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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. Bioplastics are engineered to degrade in aquatic or soil environments. However, not all bioplastics are completely biodegradable, and some, like petrochemical-based plastics, may contribute to plastic pollution. The biodegradability of bioplastics is significantly different in different environmental conditions such as soil, marine, and composting environments. At the same time, bioplastics produced from natural resources contain a mixture of known and unknown materials and show 32% cytotoxicity, 42% oxidative stress, 67% baseline toxicity, and 23% antiandrogenicity in bioassays. The extensive biodegradation of bioplastics in soil can also change the soil nutrients, leading to eutrophication or stunted plant growth. However, many concerns have arisen, according to which bioplastics may not be an alternative option for global plastic pollution in the long run, and limited studies focus on this scenario. This review aims to provide a comprehensive overview of the biodegradation of bioplastics in different environmental conditions and by microorganisms and their ecotoxicological impacts on soil and marine health. In conclusion, while bioplastics have the potential to be a sustainable alternative to conventional plastics, it is essential to address concerns regarding their complete biodegradability and toxicity. Therefore, sustainable methods must be used for their production and biodegradation to ensure a positive impact on the environment.

Keywords: anaerobic digestion; biodegradation; bioplastic; composting; microbes; poly (butylene succinate) (PBS); poly (butylene succinate-co-butylene adipate) PBSA; poly (lactic acid) (PLA)

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Citation: Ali, S.; Isha; Chang, Y.-C. Ecotoxicological Impact of Bioplastics Biodegradation: A Comprehensive Review. *Processes* **2023**, *11*, 3445. https://doi.org/10.3390/pr11123445

Academic Editor: Luigi Piga

Received: 28 November 2023
Revised: 11 December 2023
Accepted: 15 December 2023
Published: 17 December 2023

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].

Bioplastics can be classified into two primary categories: bio-based and biodegradable. Bioplastics derived from renewable biomass are classified as bio-based; however, their biodegradability is not guaranteed. For instance, bio-based polyethylene (PE) or polyethylene terephthalate (PET) possess the same chemical composition as their fossil-based equivalents and thus exhibit low biodegradability in the environment. Biodegradable bioplastics are specifically engineered to undergo decomposition in specific circumstances, such as when they encounter microbes, heat, or moisture [2]. Polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are types of biodegradable bioplastics that can undergo composting in industrial facilities. Certain bioplastics possess both bio-based and biodegradable properties, whilst others lack both [3]. Biodegradable bioplastics are engineered to decompose more rapidly than traditional plastics, although they may not decompose entirely or evenly in every setting. For instance, several types of bioplastics have the ability to decompose in soil or water, but they do not undergo degradation when exposed to air or sunlight. Certain bioplastics exhibit degradation within industrial composting facilities while remaining resistant to decomposition in household composting systems or natural surroundings [4].

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

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 have been 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 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 plastic's adverse effects on the natural world. More studies on bioplastic breakdown in various conditions are required to ensure their safe and effective use. The 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, when exposed to higher temperatures, polybutylene succinate (PBS) bioplastics biodegrade more rapidly in soil conditions [14]. In addition, studies show that biodegradation relies heavily on the existence and activity of specific microbial communities, with different communities demonstrating differing abilities 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 presents both difficulties and potential benefits in complex environments and other industrial facilities. Bioplastics are a mixture of identified and unidentified compounds, some of which can be toxic to animals and soil health. The study by Zimmermann et al. (2021) indicated that bioplastics contain a variety of unknown chemicals and showed 67% baseline toxicity, 42% oxidative stress, 32% cytotoxicity, and 23% antiandrogenicity in bioassays [17]. Bioplastics are a mixture of identified and unidentified compounds, some of which can be toxic to animals and soil health. Despite extensive research on plastic biodegradation, limited reviews discuss bioplastics' ecotoxicological impact on the soil and aquatic environment. This review will provide a comprehensive overview of the biodegradability of bioplastics in different environmental conditions and their ecotoxicological impact. The objectives of this review are as follows: (1) To assess 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. (2) What is the biodegradability of bioplastic compared to conventional plastics? (3) There is a need to assess the effects of bioplastics on the environment, ensure their long-term viability, and fostering the growth of environmentally friendly materials and practices cannot be overstated.

2. Synthesis of Bioplastics

Understanding the synthesis of bioplastics is essential before delving into their 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 the relevant 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 address 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 bioplastics 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].

Significant 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 (PHAs) raises concerns regarding the economic viability of up-scaling the bioplastic manufacturing and commercialization process. Hence, it is imperative to investigate alternative methodologies to fully unlock the microorganisms' inherent capabilities in synthesizing polyhydroxyalkanoates (PHAs) [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).

