Ecotoxicological Impact of Bioplastics Biodegradation

Subjects: Environmental Sciences

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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.

biodegradation bioplastic

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.

2. 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 1**). The process often yields eco-friendly byproducts, including water, carbon dioxide, and biomass [18].

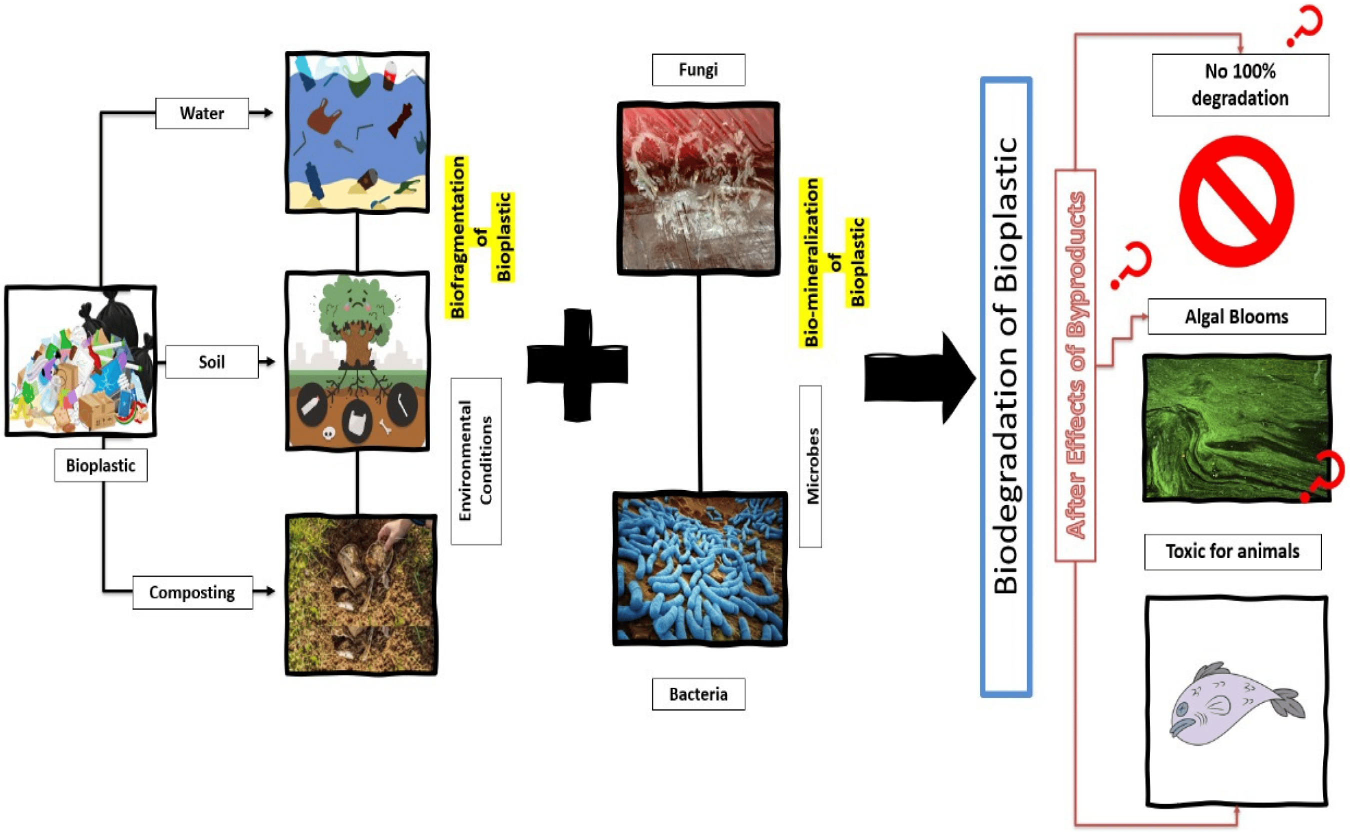

Figure 1. The fate of bioplastic in the environment.

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 [19].

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 [19].

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 2**). 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 [20][21]. 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 [22].

