastics are engineered to degrade in aquatic or soil environments. Biodegradable bioplastics can degrade in these conditions, according to sustainability standards, and have a low environmental impact. However, not all bioplastics are completely biodegradable, and some, like petrochemical-based plastics, may contribute to plastic pollution. In this comprehensive review, we identify the biodegradability of significant bioplastics, including polyhydroxyalkanoates (PHA), poly(lactic acid) (PLA), poly(butylene succinate) (PBS), and PBS-co-adipate (PBSA) in different environmental conditions given in the literature. Microbe-based bioplastics made from renewable materials like microalgae provide a sustainable alternative due to their high biodegradability compared to other bioplastics. However, we recognize concerns regarding the ecotoxicological impact of these alternatives on soil and aquatic organisms and recommend future research to observe the ecotoxicological behavior of biodegradation by-products.

Keywords: bioplastic; biodegradation; PLA; PBS; PBSA; microbes; composting; anaerobic digestion

1. Introduction

Using non-biodegradable petrochemical plastics has caused significant environmental problems, including air, soil, and water contamination. Nevertheless, a potential solution lies in utilizing bioplastics, which can degrade naturally and consist of organic substances or biodegradable polymers. Bioplastics, such as poly (hydroxylalkanoate) (PHA), poly (lactic acid) (PLA), poly (butylene succinate) (PBS), and PBS-co-adipate (PBSA), are currently being employed across many industries as a substitute for conventional plastics [1].

The degradation of plastics in marine environments can be categorized into two main processes: abiotic degradation and biotic degradation. The extended polymer chains undergo initial fragmentation into shorter molecules via abiotic mechanisms such as ultraviolet (UV) radiation, wave action, and salts, followed by subsequent biodegradation facilitated by microbial activity [2]. The biodegradation of plastics is predominantly influenced by the material's inherent characteristics and the unique abiotic and biotic factors present, which are seldom encountered in natural surroundings. Nevertheless, in natural circumstances, totally biodegradable substances can undergo mineralization, resulting in the production of carbon dioxide (CO_2), mineral salts, and microbial biomass in aerobic conditions, or carbon dioxide (CO_2), methane, mineral salts, and microbial biomass in anaerobic situations, contingent upon the presence of oxygen [3,4].

In general, the advancement and utilization of bioplastics represent a promising stride in mitigating the ecological repercussions associated with conventional plastics. It is imperative to conduct additional research and enhance comprehension of the degradation of bioplastics in various environmental settings to guarantee their secure and efficient utilization [5,6].

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In agriculture, bioplastics are disposed of in the soil after use, and soil microorganisms like *Bacillus* sp. and *Aspergillus* sp. have been identified as bioplastic degraders from the soil environment [7]. The biodegradation of bioplastics like PBS, PBSA, and PLA and the mechanism of bioplastic degradation have been studied, and the bioplastic-degrading enzymes are characterized. However, there is still much to learn about the relationship between the degradation of bioplastics and the bacterial biomass in the soil (Liu et al., 2022) [8]. More research on the ecotoxicity of bioplastic breakdown in soil is also required to comprehend its environmental effects fully [9].

The breakdown of plastics in the ocean can be broken down into two categories: abiotic and biotic. The lengthy polymer chains are initially broken down into shorter molecules through abiotic processes such as ultraviolet (UV) light, wave action, and salts, and then further biodegraded by bacteria [10]. Material qualities and certain abiotic and biotic conditions are required for the biodegradation of plastics, none of which are typically present in the natural environment. However, in the presence of oxygen, fully biodegradable materials can mineralize into carbon dioxide (CO_2), mineral salts, and microbial biomass (aerobic), or carbon dioxide (CO_2), methane, mineral salts, and microbial biomass (anaerobic) [3].

The introduction and widespread usage of bioplastics hold great promise for lessening plastics' adverse effects on the natural world. More study of bioplastic breakdown in various conditions is required to ensure their safe and effective use. Biodegradation of bioplastics occurs via a wide variety of methods. Some of these routes include hydrolysis, enzymatic degradation, and composting; each has its own set of optimal conditions for operation. The polymer chains of bioplastics like polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are typically degraded via hydrolysis, the process by which water molecules attack and dissolve them [11]. Composting in controlled settings with elevated temperature and microbial activity accelerates biodegradation, particularly in materials like PLA and starch-based bioplastics. Enzymatic degradation involves microbial enzymes targeting specific chemical bonds in bioplastics [12].

Several factors, including the kind of bioplastic, ambient circumstances, and the activity of microbial populations, influence the biodegradation of bioplastics. Polymer properties such as crystallinity, molecular weight, and chemical structure affect the biodegradability of certain bioplastics. Biodegradation rates are susceptible to environmental factors such as temperature, moisture, and pH [13]. For instance, polybutylene succinate (PBS) bioplastics biodegrade more quickly in soil conditions when exposed to higher temperatures [14]. In addition, studies show that biodegradation relies heavily on the existence and activity of specific microbial communities, with different communities demonstrating the differing ability to degrade distinct bioplastics [15].

Frameworks for biodegradation assessment are provided by standardized testing procedures such as ASTM D6400, ASTM D6868, and ISO 14855 [16]. However, difficulties arise when implementing these standards in actual, non-laboratory contexts. Layers of complexity are added to the biodegradation of bioplastics in environments including the oceans, soils with different microbial populations, and industrial settings [17]. Biodegradation has both difficulties and potential benefits in such complex environments and other industrial facilities. This comprehensive review examines the biodegradation of bioplastics in diverse environmental settings. In this article, we will thoroughly investigate these factors, illuminating the biodegradation of bioplastics under varying ecological situations. The need to assess their effects on the environment, ensure their long-term viability, and foster the growth of environmentally friendly materials and practices cannot be overstated.

Synthesis of Bioplastics

Understanding the synthesis of bioplastics is essential before getting into its biodegradability. Conventional plastics are made almost entirely from petroleum and other nonrenewable fossil fuels [18]. Our reliance on finite resources exacerbates carbon emissions and the plastic waste problem. Bioplastics, on the other hand, are made of renewable resources. Bioplastics are often derived from corn, sugarcane, and cassava crops. Bioplastics are made from fermented or chemically synthesized versions of these agricultural feedstocks [19].

The manufacture of bioplastics from renewable resources has the potential to reduce the adverse effects on the environment caused by conventional plastics. It aligns with eco-friendly ideals because it reduces fossil fuel use and CO_2 output. Growing these plants can help reduce atmospheric carbon dioxide levels; this carbon sequestration benefits both the environment and bioplastics. Without a proper appreciation of biodegradability, however, the ecological equation remains unsolved [19].

The utilization of bioplastics has emerged as a potentially viable approach to addressing the environmental challenges associated with conventional plastic materials. Biodegradable materials, predominantly sourced from diverse biological origins, including plants, bacteria, microalgae, and photosynthetic bacteria, constitute their composition. The primary components of bio-based biodegradable plastics consist of protein, polysaccharides, lipids, amino acids, and polyhydroxyalkanoates. These constituents accumulate within the microbial cell in response to different physico-chemical disturbances [20].

Various bacterial and algal strains, such as *Bacillus* sp., *Azotobacter* sp., *Alcaligenes* sp., *Pseudomonas* sp., *Methylotrophs*, and *Cupriavidus nectar*, have been intensively investigated for the production of bioplastics. *Spirulina platensis, Nostoc muscorum*, and *Synechococcus* sp. have also been studied in this context [20].

The biorefinery framework has been proposed as a sustainable strategy for microalgae growth. This technique entails the conversion of cellular biomass into various bio-based products that hold market value, including bioplastics, biogas, bioethanol, pigments, protein, carbohydrates, and biofuels. Microalgal biomass has the potential to serve as a viable and environmentally sustainable alternative to traditional plastic, thereby offering economic advantages [21].