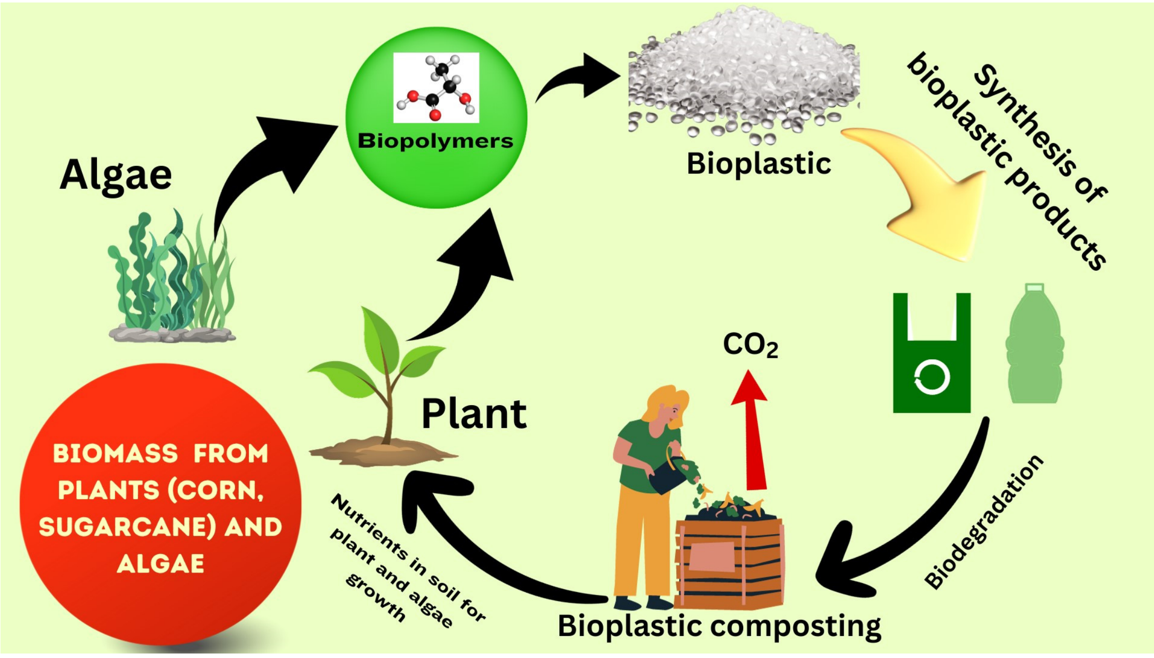

Figure 1. Bioproduction and biodegradation of bioplastic.

Presently, the majority of bioplastics are manufactured using feedstocks derived from agricultural crops, specifically sugars and plant components. However, these activities are not yet in perfect harmony with the United Nations' sustainable development goals (SDGs) because they compete for arable land, fresh water, and food production [25]. Table 1 indicates the production, biodegradation, and ecotoxicological impact of bioplastics. Theoretically, the manufacture of bioplastics using next-generation microalgae can potentially solve many of these problems by being situated on nonarable land. This technique enhances the worldwide photosynthetic capacity, presenting itself as a crucial technological intervention to counteract desertification. Furthermore, it amplifies our capability to transform CO_2 into raw materials for the production of bioplastics.

Microalgae systems have the ability to utilize saltwater and/or wastewater, allowing for the efficient recycling of nutrients such as nitrogen and phosphorus. This is performed within enclosed systems, which helps to reduce eutrophication and the need for energy-intensive chemical fertilizers. Unlike polymers derived from fossil fuels, microalgae-based bioplastics are specifically engineered for biodegradability in natural and industrial composting environments [26]. While biodegradable fossil-based polymers like polybutylene adipate terephthalate and polycaprolactone do exist, their synthesis from petrochemicals prevents them from becoming carbon dioxide (CO_2) neutral. On a global scale, microalgae systems have the capability to support decentralized production. On a local level, they have the potential to enhance self-sufficiency in regional communities and create substantial new market prospects (SDG, Decent Work and Economic Development). When deliberately designed, these systems can offer long-lasting solutions and substantially impact several UN Sustainable Development Goals (SDGs) [26].

Table 1. Bioplastic production source, cost, use, and toxicity.

Type of Bioplastic	Source	Use	Production Cost	Toxicity	Reference
Polyhydroxyalkanoate (PHA)	Wastewater, whey	Food packaging	1.40–11.80 USD/kg	Baseline toxicity	[17,27,28]
Polylactic acid (PLA)	Cassava starch	Bottles, cups, tea bags	2.71–2.82 USD/kg	Oxidative stress, baseline toxicity	[17,27,29]
Polybutylene succinate (PBS)	Food waste, fossil fuel	Food and cosmetics packaging	3.5–5.21 USD/Kg	Baseline toxicity	[17,27,30]
Polyhydroxybutyrate (PHB)	Methan	Medical purposes	4.1–6.8 USD/kg	Baseline toxicity	[17,27,31]
Cellulose-based	Cellulose	Thermoplastics	3558 USD/t	Baseline toxicity	[17,27,32]
Starch-based	Starch	Cell phone cases	1496 USD/t	Baseline toxicity Phytotoxicity	[17,27,33]
Biopolyethylene terephthalate Bio-PET	Bioethanol	Transparent packaging	Not given	Oxidative stress, baseline toxicity	[17,27]
Poly (butylene adipate-co-terephthalate (PBAT)	Polycondensation	Shopping bags	3.6 USD/Kg	Baseline toxicity	[17,27,34,35]
	of butanediol (BDO)				
	adipic acid (AA) and				
	terephthalic acid (PTA)				

3. Biodegradability of Bioplastic in Complex Environmental Conditions

Bioplastics are made to biodegrade in the environment with a specific range of conditions, including heat, humidity, and microorganisms (Table 2). 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 fast 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 [36].

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 corn flour. While PLA is compostable in industrial composting facilities, it does not readily biodegrade in natural situations [37].

Table 2. Factors affecting the biodegradation of bioplastics in environmental conditions.

Plastic Type	Biodegradation Environment	Factors Affecting the Rate of Biodegradation	Weight Loss	Time/Days	Reference
PLA	Freshwater	Temperature (25 °C)	<2%	365	[38]
PCL	Controlled	Aerobic, (30 °C), PH = 7	8%	28	[39]
PLA	Sea water	Temperature (25 °C)	<2%	365	[38]
PLA	Soil	30% moisture	10%	98	[40]
PLA	Sludge	Anaerobic, 37 °C	29–49%	277	[41]
PLA	Compost	58 °C	13%	60	[42]
Polyhydroxybutyrate (PHB)	Freshwater	Temperature (25 °C)	9%	365	[38]
PHB	Compost	55 °C, 70% humidity	80%	28	[43]
PHB	Sludge	Anaerobic, 37 °C	90%	9	[41]
PHB	Microbial culture from Soil	Aerobic	18%	18	[44]
Polyhydroxybutyrate (PHB)	Sea water	Temperature (21 °C)	99.00%	49	[45]
PHA	Soil	35% moisture	35.00%	60	[46]
PHA	Soil/compost (90/10%)	25 °C, 65% humidity	40–50%	15	[47]
PHBV	Soil	Natural conditions	8.00%	365	[48]
Starch-based bioplastic	AD	Anaerobic, 37 °C	26.40%	50	[49]
Starch-based bioplastic	Soil	Soil burial test	96.00%	28	[50]
Starch-based bioplastic	Compost	Aerobic, 58 °C	85.00%	90	[51]
Starch-based bioplastic	Aerobic	Aspergillus niger culture	20%	10	[52]
Cellulose-based	Compost	1 m depth—15.7 °C average outside temperature	100%	84	[53]
Cellulose-based	Synthetic soil containing compost	Aerobic, 58 °C	80%	154	[54]
PCL	Sludge	Anaerobic, 37 °C	3–22%	277	[41]
PCL	Compost	Aerobic, 50 °C, pH = 7–8.5	38%	6	[55]
PCL	Soil and leachate	28 °C, 60% humidity	22%	60	[56]
PBS	Compost	Aerobic, 58–65 °C, pH = 7–8, 50–55% moisture	90%	160	[57]
PBS	Landfill	Anaerobic, 25 °C	2%	100	[58]

Polyhydroxybutyrate (PHB), evaluated in seawater by Tanadchangsaeng and Pattanasupong (2022), exhibited a substantial 61.20% weight loss [59]. 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 [60].