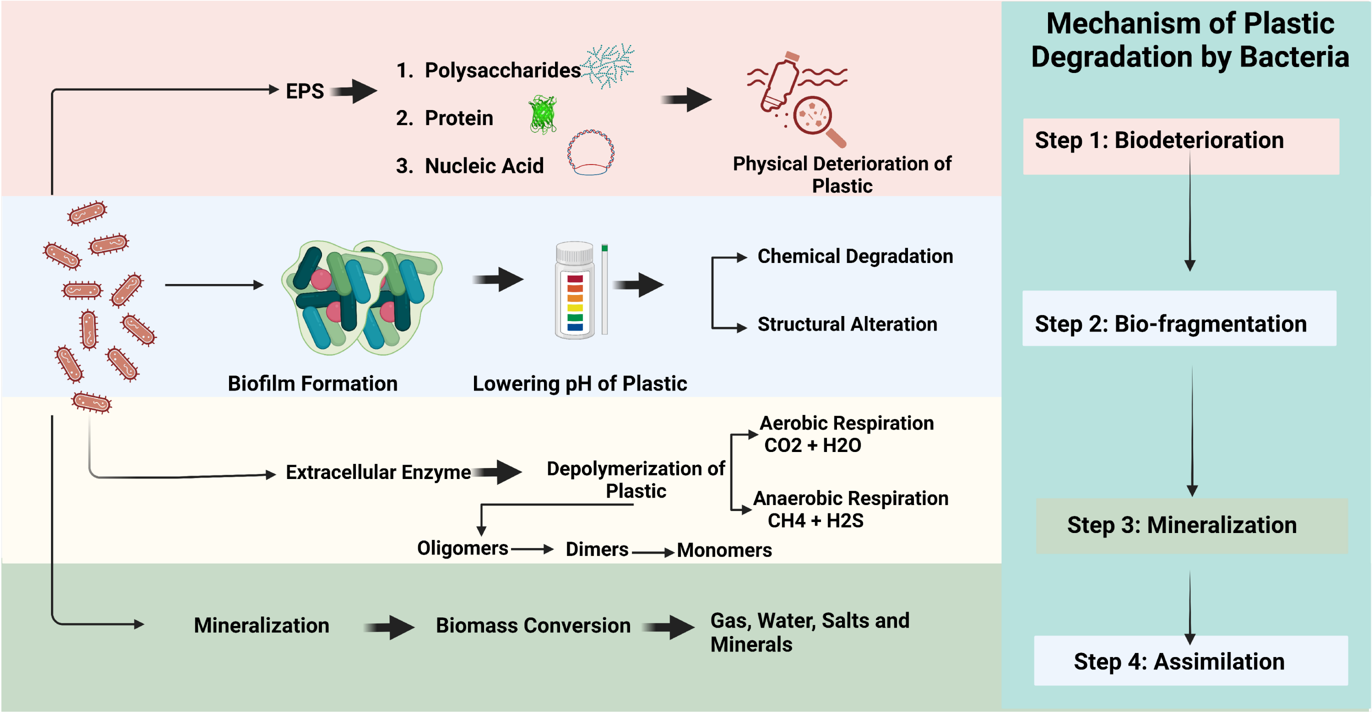

Figure 2. Metabolic pathways used by microorganisms to degrade plastics.

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 [23]. 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.

2.1. 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 [24].

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.

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 [24].

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][25].

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* [26], freshwater *Daphnia magna* [27], and the barnacle *Amphibalanus amphitrite* [28]. Although touted as superior, all PLA products have baseline toxicity comparable to PVC and PUR [29]. This contradicts the idea that bioplastics are biodegradable and safer [30].

2.2. Bioplastic Toxicity for the Aquatic Environment

Bioplastics may leach into the environment, and weathering and UV degradation will increase chemical leakage after disposal [31]. 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 [24][25]. 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 [32].

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 [33]. Biodegradable and bio-based products are not innately safer than standard plastics since PLA showed considerable baseline toxicity despite marketing claims [34]. Different plastic treatment dosages increase Artemia mortality by generating oxidative stress and neurotoxicity [35].

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 [36].

2.3. 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 [37].

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 [38].

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 [39]. 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 [39].

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 [40].

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 [40][41].

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