Numerous studies have demonstrated the superiority of bio-based plastics over fossil-based polymers in terms of their ability to preserve fossil reservoirs and mitigate carbon emissions. Bioplastics derived from biomass feedstock and agricultural raw materials exhibit comparable physical and mechanical characteristics to conventional polymers. Moreover, their considerable susceptibility to microbial degradation justifies their utilization [22].

Nevertheless, the utilization of agricultural feedstocks, such as wheat, sugar, potatoes, corn, and rice, in the manufacturing process of bioplastics has the potential to affect global food production negatively. Hence, the demand for economically efficient bioplastic feedstocks, such as microbial biomass, arises as a viable approach for the sustainable and practical manufacturing of biodegradable or non-biodegradable bioplastics [23].

Numerous research has provided evidence about the prospective utilization of microalgae, specifically *Phaeodactylum tricornutum* and *Chlamydomonas reinhardtii*, in the production of fundamental constituents of biodegradable polymers, such as polyhydroxybutyrate (PHB). Using genetically modified microalgae to manufacture polyhydroxyalkanoates (PHA) raises concerns regarding the economic viability of scaling up the bioplastic manufacturing and commercialization process. Hence, it is imperative to investigate alternative methodologies to fully unlock microorganisms' inherent capabilities in synthesizing polyhydroxyalkanoates (PHA) [24]. Overall, the development of bioplastics from microbial biomass has the potential to revolutionize the plastic industry while addressing the environmental concerns associated with traditional plastic (Figure 1).

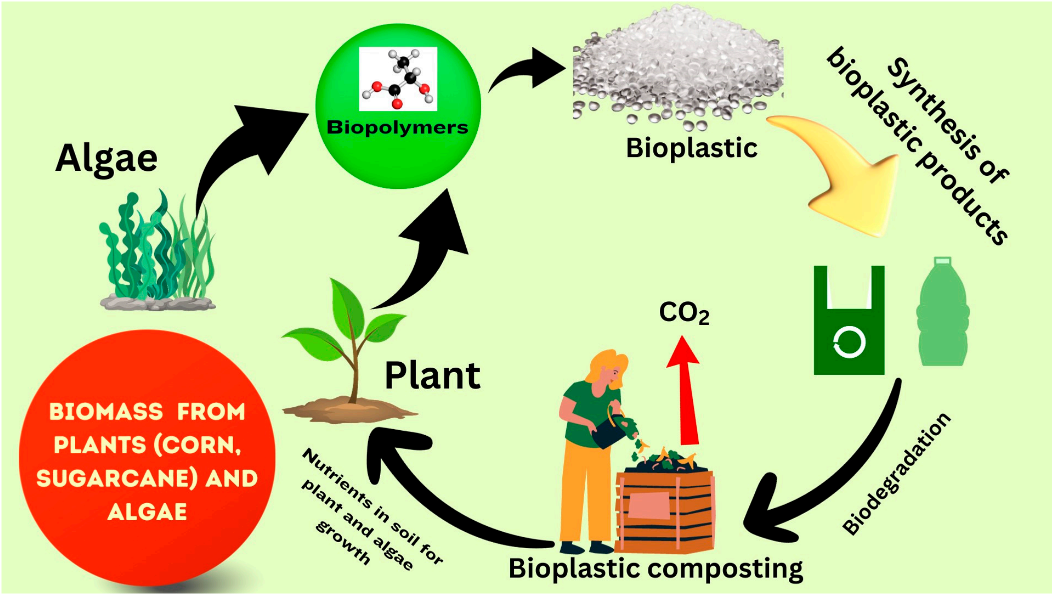

Figure 1. Bioproduction and biodegradation of bioplastic.

Biodegradability of Bioplastic in Complex Environmental Conditions

Biodegradable bioplastics are made to biodegrade environments with a specific range of conditions, including heat, humidity, and microorganisms. Composting facilities used by businesses are one type of such controlled environment. In the controlled conditions of industrial composting, biodegradable bioplastics can disintegrate while upholding sustainability goals and minimal environmental effects. These structures facilitate the quick degradation of bioplastics by providing an ideal environment for the biodegrading bacteria. Water, carbon dioxide, and biomass are just some of the environmentally beneficial consequences of the process [25].

However, it is essential to note that the degree to which these materials degrade depends on their environment. Outside of the controlled conditions of industrial composting, the biodegradation of these bioplastics may not be as effective. Natural ecosystems, such as those found in the soil or the water, may cause the process to proceed much more slowly. Non-biodegradable bioplastics, on the other hand, do not readily degrade in natural settings despite their plant-based origins. Polylactic acid (PLA) plastic, for instance, has become increasingly popular since it can be made from renewable sources like cornflour. While PLA is compostable in industrial composting facilities, it does not readily biodegrade in natural situations [26].

As shown in Table 1, polyhydroxybutyrate (PHB), evaluated in seawater by Tanadchangsaeng and Pattanasupong (2022), exhibited a substantial 61.20% weight loss [30]. Meanwhile, Polyhydroxyalkanoate (PHA) demonstrated high biodegradability in terrestrial environments. Patil et al. (2023) reported a remarkable 98.62% and 89.75% weight loss for PHA in soil and sewage, respectively, within a 30-day timeframe [31].

Table 1. Biodegradation of bioplastic in environmental conditions.

Plastic-type	Biodegradation environment	Weight Loss	Time	Reference
PLA	Composting	16%	60 days	[27]
PLA	Soil	20%	20 months	[28]
PLA	Controlled composting (Bacterial treatment)	100%	60 days	[29]
Polyhydroxybutyrate (PHB)	Sea water	61.20%		[30]
PHA	soil	98.62%	30 days	[31]
PHA	Sewage	89.75%	30 days	[31]

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Starch-based bioplastic	Compost soil	74%	120 days	[32]
Starch-Polyhroxyurethanes hybrid	Soil	88%	120 days	[33]
Starch-based bioplastic	soil	69%	120 days	[33]
Blended polylactic acid (PLA)/polybutylene adipate (PBAT)	*Soil*	60.16	105 days	[34]

Starch-based bioplastics, represented by studies such as Wicaksono et al. (2022) and Abe et al. (2021), displayed considerable degradability in compost soil and regular soil conditions, achieving weight losses of 74% and 69% over 120 days, respectively [32,33]. Moreover, a starch-polyhydroxyurethanes hybrid, investigated by Abe et al. (2021), demonstrated an 88% weight loss in soil during the same period [32].

In the case of Polylactic Acid (PLA), its degradability has been investigated in different environments. Brdlík et al. (2021) observed a 16% weight loss in PLA under composting conditions over 60 days [27]. This aligns with the findings of Karamanlioglu et al. (2017), who reported a 20% weight reduction in PLA over 20 months in soil [28]. Notably, controlled composting with bacterial treatment resulted in the complete degradation of PLA within 60 days as indicated in (Figure 2) [29].

Examining blended bioplastics, Zhang et al. (2022) explored a combination of polylactic acid (PLA) and polybutylene adipate terephthalate (PBAT). This blend exhibited a weight loss of 60.16 in soil over 105 days. These varied results emphasize the significance of considering certain biodegradation conditions and show how various bioplastics may support environmentally friendly waste management techniques [34].

This discrepancy between biodegradability and raw materials exemplifies the market's complexity for bioplastics (Figure 2). PLA is derived from plants but can stay in the environment if not disposed of properly. It requires specific conditions to break down, which are rarely met in natural settings or by conventional waste management techniques [26].