Starch-based bioplastics, represented by studies such as Wicaksono et al.'s (2022) and Abe et al.'s (2021), displayed considerable degradability in compost soil and regular soil conditions, achieving weight losses of 74% and 69% over 120 days, respectively [61,62]. Moreover, a starch–polyhydroxyurethanes hybrid, investigated by Abe et al. (2021), demonstrated an 88% weight loss in soil during the same period [61].

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 [63]. This aligns with the findings of Karamanlioglu et al. (2017), who reported a 20% weight reduction in PLA over 20 months in soil [64]. Notably, controlled composting with bacterial treatment resulted in the complete degradation of PLA within 60 days, as indicated in Figure 2 [65].

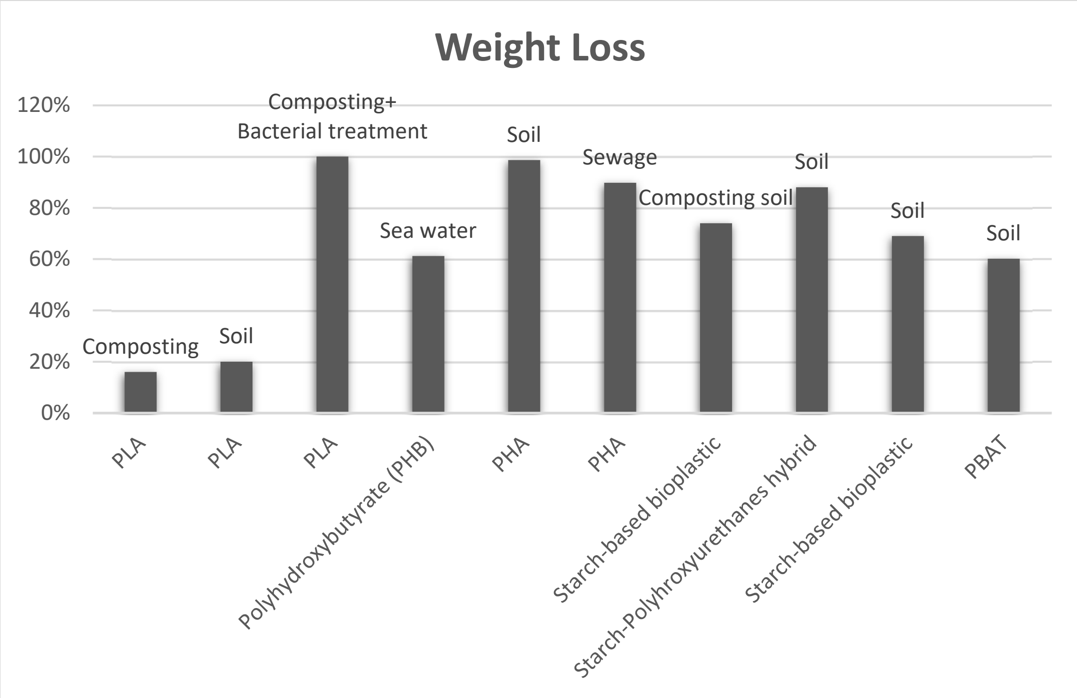

Figure 2. Biodegradability of bioplastics in different environmental conditions.

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 eco-friendly waste management techniques [66].

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 [37].

3.1. 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 biodegradation rates in regions characterized by elevated temperatures and abundant food availability [67].

According to recent research, marine microorganisms do not play a significant role in the degradation process of petrochemical-based plastics [68]. However, they can discharge dissolved organic carbon (DOC), potentially augmenting the bacterial activity inside marine ecosystems. The ongoing argument revolves around the differentiation of plastisphere communities with different polymers 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 [68].

In contrast, disparities exist in bacterial community makeup and activity between bioplastic 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 [62,69].

These investigations have yielded significant insights into the behavior of bioplastics and their potential degradation in marine ecosystems. Nevertheless, there is an absence of research which 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 important to conduct extended research to 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].

3.2. Bioplastic Biodegradation Soil

Biodegradation largely depends on soil and other terrestrial components. Soil temperature, moisture, and microbial composition can vary greatly across different regions. The soil harbors a diverse array of microorganisms that influence the biodegradation processes in this environment [70].

The biodegradation process may be impacted by the variety of microorganisms found in the soil. When native bacteria compete with bioplastics for nutrients, the degradation process of bioplastics in the soil may slow down. Variations in temperature and humidity are just two examples of the many environmental conditions that may affect biodegradation rates [70].

Numerous different environmental conditions may have an impact on the biodegradation process in the 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 affects the overall biodegradation rate [71].

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. However, high levels of petroleum hydrocarbons or heavy metals in the soil can reduce bacterial biomass and affect microbial diversity. 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 [72].

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 [73].

Conversely, several categories of bioplastics, such as PLA, exhibit a prolonged persistence in the 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 [74].

The speeds at which bioplastics degrade directly correlate with the quantity of bacterial biomass in the soil [75]. 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 [74].

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 the soil for two years. The presence of polyamide 66 (PA66) in the soil can impede aeration, affecting the optimal functioning of microorganisms [74].

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 [76].

3.3. Anaerobic Biodegradation of Bioplastic

Most bioplastics 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. Meanwhile, 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 [77].

The 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 [78]. 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 [79]. Ebrahimzade et al. (2022) studied the kinetics of methane production during the anaerobic digestion of starch-based bioplastics and used non-linear regressions and artificial neural networks to model the process [80]. 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 [81]. Another study by Ebrahimzade et al. (2021) focused on optimizing particle size and inoculum-to-substrate ratio for the anaerobic degradation of bioplastics, finding that the inoculum-to-substrate ratio had a more significant effect on biomethane yield [82].

PLA bioplastic has been studied for its anaerobic biodegradability. Studies have shown that PLA bioplastic is hardly anaerobically biodegradable at mesophilic temperatures [83]. The degree of biodegradation does not correlate with the molar composition of PLA/PBAT blends [84]. However, anaerobic biodegradation occurs mainly in the PLA fraction [46]. The biodegradation of PLA does not occur under mesophilic conditions, and pre-treatment of the polymers is recommended [81]. The biodegradability of PLA bioplastic was less than 50% after 35 days of anaerobic digestion, suggesting that complete degradation was not achieved [85].

The 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 [86]. Another study compared the biodegradation of various bioplastics under aerobic and anaerobic conditions, and PHB and PHBV were found to be biodegraded anaerobically [79]. 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 promising for co-digestion in anaerobic biogas plants [81]

The 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 [78,86]. 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 [79]. The biodegradation of PHB was also affected by factors such as particle size, with smaller particles showing higher biodegradation [78]. The study of anaerobic biodegradation of PHB is important for developing and testing biodegradable materials in the context of a circular bioeconomy [87]. 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 [81]. Another study compared the anaerobic biodegradability of different bioplastics and found that PCL had a low biodegradation rate of 3% in 277 days [79]. 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 [88]. Overall, the anaerobic biodegradation of PCL bioplastic is limited, and further research is needed to improve its biodegradability.

3.4. 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 [89]. 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 [90]. Certain gene sequences associated with the biodegradation of specific bioplastics, such as PLA, have been pinpointed, including *Paecilomyces*, *Thermomonospora*, and *Thermopolyspora* [91].

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 emphasized the intricate nature of bioplastic biodegradation in composting processes and significance of factors and microorganisms in effective organic waste management and reducing bioplastics waste [92].

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 [93]. 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 establish 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].

3.5. Bioplastic-Degrading Microbial Community in Different Environmental Conditions

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 [94]. 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 toward 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 [95].

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 [96].

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 [97].

Firmicutes, *Proteobacteria*, *Ascomycetes*, and *Basidiomycetes* are only some of the many microbial taxa capable of degrading bioplastics [98]. 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 growth conditions 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 generally do 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 [99]. Therefore, the breakdown of bioplastics can supply organisms with carbon. Many researchers use plastic as the only carbon source to enrich bioplastic-degrading microbes.

3.6. Biodegradation of Conventional Plastic and Bioplastic via Microbes

As the most common microbes, bacteria are essential for transforming contaminants in soil, water, and the atmosphere. Recent studies have examined how microorganisms break down plastics and microplastics [100]. Environmental factors contribute to the fragmentation of big plastic waste into micro- and nanoplastic particles, even if the precise role of microorganisms in natural plastic breakdown remains unknown [101]. In Table 3, laboratory microorganisms have been shown to depolymerize man-made polymers, such as those in plastics [102].

3.6.1. Biodegradation of Conventional Plastics by Microorganisms

Scientists, plastic end users, and politicians have differing views about the viability of microbial biotechnology as a sustainable approach to disposing of plastic waste because the microbial breakdown of petroleum-based polymers, like PE and PS, may differ from that of biodegradable polyesters, like polylactic acids [103].

Numerous bacteria capable of digesting plastics have been discovered recently. For example, Skariyachan et al. (2021) found that a mixture of new *Enterobacter* and *Pseudomonas* spp. from cow dung accelerated the degradation of polyethylene and polypropylene. After 160 days in the laboratory, low-density polyethylene (LDPE) had lost 64% of its weight [104]. *Bacillus siamensis*, *B. cereus*, and *B. wiedmannii* are among the plastic-degrading bacteria that Maroof et al. (2021) isolated from waste disposal site soils. The percentage of LDPE weight that the bacteria could lower ranged from 5.39% to 8.46% [105].

A popular material for making plastic is low-density polyethylene or LDPE. This study details the results of a weight reduction test that investigated the degradation capabilities of 23 *Rhodococcus* isolates from Malaysia. The test material was low-density polyethylene (LDPE). The experiment involved the use of shake flask incubation. Despite varying degradation rates, all of the isolates demonstrated the capacity to break down the LDPE added to the culture media. With an 8.69% loss in LDPE weight, RhodococcusUCC0018 showed the highest degradation rate among the 23 isolates [106].

It was observed that microorganisms can alter the composition, functional units, and additional attributes of polymers. For instance, when *Alcaligens faecalis* was grown on polyethylene, the FTIR carbonyl group was removed, according to Nag et al. (2021) [107]. The incubation of *Streptomyces* sp. reduced polyethylene terephthalate's molecular weight and tensile characteristics [108]. Similarly, *Lysinibacillus fusiformis* was shown by Shahnawaz et al. (2016) to break down polyethylene, with a maximum degradation rate of 21.87% [109].

Insect gut microorganisms have also been linked to the degradation of plastic. In an environment containing polyethylene, *Galleria mellonella* larvae that harbored bacteria such as *Bacillus aryabhatai*, *Microbacterium oxydans*, and *Lysinibacillus fusiformis* demonstrated the capacity to affect the generation of cell mass and the weight loss of LDPE. Remarkably, a combination of bacteria outperformed a single species of bacteria in the breakdown of LDPE [110].

Patil discovered four bacteria—*Bacillus amylolyticus*, *Bacillus subtilis*, *Pseudomonas putida*, and *Pseudomonas fluorescens*—isolated from soil that could break down polyethylene plastic [111]. These bacteria were grown in a broth containing polyethylene film for a month. According to the study, *B. subtilis*, *P. putida*, *B. amylolyticus*, and *P. fluorescens* all decreased the weight of the polyethylene film by 14%, 22%, 18%, and 32%, respectively. The FTIR analysis demonstrated the fast breakdown of carbon chains through wave absorption. These bacteria use polythene polymers as a carbon source [112]. Furthermore, it was discovered that *Pseudomonas stutzeri* and *Pseudomonas aeruginosa* also degraded polyethylene [113]. *Pseudomonas* spp. possess induced operons that produce lipase, esterase, and serine hydrolase, among other enzymes required to metabolize non-traditional carbon sources [114]. Moreover, it was discovered that *Staphylococcus. aureus*, *B. subtilis*, and *Streptococcus pyogenes* degraded both polyethylene terephthalate (PET) and polystyrene (PS). PET material has also been observed to be degraded by *Ideonella sakaiensis* [115,116].