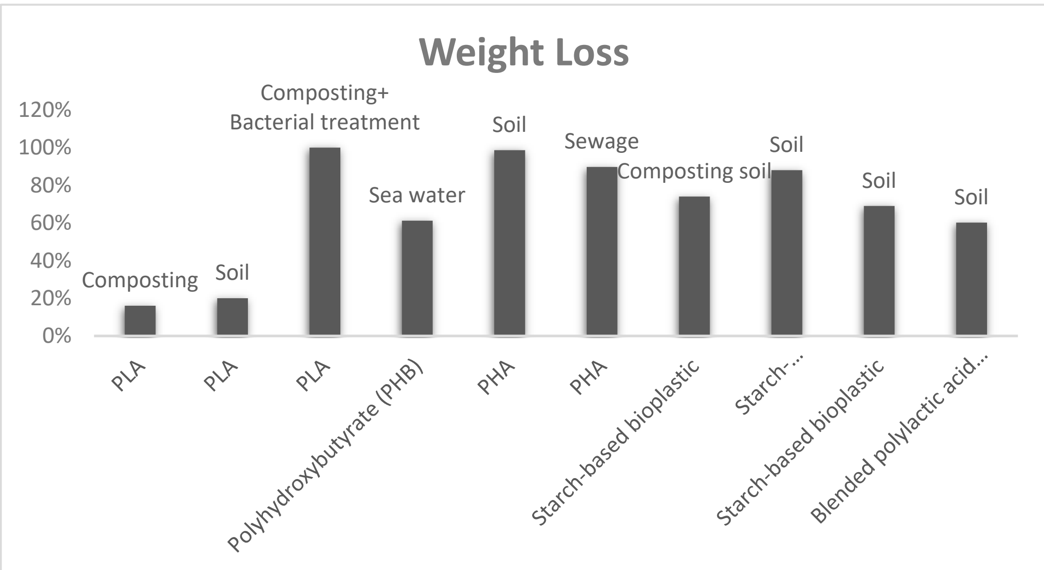

Figure 2. The graph shows the biodegradability of bioplastics in different environmental conditions.

1. Bioplastic biodegradation in Ocean

Marine habitats are essential for promoting biodegradation processes. The biodegradation of PHA in the North Atlantic Ocean was investigated in a study conducted by Cao et al. (2022). The findings indicated that the rates of PHA biodegradation exhibited variations based on the specific locations within the ocean where they were assessed. The study revealed a notable increase in

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biodegradation rates in regions characterized by elevated temperatures and abundant food availability[35].

According to recent research, it has been indicated that marine microorganisms do not play a significant role in the degrading process of petrochemical-based plastics [36]. Nevertheless, it is widely acknowledged that they can discharge dissolved organic carbon (DOC), potentially augmenting bacterial activity inside marine ecosystems. The ongoing argument revolves around the differentiation of plastisphere communities, microbial communities that develop on plastic surfaces in saltwater, regarding polymer kinds and other surfaces. The dissimilarities within the plastisphere community appear to be influenced mainly by environmental factors rather than the specific type of polymer present [36].

In contrast, disparities exist in bacterial community makeup and activity between biodegradable plastic materials and reference materials. This finding suggests that specific types of bioplastics have the potential to support the growth of microbial communities that are capable of biodegrading them [3]. Nevertheless, the current body of research about biodegradable polymers has predominantly concentrated on two specific types: polylactic acid (PLA) and polyhydroxybutyrate (PHB). Research findings indicate that PHB is more susceptible to seawater biodegradation than PLA [27,37].

These investigations have yielded significant insights into the behavior of bioplastics and their potential degradation in marine ecosystems. Nevertheless, an absence of research integrates several approaches to investigate the actual biodegradation process, specifically focusing on biological oxygen consumption. Additionally, there is a scarcity of in situ experiments encompassing weight loss and analysis of bacterial community composition. This research gap is particularly evident when examining multiple types of bioplastic materials. In addition, it is imperative to conduct extensive, extended research to comprehensively comprehend the intricate dynamics of bacterial communities on bioplastic materials. Given the objective of substituting non-degradable fossil-based materials with bioplastics, evaluating the latter's inherent biodegradability is imperative [3].

2. Bioplastic biodegradation Soil

The biodegradation process heavily relies on soil and other components of terrestrial ecosystems. Variations in soil temperature, moisture levels, and microbial composition can exhibit substantial fluctuations across different geographical regions. The soil harbors a diverse array of microorganisms that influence the biodegradation processes in this environment [38].

The biodegradation process may be impacted by the variety of microorganisms found in soil. When native bacteria compete with bioplastics for nutrients, the degradation process of bioplastics in soil may slow down. Variations in temperature and humidity are just two examples of the many environmental conditions that might affect biodegradation rates [38].

Numerous different environmental conditions might have an impact on the biodegradation process in soil. Mosquera Rodríguez et al. (2023) investigated how polycaprolactone (PCL) bioplastics break down in a soil environment. Researchers discovered that soil temperature and moisture substantially impacted PCL biodegradation rates. Furthermore, the existence of rival bacteria affected the overall biodegradation rate[39].

Soil microorganisms exhibit a heightened susceptibility to alterations in their surroundings caused by pollution. Hence, assessing soil microorganisms can be a reliable indicator of the prevailing environmental state. Nevertheless, elevated concentrations of petroleum hydrocarbons or heavy metals in the soil reduce bacterial biomass. Moreover, the microbial diversity might be influenced by several soil contaminants. The interplay between nitrogen and phosphorus circulation in agricultural soils is intricately linked to the presence and activities of soil microbial biomass. Examining nitrogen circulation activity is essential as a diagnostic tool for identifying soil pollution. Consequently, assessing microbial biomass and diversity can provide valuable insights into the impact of bioplastic degradation on the soil ecosystem [40].

The degradability of bioplastics in the soil environment exhibits considerable variation depending on the primary polymer constituent. The rate of deterioration of PBS-starch surpasses that of PLA and PBS after 28 days. Specifically, the powdered PBS starch, a composite of PBS and starch, saw a degradation rate of 24%. Prior research has demonstrated that soil microorganisms can degrade and utilize both PBS and PBS starch [41].

Conversely, several categories of bioplastics, such as PLA, exhibit a prolonged persistence in soil. In this study, it was observed that the degradation speed of some bioplastics was enhanced by lowering their size and increasing their surface area through powdering. However, it was shown that powdered PLA still exhibited challenges in terms of degradation when exposed to soil. PLA degradation necessitates alterations in its structural composition and the action of microorganisms. Hence, to facilitate the degradation of PLA, it may be necessary to introduce microbial activity at elevated temperatures, such as through the involvement of thermophilic bacteria during a composting procedure [42].

The speeds at which bioplastics degrade directly correlate with the quantity of bacterial biomass in the soil [43]. Several strains of bacteria capable of degrading bioplastics may be present in soil environments, and there appears to be a greater abundance of bioplastic-degrading bacteria in soils with a higher overall bacterial biomass. Given the amount of bacterial biomass in fertile soil, bioplastics exhibit a high degree of efficiency in terms of degradation within such conditions [42].

The degradation of bioplastics did not significantly impact bacterial biomass and diversity when they were subjected to burial in soils for 28 days and two years. The use of powdered bioplastics did not substantially alter bacterial biomass, as indicated by the absence of data illustrating such changes. Nevertheless, the bacterial biomass exhibited a decline following the burial of PA66 in soil for two years. The presence of polyamide 66 (PA66) in the soil can impede aeration, affecting the optimal functioning of microorganisms [42].

The anticipated rise in the utilization of bioplastics within agricultural domains necessitates a comprehensive analysis of bioplastic degradation on the circulation of materials within agricultural soil. Nitrogen is a fundamental nutrient required for the optimal growth of plants. Consequently, the circulation of nitrogen holds paramount importance in both conventional and organic agricultural practices. The study of Ghasemlou et al. (2022) aimed to assess the nitrogen circulation activity in the soil where bioplastic was buried. The findings revealed a detrimental impact of PLA degradation on the activity above. Furthermore, the experiment did not result in an increase in fungal biomass through the degradation of bioplastics. Nevertheless, it is imperative to research to investigate the impact of substantial quantities of buried bioplastics in agricultural fields on the proliferation of phytopathogens to ensure the safe and responsible use of bioplastics [44].