After a month of incubation, Jamil et al. observed that LDPE plastic films were damaged by *Serratia* sp. *KCI-MRL*, *Bacillus licheniformis KC2-MRL*, *Bacillus KC3-MRL*, and *Stenotrophomonas KC4-MRL* from Kashmir Smast, Pakistan [117]. *Alcanivorax borkumensis* demonstrated its ability to degrade LDPE by forming substantial biofilms on LDPE waste [118].

It was also discovered that actinomycetes contribute to the degradation of plastic trash. Actinomycetes that break down LDPE, such as *Streptomyces coelicoflavus NBRC 15399T* [119], *SSP2*, *SSP4*, and *SSP14*, may aid in the breakdown of plastic waste by generating bioemulsifiers. According to this study, microorganisms engaged in the degradation of plastic polymers produce biosurfactants [120]. It has been demonstrated that actinomycetes' metabolites aid in the breakdown of polymers [121]. *Ochrobacterum anthropi* may eat HDPE, which led to a 20% decrease in HDPE film after 45 days [122]. It was shown that *Bacillus cereus* and *Sporosarcina globispora* were PP degraders; however, *B. cereus* broke plastic down faster than *S. globispora*, using 0.003 g of plastic each day [123].

3.6.2. Biodegradation of Bioplastic by Microorganisms

Many types of bacteria and fungi can break down bioplastics. Numerous strains can biodegrade different types of bioplastics, including *Bacillus pumilus A-1* [124], *Paenibacillus amyloyticus TB-13* [125], and *Actinomadura* sp. *TF1*, *Streptomyces* sp. *APL3*, *Laceyella* sp. *TP4* [126], and *Aspergillus fumigatus NKCM1706* (I). Different microorganisms and environmental circumstances cause diverse breakdown processes in different types of bioplastics. Studies reveal that bioplastics derived from petroleum, like PLA, degrade in a manner similar to that of conventional polymers. Research indicates that microorganisms such as *Pseudomonas* and *Bacillus MKY1* and *MKY2* are involved in PLA degradation [127]. It has been discovered that *Streptomyces lydicus MM10* can degrade plastic by producing PHB depolymerase, which specifically targets the PHB polymer [128]. Furthermore, it is known that Bacillus and Azotobacter contribute to the breakdown of PHB [129]. Relevant bacteria for PCL degradation have been identified as Psychrobacter, Shewanella, Moritella, and Pseudomonas [130]. It is important to remember that, in some situations, bacteria can build up poly-hydroxybutyrate (PHB) in their cells and use PHB depolymerase to help break it down.

Polyhydroxybutyrate (PHB) is remarkably biodegradable, achieving a substantial 98% weight loss within a brief 14-day period when subjected to *Bacillus* sp. JY14 [131]. 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% of weight loss, respectively, by *Sclerotinia* sp. B11IV, *Sclerotinia* sp. B11IV, and *Fusarium* sp. B3′M, respectively [132]. Notably, the blend of Polylactic Acid/Polybutylene Adipate-co-Terephthalate (PLA/PBAT) displayed lower biodegradability, with only 12.94% and 9.27% of weight loss when exposed to *Pseudomonas mendocina* and *Arthrobacter elegans*, respectively, over five days [133].

The biodegradation of bioplastic by microbes is affected by different environmental factors such as temperature, PH, oxygen availability, and polymer size and structure. Three fungal strains (*Fusarium* sp. B30 M, *Geomyces* sp. B10I, and *Sclerodinia* sp. B11IV) were assessed for biodegradability at 4, 20, and 28 °C in a different investigation. Following four weeks of incubation, the strains of *Fusarium* sp. B30 M and *Sclerotinia* sp. B11IV biodegraded most efficiently at 20 °C, with 45.99% and 49.65% biodegradability rates, respectively, and 49.68% (PBSA) and 33.7% (PCL). At 20 °C, PCL and PBSA were biodegraded by *Geomyces* sp. B10I at 11.34% and 4.46%, respectively, while at 14 °C, the degradation rates were 25.67% and 5.71%. At 28 °C, biodegradation was the least effective. These results suggest that 14–20 °C is the ideal biodegradation temperature for *Geomyces* sp. B10I [133].

Table 3. Biodegradation of bioplastic and conventional plastic by microbes.

	Plastic Type	Microorganism	Weight Loss	Time/Days	Reference
	Polyhydroxybutyrate (PHB)	*Bacillus* sp. JY14	98%	14	[134]
	Polybutylene succinate (PBS)	*Terribacillus* sp. JY49	31.40%	10	[135]
	Poly(butylene succinate-co-butylene adipate) (PBSA)	*Sclerotinia* sp. B11IV	49.68%	28	[132]
	Poly(ε-caprolactone) (PCL)	*Sclerotinia* sp. B11IV	33.70%	28	[132]
Bioplastics	Poly(butylene succinate-co-butylene adipate) (PBSA)	*Fusarium* sp. B3′M	45.99%	28	[132]
	Poly(ε-caprolactone) (PCL)	*Fusarium* sp. B3′M	49.65%	28	[132]
	Poly(butylene adipate-*co*-terephthalate) (PBAT)	*Bacillus* sp. JY35	50%	21	[131]
	Polylactic acid/polybutylene adipate-*co*-terephthalate (PLA/PBAT)	*Pseudomonas mendocina*	12.94%	5	[133]
	Polylactic acid/polybutylene adipate-*co*-terephthalate (PLA/PBAT)	*A. elegans*	9.27%	5	[133]
	Low-density polyethylene (LDPE)	*Enterobacter and Pseudomonas* spp.	64%	160	[104]
	Polyethylene terephthalate (PET)	*Streptomyces* sp.	68.80%	18	[107]
	Low-density polyethylene (LDPE)	*Acinetobacter pitti*	26.80%	28	[110]
Conventional plastics	Low-density polyethylene (LDPE)	*Bacillus siamensis*	8.46%	90	[105]
	LDPE	*Bacillus amylolyticus*	32%	30	[110]
	Polyethylene	*Pseudomonas*	51.50%	90	[111]
	Low-density polyethylene (LDPE)	*Streptomyces coelicoflavus*	30%	28	[118]
		Enterobacter sp.			
	Polypropylene	*Enterobacter cloacae*	63%	160	[104]
		and Pseudomonas aeruginosa			
	Polyethylene	*Pseudomonas aeruginosa* SH6B	25%	120	[93]
	Low-density polyethylene (LDPE)	*Rhodococcus* UCC0018	8.69%	120	[106]

3.6.3. Mechanism of Biodegradation of Plastics by Microorganisms

Bioplastics and conventional plastics follow the exact mechanism of biodegradation by microbes. Numerous microbes can break down plastic polymers, with some generating both intracellular and extracellular enzymes responsible for degrading these polymers into harmless fragments [136]. Using microbial cells to break down plastic C-C linkages exhibits superior efficacy. The enzymatic breakdown of plastic waste encompasses biodeterioration, depolymerization, and absorption. Biodeterioration involves the degradation of polymers by microbes and abiotic forces, with the persisting depolymerization process. Microbes form biofilms on plastic surfaces, constituting living communities that gradually release enzymes and free radicals to dismantle polymer chains. Specific microbes on plastic surfaces biodegrade polymers through chemical, physical, and mechanical changes [137]. The acceleration of this process is facilitated by microorganism-formed biofilms on plastic. These biofilms are established on surfaces through the extracellular substance of microbes (Figure 3), forming a polymer matrix comprising polysaccharides and proteins that bind microbial cells together in biofilms [138].

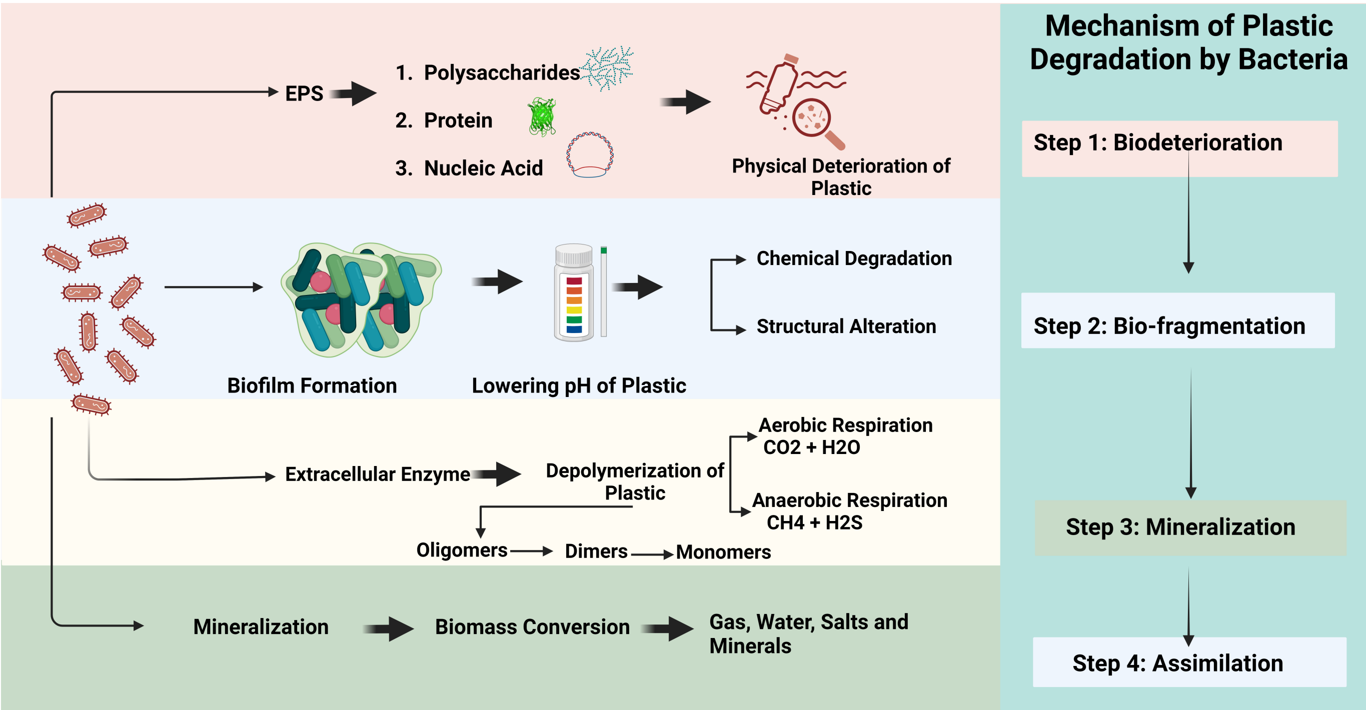

Figure 3. Metabolic pathways used by microorganisms to degrade plastics.

Microorganisms employ extracellular polymeric substances (EPSs), composed of polysaccharides, proteins, and nucleic acids, to degrade plastic. As the EPS penetrates, holes on plastic surfaces increase, promoting the degradation process. Microbes and bacteria collaborate to degrade plastic polymers, creating holes and inducing physical deterioration [139]. Biofilms on plastic surfaces stimulate the production of acid compounds, leading to changes in plastic polymer pH and subsequently causing chemical degradation and structural alterations (Figure 3). Nitrous, nitric, sulfuric, citric, fumaric, gluconic, glutaric, glyoxylic, oxalic, and oxaloacetic acids are produced during this process [140].