3. Anaerobic biodegradation of bioplastic

Most biodegradable plastics undergo one of three disposal methods: recycling, composting, or landfilling. Disposing of bioplastics in landfills, alongside other organic waste, results in the generation of methane, a potent greenhouse gas that is subsequently released into the environment. Conversely, composting processes produce carbon dioxide, another greenhouse gas, contributing to greenhouse gas emissions. Conversely, the anaerobic digestion process entails the degradation of organic matter in an oxygen-deprived environment, producing biogas. When comparing anaerobic digestion to aerobic digestion, it is seen to generate energy in biogas and have a shorter retention time [45].

Anaerobic biodegradation of bioplastics has been studied in comprehensive research. Üveges et al. (2023) found that cellulose-based materials can efficiently convert into methane under mesophilic conditions, making them suitable for co-digestion in anaerobic biogas plants [46]. Zhang et al. (2022) investigated the biodegradation of PHB-based bioplastics in anaerobic digesters treating food waste and found that bioaugmentation with specific bacteria accelerated the degradation process [47]. Ebrahimzade et al. (2022) studied the kinetics of methane production during anaerobic digestion of starch-based bioplastics and used non-linear regressions and artificial neural networks to model the process [48]. García-Depraect et al. (2022) compared the biodegradation of various bioplastics under aerobic and anaerobic conditions. PHB and PHBV were biodegraded in both environments, while PCL was only biodegraded aerobically [49]. Another study by Ebrahimzade et al. (2021) focused on optimizing particle size and inoculum-to-substrate ratio for anaerobic degradation of bioplastics, finding that the inoculum-to-substrate ratio had a more significant effect on biomethane yield [50].

PLA bioplastic has been studied for its anaerobic biodegradability. Studies have shown that PLA bioplastic is hardly anaerobically biodegradable at mesophilic temperatures [51]. The degree of biodegradation does not correlate with the molar composition of PLA/PBAT blends [52]. However, anaerobic biodegradation occurs mainly in the PLA fraction [46]. Biodegradation of PLA does not occur under mesophilic conditions, and pre-treatment of the polymers is recommended [49]. The biodegradability of PLA bioplastic was less than 50% after 35 days of anaerobic digestion, suggesting that complete degradation was not achieved [53].

Anaerobic biodegradation of PHA bioplastics has been studied in several papers. The biodegradation of PHB-based bioplastic in anaerobic digesters treating food waste was investigated, and it was found that the plastic film could be partially biodegraded [54]. Another study compared the biodegradation of various bioplastics under aerobic and anaerobic conditions, and PHB and PHBV were found to be biodegraded anaerobically [47]. Additionally, the biodegradation of bioplastics under mesophilic conditions was examined, and it was observed that cellulose-based materials can efficiently convert into methane, making them promise for co-digestion in anaerobic biogas plants [49]

Anaerobic biodegradation of poly(3-hydroxybutyrate) (PHB) bioplastic has been studied in several papers. The biodegradation of PHB was observed under anaerobic conditions in both aqueous environments and anaerobic digesters treating food waste [46,54]. The degradation efficiency of PHB-based bioplastic was found to be influenced by the presence of specific functional microbes, such as *Alcaligenes faecalis* and *Bacillus megaterium*, which accelerated the degradation process [47]. The biodegradation of PHB was also affected by factors such as particle size, with smaller particles showing higher biodegradation [46]. The study of anaerobic biodegradation of PHB is important for developing and testing biodegradable materials in the context of a circular bioeconomy [55]. Overall, these findings contribute to understanding PHB bioplastic degradation and its potential applications in anaerobic bioremediation and clean energy recovery.

The anaerobic biodegradation of PCL bioplastic was studied in multiple papers. One study found that PCL was only biodegraded aerobically, with a degradation rate of 77.6% in 177 days [49]. Another study compared the anaerobic biodegradability of different bioplastics and found that PCL had a low biodegradation rate of 3% in 277 days [46]. However, a different study investigated ways to increase the PCL biodegradation rate and found that adding calcium carbonate as an additive could improve biodegradation rates [56]. Overall, the anaerobic biodegradation of PCL bioplastic is limited, and further research is needed to improve its biodegradability.

4. Bioplastic biodegradation by Composting

Extensive research has been conducted to investigate the biodegradation of bioplastics during composting processes, primarily driven by their widespread use in household organic waste collection [57]. Many bioplastics available in the market are labeled as both compostable and biodegradable. Researchers have explored this phenomenon at different scales, including industrial settings, field conditions, and laboratory simulations. These investigations involve controlling variables such as temperature, moisture content, pH levels, carbon-to-nitrogen ratios, sample sizes, compost types (sourced from various places), and feedstock compositions (typically a mix of food and green waste or organic fractions of municipal solid waste) [13].

Composting trials have been conducted over various timeframes, with bioplastic degradation ranging from relatively low (around 10%) to more significant levels (over 90%). The tests utilize compost, which naturally contains a diverse microbial community, as the experiment environment, eliminating the need for additional inoculums. Both compost and soil are rich in microbial diversity, making them conducive for the biodegradation of bioplastics. Studies have identified a range of microorganisms, including bacteria like *Stenotrophomonas*, fungi such as *Penicillium*, *Aspergillus*, and various others, as well as actinobacteria species like *Streptomyces*, capable of breaking down different biopolymers when isolated from compost environments [58]. Certain gene sequences associated with the biodegradation of specific bioplastics, such as PLA, have been pinpointed, including *Paecilomyces, Thermomonospora,* and *Thermopolyspora* [59].

Moreover, in some cases, researchers have observed a synergistic effect in bioplastic degradation when combining different microorganisms. For instance, the thermophilic actinomycete *Streptomyces thermonitrificans* PDS-1, when used in conjunction with other microorganisms like *Bacillus licheniformis* HA1, has been found to enhance the degradation of PCL under composting conditions. This research underscores the intricate nature of bioplastic biodegradation in composting processes, emphasizing the significance of understanding the involved factors and microorganisms for effective organic waste management and reducing bioplastics' environmental impact [60].

After visually inspecting the residues, the primary indicators of biodegradation are degradation and mass loss. Some investigations also reported changes in the polymeric structure using techniques like FTIR analysis [61]. To assess the extent of biomaterial degradation by microorganisms more accurately, the production of CO_2 was utilized, especially in aerobic composting processes. However, it is worth noting that tracking CO_2 production in field-scale testing can be challenging. Observing microbial growth near the bioplastic, typically in proximity, is a qualitative indicator of degradation and biodegradation [10].

Compared to industrial composting, home composting typically operates at lower temperatures, which may necessitate longer durations for biodegradation. Most studies in this context followed established standards such as ASTM D6400, ISO 20200, and ISO 14855-1. These standards define that to label a bioproduct as compostable, at least 90% weight loss and degradation of the mass into fragments smaller than 2 mm should occur within six months. However, existing composting facilities are not optimized for processing bioplastics, which can lead to challenges in their treatment. It is important to note that while residual fragments from bioplastics can impact compost quality, ecotoxicity tests on the final compost are rarely conducted in research studies [10].

5. Bioplastics biodegradability by microbes

There are countless ways in which plastics have been incorporated into our contemporary lives. Traditional plastics made from petroleum have been widely used, but their persistence in the environment has caused a severe environmental catastrophe. Researchers have been looking into bioplastics as a more environmentally friendly solution to this problem [62]. Bioplastics are created from renewable resources and are designed to be biodegradable, decreasing the environmental impact of plastic pollution. Several recent studies have investigated whether microorganisms can biodegrade different types of bioplastics, an encouraging step towards a greener tomorrow.

Oceans, soil, and man-made environments all host unique microbial populations. The composition and variety of these communities can have a significant effect on the biodegradation of bioplastics. There are several contributors to the rich cultural variety found in these areas. For instance, due to temperature, nutrition availability, and other environmental conditions, microbe populations can vary significantly between different sites within the same habitat, a common feature of complex environments that display spatial heterogeneity [63].

Microbial colonies find favorable circumstances and resources in narrow ecological niches in highly variable settings. When bioplastics are dispersed widely, they can affect the ecosystems that break them down. Within these communities, microorganisms engage in both cooperative and competitive interactions. Different microbial species contribute to different stages of the degradation process, and these interactions can impact the dynamics of biodegradation [64].

Adapting microbial communities in complex environments is a significant component in the success of biodegradation in various conditions. These communities may be able to adjust to new surroundings, such as the introduction of bioplastics. Consequently, devising efficient strategies for biodegrading bioplastics in these environments requires understanding the diversity and dynamics of microbial communities in these settings [65].

Firmicutes, Proteobacteria, Ascomycetes, and *Basidiomycetes* are only some of the many microbial taxa capable of degrading bioplastics [66]. These microbes are spread throughout numerous environments, including terrestrial and marine soil, compost facilities, and insect stomachs. This shows how different microbial metabolisms can be from one another. Many biodegradable species discovered so far are often found in a growth condition analogous to the stationary phase when cultured in the laboratory. In this growth stage, cells make proteins that help scavenge and overcome nutritional stress (e.g., proteinases that feed cells with amino acids to sustain growth).

Enzymes that break down bioplastics typically belong to the proteinase, cutinase, or esterase families. These enzymes are somewhat promiscuous, allowing them to degrade bioplastics they do generally not digest. However, large polymers must frequently be broken down into monomers and smaller polymers before they can be transported into the cells. Enzymes that break down bioplastics are often released [67]. Therefore, the breakdown of bioplastics can supply organisms with carbon. Many researchers use plastic as the only carbon source to enrich bioplastic-degrading microbes.

Table 2 indicates that in assessing the biodegradation performance of diverse plastic polymers in the presence of specific microbial strains, Polyhydroxybutyrate (PHB) stands out as remarkably biodegradable, achieving a substantial 98% weight loss within a brief 14-day period when subjected to *Bacillus* sp. JY14 [68]. This underscores the effectiveness of microbial interaction in hastening PHB breakdown. Comparatively, other plastics such as Polybutylene Succinate (PBS), Poly(butylene succinate-co-butylene adipate) (PBSA), Poly(ε-caprolactone) (PCL), and Poly(butylene adipate-co-terephthalate) (PBAT) exhibited varying degrees of biodegradation, with PBSA, PCL, and PBAT showcasing approximately 50%, 33.70%, and 50.0% weight loss, respectively, by *Sclerotinia* sp. B11IV, *Sclerotinia* sp. B11IV, and *Bacillus* sp. JY35 [69,68]. Notably, the blend of Polylactic Acid/Polybutylene Adipate-co-Terephthalate (PLA/PBAT) displayed lower biodegradability, with only 12.94% and 9.27% weight loss when exposed to *Pseudomonas mendocina* and *Arthrobacter elegans*, respectively, over 5 days [70]. Overall, the findings highlight PHB's exceptional biodegradability potential, suggesting its favorable environmental impact in the context of plastic waste management.

Table 2. Biodegradation of bioplastic by microbes.

Plastic-type	Biodegradation environment	Weight Loss	Time	Reference
Polyhydroxybutyrate (PHB)	*Bacillus* sp. JY14	98%	14 days	[68]
Polybutylene succinate (PBS)	*Terribacillus* sp. JY49	31.40%	10 days	[69]
Poly(butylene succinate-co-butylene adipate) (PBSA)	*Sclerotinia* sp. B11IV	49.68%	28 days	[70]
Poly(ε-caprolactone) (PCL)	*Sclerotinia* sp. B11IV	33.70%	28 days	[70]
Poly(butylene succinate-co-butylene adipate) (PBSA)	*Fusarium* sp. B3′M	45.99%	28 days	[70]
Poly(ε-caprolactone) (PCL)	*Fusarium* sp. B3′M	49.65%	28 days	[70]
Poly(butylene adipate-*co*-terephthalate) (PBAT)	*Bacillus* sp. JY35	50.0%	21 days	[71]
Polylactic acid/polybutylene adipate-*co*-terephthalate (PLA/PBAT)	*P. mendocina*	12.94%	5 days	[72]
Polylactic acid/polybutylene adipate-*co*-terephthalate (PLA/PBAT)	*A. elegans*	9.27%	5 days	[72]

Environmental Consequences of Biodegradation

There is hope and risk for ecosystems from the biodegradation of bioplastics in complicated contexts. A thorough study of biodegradation in these situations requires understanding the ecological ramifications, monitoring and assessment methodologies, potential dangers, and the fine balance between these benefits and drawbacks. The objectives of sustainability and low environmental effects are upheld in the regulated settings of industrial composting, where

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biodegradable bioplastics can degrade. These structures create an optimal environment for the biodegrading bacteria, leading to the rapid breakdown of bioplastics. The process often yields eco-friendly byproducts, including water, carbon dioxide, and biomass [45].

However, it must be understood that the biodegradability of these substances varies depending on the setting. The biodegradation of these bioplastics may not be as effective outside of the regulated conditions of industrial composting. The process may be slower or not happen in natural environments like soil or aquatic ecosystems [26].

Non-biodegradable bioplastics, on the other hand, do not readily degrade in natural settings despite their plant-based origins. Polylactic acid (PLA) plastic, for instance, has become increasingly popular since it can be made from renewable sources like cornflour. While PLA is compostable in industrial composting facilities, it does not readily biodegrade in natural situations [3].

This disparity between raw materials and biodegradability is emblematic of the multifaceted nature of the bioplastics market. Even though PLA comes from plants, it can remain in the environment if not disposed of properly. It can only degrade under particular conditions, which are rarely met in natural environments or traditional waste management methods [26].

Biodegradation is a multifaceted process with far-reaching ecological consequences, the effects of which are context- and material-specific . These ramifications must be considered to guarantee that the advantages of biodegradation outweigh any disadvantages (Figure 3). When bioplastics break down in the environment, they release nutrients that are beneficial to ecosystems because they encourage nutrient cycling and boost microbial development. However, eutrophication, which is harmful to aquatic life, can be avoided with careful management of nutrient delivery. Ecosystem dynamics and microbial diversity may be affected by the competitive interactions between biodegrading microorganisms and native microbial communities [41]. Understanding these interactions is crucial to evaluating the influence of indigenous microorganisms and their roles in ecological processes. Because of biodegradation, bioplastics may become less accessible to organisms higher up the food chain. Higher trophic levels can consume degraded products from bioplastics as they are released during degradation. This may affect the structure of food webs and the amplification of toxins. Therefore, it is vital to control biodegradation in complex ecosystems to establish a balance between the advantages and potential dangers [73].

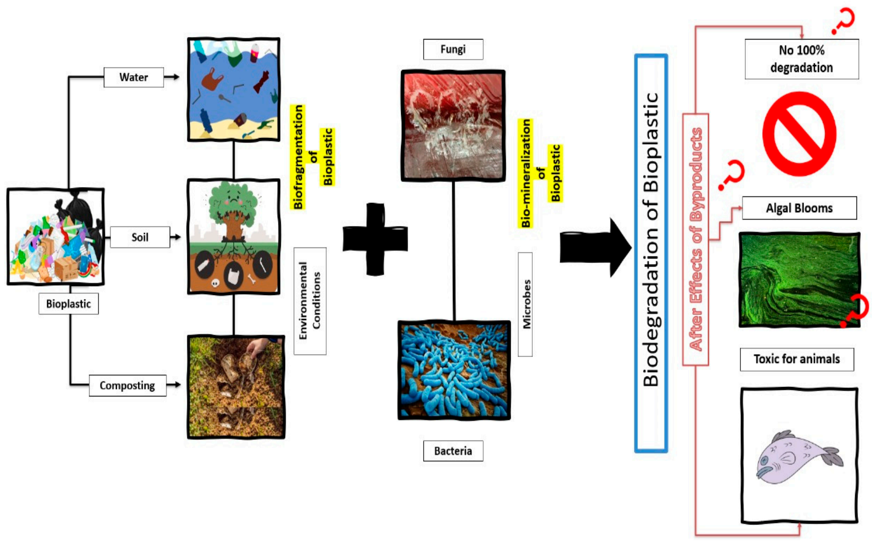

Figure 3. Fate of bioplastic in the environment.