Bacterial metabolites and extracellular enzymes contribute to the degradation of plastic surfaces. Depolymerase enzymes initiate the depolymerization of plastic, resulting in simpler oligomers, dimers, and monomers than polymers. The presence of oxygen molecules determines the metabolic processing of these components. Aerobic breakdown produces microbial biomass, CO_2, and H_2O, while anaerobic breakdown yields microbial biomass, CO_2, H_2O, and CH_4 or H_2S [141]. The breakdown of plastic waste involves the secretion of extracellular and intracellular depolymerase enzymes by microbes. These enzymes break down complex polymers into simpler strands, allowing decomposed molecules to be easily dissolved in water and absorbed by microbial semipermeable cell membranes for carbon and energy. The assimilation in microbial cytoplasms produces energy, biomass, food reserves, and primary and secondary metabolites. Monomers resulting from the degradation of plastic pieces enter cells, wherein the microbial cell metabolism system breaks down these components to provide energy and biomass. While monomers may not be fully absorbed, they exit cells and are utilized by bacteria through a monomer assimilation route [142].

The biodegradation process advances to mineralization, representing the final metabolic step for hazardous chemicals in plastic waste. Mineralization transforms biogenic materials or biomass into gases, water, salt, minerals, and other residual substances. The emitted gases include carbon dioxide, methane, and nitrogen. Mineralization concludes when bacteria consume all biodegradable chemicals, converting all carbons into carbon dioxide [143].

Enzymes from microbes break down biodegradable polymers. PHA has a breakdown enzyme, unlike chemically synthesized biodegradable polymers. Lipases use fat, whereas cutinases employ polyester cutin (found in plant cuticular layers) to hydrolyze synthetic biodegradable polymers [144]. Lipases and esterases break polyester ester, carbonate, amide, and glycosidic bonds. Warmer (15–37 °C) and alkaline environments accelerate PHA and PLA decomposition—non-degradable carbon-only non-polyesters. PE, PC, PP, PS, and their carbon-based derivatives are difficult for microorganisms to split and destroy enzymatically. Biotic or enzyme-catalyzed polymer breakdown is more efficient. After biotic or abiotic breakdown, bacteria can bio-assimilate polymers for growth and respiration [145].

4. 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 delicate balance between these benefits and drawbacks. The objectives of sustainability and low environmental effects are upheld in the regulated settings of industrial composting, where biodegradable bioplastics can degrade. These structures create an optimal environment for the biodegrading bacteria, leading to the rapid breakdown of bioplastics (Figure 4). The process often yields eco-friendly byproducts, including water, carbon dioxide, and biomass [76].

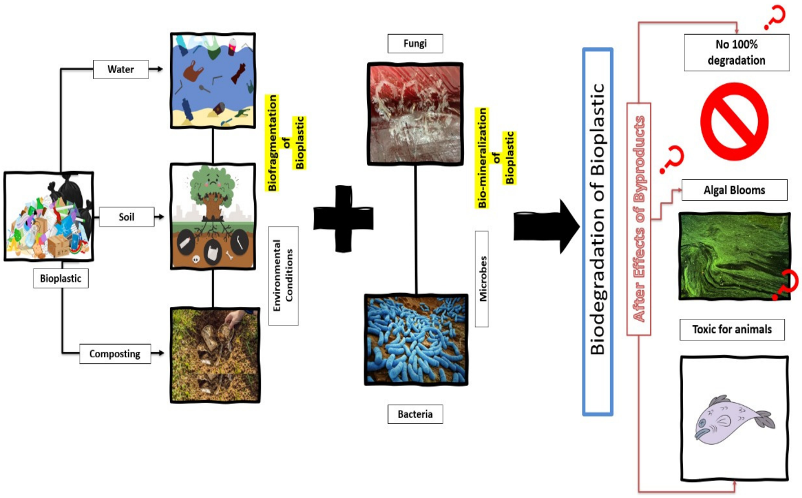

Figure 4. The fate of bioplastic in the environment.

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 [37].

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 corn flour. 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 [37].

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 [74,75]. Understanding these interactions is crucial to evaluating the influence of indigenous microorganisms and their roles in ecological processes. Due to 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, controlling biodegradation in complex ecosystems is vital to balance the advantages and potential dangers [146].

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 bio-degraders. Ecosystem services may be negatively impacted if the delicate balance of microorganism populations is upset. Bioplastic degradation results in byproducts and 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 [147]. 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.

4.1. Bioplastics Contain a Complex Mixture of Chemicals

Plastics contain a complex mixture of known and unknown substances, some of which may be harmful. Starch and cellulose-based bioplastics are advertised as environmentally friendly plastic alternatives, but their safety and chemical makeup remain unknown. To resolve this issue, 43 common bio-based and biodegradable goods, including food-contact materials and their antecedents, were identified. High-resolution mass spectrometry and in vitro bioassays characterized the extracts [148].

The study found that 67% of the samples caused baseline toxicity, 42% oxidative stress, and 23% antiandrogenicity. A total of 41,395 chemical properties were discovered, with wide sample variation. Over 80% of the extracts included 1000 character traits, mainly unique to each sample. We provisionally identified 343 priority compounds, including lubricants, additives, oligomers, monomers, and unwanted substances [148].

Cellulose and starch materials were poisonous and had many chemical properties in vitro. Different bio-based materials had different chemical and toxicological signatures, impacted more by the product than the ingredient. Compared to final products, raw components were less hazardous. Bioplastics and plant-based products are as hazardous as conventional plastics [148].

An independent study used high-resolution mass spectrometry and in vitro bioassays to evaluate eight major polymers in consumer plastics. Baseline toxicity (62%), oxidative stress (41%), cytotoxicity (32%), estrogenicity (12%), and antiandrogenicity (27%) were found in 74% of the 34 plastic sample extracts [17,27].

Bio-based ethylene bioplastics like PET and HDPE had little to no in vitro effects, whereas bio-based plastics like PVC and PUR were the most hazardous across most endpoints. Due to their hazardous classification and need for additional additives, PVC and PUR have higher harmful chemical concentrations and cause acute toxicity in the marine *Nitocra spinipes* [149], freshwater *Daphnia magna* [150], and the barnacle *Amphibalanus amphitrite* [151]. Although touted as superior, all PLA products have baseline toxicity comparable to PVC and PUR [152]. This contradicts the idea that bioplastics are biodegradable and safer [153].

4.2. Bioplastic Toxicity for the Aquatic Environment

Bioplastics may leach into the environment, and weathering and UV degradation will increase chemical leakage after disposal [154]. Leakage from plastic materials can harm ecosystems, wildlife, and humans. Hence, their safety must be considered. Plastics often wind up in the water and poison marine life due to some toxins. When wastewater and landfill runoff carry phthalates from starch and cellulose bioplastics into marine habitats, they harm sea urchin larvae and bioluminescent bacteria [27,148]. Bio-polyethylene bottles, grocery bags, and cups are made from sustainable biomass-based polylactide (PLA). PLA comprises Bisphenol A (chemical emergence concerns (CECs)) and induced dose-dependent malformed mussel larvae [155].

In PE, PLA, and PBS microplastic toxicity testing, hatching Artemia cysts decreased slightly after 24 h. After 48 h, PE and PLA polymers drastically reduced hatching, but PBS had no effect. Thus, polymers vary in cyst toxicity [156]. Biodegradable and bio-based products are not innately safer than standard plastics since PLA showed considerable baseline toxicity despite marketing claims [157]. Different plastic treatment dosages increase Artemia mortality by generating oxidative stress and neurotoxicity [158].

A study on PLA's toxicological effects on tadpoles indicated that PLA BioMP dosages affected growth and development after 14 days. This exposure altered REDOX homeostasis, causing oxidative stress and nutritional deficits, primarily lipid reserves. This was the first report of PLA BioMP toxicity in tadpoles, predicting neurotoxicity changes. These data support bio-microplastic pollution reduction recommendations and encourage future research in this understudied field [159].

4.3. Bioplastic Toxicity for the Soil

Bioplastics include biodegradable and biomass-based polymers. Bioplastics made from renewable biomass may last long, making this classification misleading. Bioplastics degrade depending on their chemical makeup and environment. Long-term field-scale study is recommended to better understand soil physiochemistry and function after plastic loading because mesocosm studies may overestimate soil responses. Old oil-based polymers used in agriculture are being replaced because microplastic pollution threatens the agroecosystem. Alternative biodegradable replacements with rapid breakdown are being considered. However, little is known about how bioplastics influence plants and soil [160].

As seasonal, climatic, and biogeographical factors influenced bioplastic stability in the soil, laboratory and field investigations showed consistent variations. Multiple studies have demonstrated that microplastic concentrations above 1% w/w are considerably affected.

Bioplastic residues dramatically affected the soil C/N ratio, affecting microbial diversity and favoring certain species: this altered soil structure and aggregate formation. Higher bioplastic concentrations harmed plant health and germination. Long-term field experiments are needed to fully understand bioplastic residue's effects on soil properties like physico-chemical and mechanical properties, soil biology, soil–bioplastic–plant response, nutrients, and toxicity. Micro- and nano-bioplastic mobility and transportation in the soil have been poorly studied [161].

Old oil-based polymers used in agriculture are being replaced because microplastic pollution threatens the agroecosystem. Alternative biodegradable replacements with rapid breakdown are being considered. However, little is known about how bioplastics influence plants and soil. Bio-based microplastic poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) soil loading (0.01%, 0.1%, 1%, and 10%) affected soil and Zea mays plant health. The results demonstrate that PHBV decreases plant growth and foliar nitrogen dose-dependently. Metabolite testing showed significant changes in foliar metabolic activity, and PHBV reduced soil nitrate and ammonium availability [71]. According to soil 14C-isotope tracing and 16S metabarcoding, PHBV reduced bacterial diversity, microbial community organization, and activity, altering soil metabolism and function. PHBV is environmentally harmful at 0.01% contamination, according to studies. It temporarily altered plant and soil microbial functioning, affecting agroecosystem health [71].

Bioplastics are replacing plastic mulch films in agricultural soils to reduce plastic accumulation. However, this alteration may harm soil, plants, and agroecosystem functions. Bioplastics provide the soil's biological inhabitants with carbon since they break down faster than ordinary plastics. This alters microplastic formation and persistence but may not eliminate its hazard in the soil system [162].

This emphasizes how important it is to put chemical safety first when designing proper substitutes for conventional plastics and how important it is to concentrate on complex design in order to create a truly superior substitute. Nanoplastic absorption and movement produce long-term soil system issues, although conventional plastics may not. However, bioplastics' rapid breakdown can make additives more accessible and have long-lasting effects; they may make up a large portion of their mass. This acceleration of micro-bioplastic synthesis may harm soil and plants, and carbon may prime soil organic matter. The long-term effects of bioplastics on soil must be studied immediately in various soil and crop types [162,163].

5. Conclusions

In conclusion, as bioplastics (BPs) are considered safe and biodegradable, studies are assessing them as a potential solution to the accumulation of plastic waste. In the long run, whether BPs can manage global plastic pollution and waste disposal effectively remains unclear because they depend on particular environmental conditions for their biodegradation, which are not always available in the environment. Therefore, BPs have certain limits to being considered alternatives to conventional plastics. Moreover, bioplastics may contain unidentified materials hazardous to aquatic life and soil health. White pollution is caused by plastic waste, which is a severe environmental issue. Large plastics harm the environment and people less than accumulated waste plastics, which can break down into micro- and nanoplastics. Shifts in human behavioral awareness also impact the creation and use of BPs. Since the development of efficient technology does not alter littering behavior, BPs should not be viewed as a technical justification for disregarding environmental responsibilities.

Unlike petroleum-based plastics, bioplastic polymers have not yet been sufficiently studied or adapted to determine their potential for use in present and future applications. With so many alternatives for developing bioplastics, there is an excellent chance that their application range will be expanded to a level as large as that of thermoplastics derived from fossil fuels and beyond. Researchers and the bioplastics business should collaborate to find the safest and most sustainable plastic substitutes rather than just swapping out one dangerous material with another. There may be less demand for landfills and ocean plastic waste management if bioplastic with low carbon footprints is developed and prioritized for production. Future developments in related and emerging fields can be anticipated as our understanding and ability to manipulate biopolymers expands. Developing high-performance plastics free from resource depletion, pollution, and resistance, along with the transition to low-carbon, regenerative circularity, holds great promise for preserving and advancing the planet's and its people's future well-being.

Author Contributions: Conceptualization, S.A.; Writing and image creation—original draft preparation, S.A. and I.; Writing—review and editing, S.A. and Y.-C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article or can be obtained upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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