The biodegradation of bioplastics has both benefits and drawbacks, especially in more complicated ecosystems. Microbial populations may shift due to biodegradation, with the advantage going to more proficient biodegraders. Ecosystem services may be negatively impacted if the delicate balance of microorganism populations is upset. Bioplastic degradation results in byproducts and

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intermediates that could be hazardous to the environment. For instance, the degradation process may endanger aquatic or terrestrial creatures if it releases specific monomers or hazardous chemicals [74]. Biodegradation can cause bioplastics to mineralize, releasing their contained carbon in some circumstances completely. The environmental benefits of biodegradable materials may be nullified if this process increases carbon emissions in some ecosystems. Particularly in aquatic environments, eutrophication caused by excessive nutrient release from biodegradation can promote the establishment of toxic algal blooms. Oxygen depletion and the death of marine animals are just two of the many adverse ecological effects that can result from these blooms.

Future Directions

Although bioplastics are generally considered to be more environmentally friendly than traditional petroleum-based plastics due to their biodegradability and lower carbon emissions, not all bioplastics are created equal. For instance, some bioplastics, like PLA, are just as challenging to break down in the environment as their petroleum-based counterparts. While microbe-based bioplastics are a more sustainable solution, few studies have investigated the ecological impact of the byproducts released after their biodegradation on soil and marine life. Ecosystem-based biodegradation strategies can ensure that bioplastics are introduced in a manner compatible with the native ecosystem's natural mechanisms, considering microbial communities, nutrient cycles, and food webs. Long-term studies on the ecological effects of biodegradation in complex contexts are crucial for understanding how ecosystems adapt and respond to the presence of biodegradable materials over time.

Life cycle assessment, or LCA, is a popular method for assessing a product or process's economic and environmental performance. When producing different polymers, life cycle assessment (LCA) is frequently used to analyze various polymer types' environmental effects or assess the advantages of employing biopolymers before advocating for their widespread use. Well-designed and thorough life cycle assessment (LCA) studies are necessary to offer reliable data on the sustainability of bioplastics and their comparative analysis with traditional petrochemical plastics.

Conclusion

In conclusion, bioplastics are viable solutions to plastic pollution in this era. Bioplastics, particularly microbe-based bioplastics, produce less pollution to the environment as compared to petroleum-based plastics. However, the Biodegradability of bioplastics can vary in different environmental conditions such as soil, marine, anaerobic, composting, and microbial biodegradation in the laboratory. The study highlights the complicated ecological implications of examining the environmental effects of biodegradation. It is very crucial to assess the biodegradability of bioplastics in natural conditions. However, there are limited studies on the ecotoxicological impact of bioplastic byproducts. In the future, Careful control is required to minimize eutrophication and potential harm to aquatic life, even while biodegradation releases helpful nutrients and encourages microbial development. Developing environmentally friendly materials and assessing the ecological effect of bioplastic biodegradation on soil and marine is crucial.

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References

1. Nanni, A., Parisi, M., & Colonna, M. (2021). Wine by-products as raw materials for the production of biopolymers and of natural reinforcing fillers: A critical review. *Polymers*, *13*(3), 381.
2. Paul-Pont, I., Ghiglione, J. F., Gastaldi, E., Ter Halle, A., Huvet, A., Bruzaud, S., ... & Fabre, P. (2023). Discussion about suitable applications for biodegradable plastics regarding their sources, uses and end of life. *Waste Management*, *157*, 242-248.
3. Eronen-Rasimus, E. L., Nakki, P. P., & Kaartokallio, H. P. (2022). Degradation rates and bacterial community compositions vary among commonly used bioplastic materials in a brackish marine environment. Environmental Science & Technology, 56(22), 15760-15769.
4. Dirpan, A., Ainani, A. F., & Djalal, M. (2023). A Review on Biopolymer-Based Biodegradable Film for Food Packaging: Trends over the Last Decade and Future Research. *Polymers*, *15*(13), 2781.
5. Kochanska, E., Wozniak, K., Nowaczyk, A., Piedade, P. J., de Almeida Lavorato, M. L., Almeida, A. M., ... & Lukasik, R. M. (2022). Global Ban on Plastic and What Next? Are Consumers Ready to Replace Plastic with the Second-Generation Bioplastic? Results of the Snowball Sample Consumer Research in China, Western and Eastern Europe, North America and Brazil. *International Journal of Environmental Research and Public Health*, *19*(21), 13970.
6. Goel, V., Luthra, P., Kapur, G. S., & Ramakumar, S. S. V. (2021). Biodegradable/bio-plastics: myths and realities. *Journal of Polymers and the Environment*, *29*, 3079-3104.
7. Mahmoud Nasrollahzadeh, Nasrin Shafiei, & Zahra Nezafat. (2021). Application of biopolymers in bioplastics. Elsevier EBooks, 1–44. https://doi.org/10.1016/b978-0-323-89970-3.00001-9
8. Liu, L., Xu, M., Ye, Y., & Zhang, B. (2022). On the degradation of (micro) plastics: Degradation methods, influencing factors, environmental impacts. *Science of the Total Environment*, *806*, 151312.
9. Gricajeva, A., Nadda, A. K., & Gudiukaite, R. (2022). Insights into polyester plastic biodegradation by carboxyl ester hydrolases. *Journal of Chemical Technology & Biotechnology*, *97*(2), 359-380.
10. Folino, A., Karageorgiou, A., Calabrò, P. S., & Komilis, D. (2020). Biodegradation of wasted bioplastics in natural and industrial environments: A review. *Sustainability*, *12*(15), 6030.
11. Ainali, N. M., Kalaronis, D., Evgenidou, E., Kyzas, G. Z., Bobori, D. C., Kaloyianni, M., ... & Lambropoulou, D. A. (2022). Do poly (lactic acid) microplastics instigate a threat? A perception for their dynamic towards environmental pollution and toxicity. *Science of the total environment*, *832*, 155014.
12. Gioia, C., Giacobazzi, G., Vannini, M., Totaro, G., Sisti, L., Colonna, M., ... & Celli, A. (2021). End of life of biodegradable plastics: composting versus Re/upcycling. *ChemSusChem*, *14*(19), 4167-4175.
13. Meereboer, K. W., Misra, M., & Mohanty, A. K. (2020). Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites. *Green Chemistry*, *22*(17), 5519-5558.
14. Rafiqah, S. A., Khalina, A., Harmaen, A. S., Tawakkal, I. A., Zaman, K., Asim, M., ... & Lee, C. H. (2021). A review on properties and application of bio-based poly (butylene succinate). *Polymers*, *13*(9), 1436.
15. Polman, E. M., Gruter, G. J. M., Parsons, J. R., & Tietema, A. (2021). Comparison of the aerobic biodegradation of biopolymers and the corresponding bioplastics: A review. *Science of the Total Environment*, *753*, 141953.
16. Rashidi, L. (2022). Standards and Guidelines for Testing Biodegradability of Bioplastic. In *Biodegradable Polymer-Based Food Packaging* (pp. 297-325). Singapore: Springer Nature Singapore.
17. Ahsan, W. A., Hussain, A., Lin, C., & Nguyen, M. K. (2023). Biodegradation of Different Types of Bioplastics through Composting—A Recent Trend in Green Recycling. Catalysts, 13(2), 294.
18. Choudhury, B. K., Haloi, R., Bharadwaj, K. K., Rajkhowa, S., & Sarma, J. (2022). Bio-Based and Biodegradable Plastics as Alternatives to Conventional Plastics. *Plastic and Microplastic in the Environment: Management and Health Risks*, 170-186.
19. Nanda, S., Patra, B. R., Patel, R., Bakos, J., & Dalai, A. K. (2022). Innovations in applications and prospects of bioplastics and biopolymers: A review. *Environmental Chemistry Letters*, *20*(1), 379-395.
20. Samadhiya, K., Sangtani, R., Nogueira, R., & Bala, K. (2022). Insightful advancement and opportunities for microbial bioplastic production. Frontiers in Microbiology, 12, 674864.
21. Uma, V. S., Usmani, Z., Sharma, M., Diwan, D., Sharma, M., Guo, M., ... & Gupta, V. K. (2023). Valorisation of algal biomass to value-added metabolites: Emerging trends and opportunities. *Phytochemistry Reviews*, *22*(4), 1015-1040.

22. Ferreira-Filipe, D. A., Paço, A., Duarte, A. C., Rocha-Santos, T., & Patrício Silva, A. L. (2021). Are biobased plastics green alternatives?—a critical review. *International Journal of Environmental Research and Public Health*, *18*(15), 7729.
23. García-Depraect, O., Lebrero, R., Rodriguez-Vega, S., Bordel, S., Santos-Beneit, F., Martínez-Mendoza, L. J., ... & Munoz, R. (2022). Biodegradation of bioplastics under aerobic and anaerobic aqueous conditions: Kinetics, carbon fate and particle size effect. *Bioresource Technology*, *344*, 126265.
24. Chong, J. W. R., Yew, G. Y., Khoo, K. S., Ho, S. H., & Show, P. L. (2021). Recent advances on food waste pretreatment technology via microalgae for source of polyhydroxyalkanoates. *Journal of Environmental Management*, *293*, 112782.
25. Awasthi, S. K., Kumar, M., Kumar, V., Sarsaiya, S., Anerao, P., Ghosh, P., ... & Awasthi, M. K. (2022). A comprehensive review on recent advancements in biodegradation and sustainable management of biopolymers. *Environmental Pollution*, *307*, 119600.
26. Kalita, N. K., Sarmah, A., Bhasney, S. M., Kalamdhad, A., & Katiyar, V. (2021). Demonstrating an ideal compostable plastic using biodegradability kinetics of poly (lactic acid)(PLA) based green biocomposite films under aerobic composting conditions. *Environmental Challenges*, *3*, 100030.
27. Tanadchangsaeng, N., & Pattanasupong, A. (2022). Evaluation of Biodegradabilities of Biosynthetic Polyhydroxyalkanoates in Thailand Seawater and Toxicity Assessment of Environmental Safety Levels. Polymers, 14(3), 428.
28. Patil, P. B., Sarkar, D., Poddar, K., Gu, J. D., & Sarkar, A. (2023). Degradation profiling of in-vitro-produced polyhydroxyalkanoate synthesized by the soil bacterium Bacillus sp. PhNs9 under different microenvironments. International Biodeterioration & Biodegradation, 181, 105615.
29. Wicaksono, J. A., Purwadaria, T., Yulandi, A., & Tan, W. A. (2022). Bacterial dynamics during the burial of starch-based bioplastic and oxo-low-density-polyethylene in compost soil. BMC microbiology, 22(1), 309.
30. Abe, M. M., Branciforti, M. C., & Brienzo, M. (2021). Biodegradation of hemicellulose-cellulose-starch-based bioplastics and microbial polyesters. Recycling, 6(1), 22.
31. Brdlík, P., Borůvka, M., Běhálek, L., & Lenfeld, P. (2021). Biodegradation of poly (lactic acid) biocomposites under controlled composting conditions and freshwater biotope. Polymers, 13(4), 594.
32. Karamanlioglu, M., Preziosi, R., & Robson, G. D. (2017). Abiotic and biotic environmental degradation of the bioplastic polymer poly (lactic acid): A review. Polymer Degradation and Stability, 137, 122-130.
33. Boonluksiri, Y., Prapagdee, B., & Sombatsompop, N. (2021). Promotion of polylactic acid biodegradation by adding PLA-degrading bacterium and nitrogen source under submerged and soil burial conditions. Polymer Degradation and Stability, 188, 109562.
34. Zhang, Y., Gao, W., Mo, A., Jiang, J., & He, D. (2022). Degradation of polylactic acid/polybutylene adipate films in different ratios and bacterial community response in soil environments. Environmental Pollution, 313, 120167.
35. Cao, Y., Zhang, B., Cai, Q., Zhu, Z., Liu, B., Dong, G., ... & Chen, B. (2022). Responses of Alcanivorax species to marine alkanes and polyhydroxybutyrate plastic pollution: Importance of the ocean hydrocarbon cycles. *Environmental Pollution*, *313*, 120177.
36. Kumari, A., Chaudhary, D. R., & Jha, B. (2021). Microbial degradation of plastics and its biotechnological advancement. *Environmental Biotechnology Vol. 3*, 1-30.
37. G. Engler, L., Farias, N. C., S. Crespo, J., Gately, N. M., Major, I., Pezzoli, R., & Devine, D. M. (2023). Designing sustainable polymer blends: tailoring mechanical properties and degradation behaviour in PHB/PLA/PCL blends in a seawater environment. *Polymers*, *15*(13), 2874.
38. Huang, F., Zhang, Q., Wang, L., Zhang, C., & Zhang, Y. (2023). Are biodegradable mulch films a sustainable solution to microplastic mulch film pollution? A biogeochemical perspective. *Journal of Hazardous Materials*, 132024.
39. Mosquera Rodríguez, F. S., Quintero Vélez, A., Córdoba Urrutia, E., Ramírez-Malule, H., & Mina Hernandez, J. H. (2023). Study of the Degradation of a TPS/PCL/Fique Biocomposite Material in Soil, Compost, and Water. *Polymers*, *15*(19), 3952.
40. Brown, R. W., Chadwick, D. R., Zang, H., Graf, M., Liu, X., Wang, K., ... & Jones, D. L. (2023). Bioplastic (PHBV) addition to soil alters microbial community structure and negatively affects plant-microbial metabolic functioning in maize. *Journal of Hazardous Materials*, *441*, 129959.
41. Yasin, N. M., Akkermans, S., & Van Impe, J. F. (2022). Enhancing the biodegradation of (bio) plastic through pretreatments: A critical review. *Waste Management*, *150*, 1-12.

42. Adhikari, D., Mukai, M., Kubota, K., Kai, T., Kaneko, N., Araki, K. S., & Kubo, M. (2016). Degradation of bioplastics in soil and their degradation effects on environmental microorganisms. *Journal of Agricultural Chemistry and Environment*, *5*(01), 23.
43. Han, Y., Teng, Y., Wang, X., Ren, W., Wang, X., Luo, Y., ... & Christie, P. (2021). Soil type driven change in microbial community affects poly (butylene adipate-co-terephthalate) degradation potential. *Environmental Science & Technology*, *55*(8), 4648-4657.
44. Ghasemlou, M., Daver, F., Murdoch, B. J., Ball, A. S., Ivanova, E. P., & Adhikari, B. (2022). Biodegradation of novel bioplastics made of starch, polyhydroxyurethanes and cellulose nanocrystals in soil environment. *Science of The Total Environment*, *815*, 152684.
45. Hobbs, S. R., Parameswaran, P., Astmann, B., Devkota, J. P., & Landis, A. E. (2019). Anaerobic codigestion of food waste and polylactic acid: effect of pretreatment on methane yield and solid reduction. *Advances in Materials Science and Engineering*, *2019*.
46. Üveges, Z., Damak, M., Klátyik, S., Ramay, M. W., Fekete, G., Varga, Z., ... & Aleksza, L. (2023). Biomethane Potential in Anaerobic Biodegradation of Commercial Bioplastic Materials. *Fermentation*, *9*(3), 261.
47. Zhang, L., Tsui, T. H., Fu, J., Dai, Y., & Tong, Y. W. (2022). Valorization of poly-β-hydroxybutyrate (PHB)-based bioplastic waste in anaerobic digesters of food waste for bioenergy generation: reactor performance, microbial community analysis, and bioplastic biodegradation. *Carbon Neutrality*, *1*(1), 8.
48. Ebrahimzade, I., Ebrahimi-Nik, M., Rohani, A., & Tedesco, S. (2022). Towards monitoring biodegradation of starch-based bioplastic in anaerobic condition: Finding a proper kinetic model. *Bioresource Technology*, *347*, 126661.
49. García-Depraect, O., Bordel, S., Lebrero, R., Santos-Beneit, F., Börner, R. A., Börner, T., & Muñoz, R. (2021). Inspired by nature: Microbial production, degradation and valorization of biodegradable bioplastics for life-cycle-engineered products. *Biotechnology Advances*, *53*, 107772.
50. Ebrahimzade, I., Ebrahimi-Nik, M., Rohani, A., & Tedesco, S. (2021). Higher energy conversion efficiency in anaerobic degradation of bioplastic by response surface methodology. *Journal of Cleaner Production*, *290*, 125840.
51. Álvarez-Méndez, S. J., Ramos-Suárez, J. L., Ritter, A., González, J. M., & Pérez, Á. C. (2023). Anaerobic digestion of commercial PLA and PBAT biodegradable plastic bags: Potential biogas production and 1H NMR and ATR-FTIR assessed biodegradation. *Heliyon*, *9*(6).
52. Bracciale, M. P., De Gioannis, G., Falzarano, M., Muntoni, A., Polettini, A., Pomi, R., ... & Zonfa, T. (2023). Anaerobic biodegradation of disposable PLA-based products: Assessing the correlation with physical, chemical and microstructural properties. *Journal of Hazardous Materials*, *452*, 131244.
53. Shrestha, A., van-Eerten Jansen, M. C., & Acharya, B. (2020). Biodegradation of bioplastic using anaerobic digestion at retention time as per industrial biogas plant and international norms. Sustainability, 12(10), 4231.
54. Raunhan, R., Jantharadej, K., Mhuantong, W., Napathorn, S. C., & Suwannasilp, B. B. (2023). Valorization of food waste derived anaerobic digestate into polyhydroxyalkanoate (PHA) using Thauera mechernichensis TL1. *Waste Management*, *171*, 248-258.
55. Jeon, Y., Jin, H., Kong, Y., Cha, H. G., Lee, B. W., Yu, K., ... & Park, K. (2023). Poly (3-hydroxybutyrate) Degradation by Bacillus infantis sp. Isolated from Soil and Identification of phaZ and bdhA Expressing PHB Depolymerase. *Journal of Microbiology and Biotechnology*, *33*(8), 1076.
56. Hegde, S., Dell, E., Lewis, C., Trabold, T. A., & Diaz, C. A. (2018). Anaerobic biodegradation of bioplastic packaging materials. In *The 21st IAPRI World Conference on Packaging*.
57. Folino, A., Pangallo, D., & Calabrò, P. S. (2023). Assessing bioplastics biodegradability by standard and research methods: current trends and open issues. *Journal of Environmental Chemical Engineering*, 109424.
58. Dahdah, K., Charchar, N., Bouchaala, L., Nourine, H., Belkabla, N., Melo, J., & Nabti, E. H. (2022). Isolation, in vitro evaluation and construction of Versatile Microbial Consortia. *Cellular and Molecular Biology*, *68*(8), 173-181.
59. Binti Jalani, J. C., & Arshad, Z. I. M. (2022). PLA Degradation and PLA-Degrading Bacteria: A Mini-Review. *Key Engineering Materials*, *932*, 103-110.
60. Bhattacharya, A., & Gupta, A. (2022). Current trends in applicability of thermophiles and thermozymes in bioremediation of environmental pollutants. In *Microbial Extremozymes* (pp. 161-176). Academic Press.
61. Ali, S., Rehman, A., Hussain, S. Z., & Bukhari, D. A. (2023). Characterization of plastic degrading bacteria isolated from sewage wastewater. *Saudi Journal of Biological Sciences*, *30*(5), 103628.

 doi:10.20944/preprints202311.1858.v1

62. Moshood, T. D., Nawanir, G., Mahmud, F., Mohamad, F., Ahmad, M. H., & AbdulGhani, A. (2022). Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution?. *Current Research in Green and Sustainable Chemistry*, *5*, 100273.
63. Sharma, S., Sharma, V., & Chatterjee, S. (2023). Contribution of plastic and microplastic to global climate change and their conjoining impacts on the environment-A review. *Science of The Total Environment*, *875*, 162627.
64. Feijoo, P., Marín, A., Samaniego-Aguilar, K., Sánchez-Safont, E., Lagarón, J. M., Gámez-Pérez, J., & Cabedo, L. (2023). Effect of the Presence of Lignin from Woodflour on the Compostability of PHA-Based Biocomposites: Degradation, Biodegradation and Microbial Dynamics. *Polymers*, *15*(11), 2481.
65. Ruggero, F., Roosa, S., Onderwater, R., Delacuvellerie, A., Lotti, T., Gori, R., ... & Wattiez, R. (2023). Characterization of bacterial communities responsible for bioplastics degradation during the thermophilic and the maturation phases of composting. *Journal of Material Cycles and Waste Management*, 1-16.
66. Aguilar-Paredes, A., Valdés, G., Araneda, N., Valdebenito, E., Hansen, F., & Nuti, M. (2023). Microbial Community in the Composting Process and Its Positive Impact on the Soil Biota in Sustainable Agriculture. *Agronomy*, *13*(2), 542.
67. Lai, J., Huang, H., Lin, M., Xu, Y., Li, X., & Sun, B. (2023). Enzyme catalyzes ester bond synthesis and hydrolysis: The key step for sustainable usage of plastics. *Frontiers in Microbiology*, *13*, 1113705.
68. Cho, J. Y., Park, S. L., Lee, H. J., Kim, S. H., Suh, M. J., Ham, S., ... & Yang, Y. H. (2021). Polyhydroxyalkanoates (PHAs) degradation by the newly isolated marine Bacillus sp. JY14. Chemosphere, 283, 131172.
69. Kim, S. H., Cho, J. Y., Cho, D. H., Jung, H. J., Kim, B. C., Bhatia, S. K., ... & Yang, Y. H. (2022). Acceleration of Polybutylene Succinate Biodegradation by Terribacillus sp. JY49 Isolated from a Marine Environment. Polymers, 14(19), 3978.
70. Urbanek, A. K., Strzelecki, M. C., & Mirończuk, A. M. (2021). The potential of cold-adapted microorganisms for biodegradation of bioplastics. Waste Management, 119, 72-81.
71. Cho, J. Y., Park, S. L., Kim, S. H., Jung, H. J., Cho, D. H., Kim, B. C., ... & Yang, Y. H. (2022). Novel Poly (butylene adipate-co-terephthalate)-degrading Bacillus sp. JY35 from wastewater sludge and its broad degradation of various bioplastics. Waste Management, 144, 1-10.
72. Jia, H., Zhang, M., Weng, Y., & Li, C. (2021). Degradation of polylactic acid/polybutylene adipate-co-terephthalate by coculture of Pseudomonas mendocina and Actinomucor elegans. Journal of hazardous materials, 403, 123679.
73. Malafeev, K. V., Apicella, A., Incarnato, L., & Scarfato, P. (2023). Understanding the Impact of Biodegradable Microplastics on Living Organisms Entering the Food Chain: A Review. *Polymers*, *15*(18), 3680.
74. Horie, Y., & Okamura, H. (2023). Ecotoxicity Assessment of Biodegradable Plastics in Marine Environments. In *Photo-switched Biodegradation of Bioplastics in Marine Environments* (pp. 135-152). Singapore: Springer Nature Singapore.