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Review

Biodegradation of Different Types of Bioplastics through Composting—A Recent Trend in Green Recycling

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Abstract: In recent years, the adoption of sustainable alternatives has become a powerful tool for replacing petroleum-based polymers. As a biodegradable alternative to petroleum-derived plastics, bioplastics are becoming more and more prevalent and have the potential to make a significant contribution to reducing plastic pollution in the environment. Meanwhile, their biodegradation is highly dependent on their environment. The leakage of bioplastics into the environment and their long degradation time frame during waste management processes are becoming major concerns that need further investigation. This review highlights the extent and rate of the biodegradation of bioplastic in composting, soil, and aquatic environments, and examines the biological and environmental factors involved in the process. Furthermore, the review highlights the need for further research on the long-term fate of bioplastics in natural and industrial environments. The roles played by enzymes as biocatalysts and metal compounds as catalysts through composting can help to achieve a sustainable approach to the biodegradation of biopolymers. The knowledge gained in this study will also contribute to the development of policies and assessments for bioplastic waste, as well as provide direction for future bioplastics research and development.

Keywords: biopolymers; aerobic composting; sustainability; depolymerization; enzymes

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1. Introduction

Single-use plastic consumption has been increasing for years due to its durability, light weight, and low cost [1]. The use of plastic has led to many technological advances, including high strength-to-weight ratio construction, automotive materials, and highly resistant packaging materials for food [2]. Approximately 9.2 billion tons of plastic have been produced worldwide, and the annual global production of plastic increased to 368 million tons in 2019 [3,4]. As estimated, the annual production of plastic waste is 34 million tons, and 93% of it is disposed of in landfills and oceans [5]. In 2015, 322 million tons of petroleum-based plastic were produced globally, compared with 1.7 million tons in 1950 [6]. Synthetic petroleum-based plastic leads to an increase in plastic waste, which contributes to adverse effects on the environment, such as ozone depletion, eco-toxicity, the release of carcinogens, global warming, and eutrophication [7]. Approximately 2.8 kg of CO_2 is released into the environment when 1 kg of plastic is burned [8]. Bioplastics emerged in response to environmental concerns about non-biodegradable plastics.

In the circular economy, bioplastics are expected to play an important role in achieving sustainable development goals, such as avoiding fossil fuels, introducing new degradation or recycling approaches, and reducing toxic chemicals during the manufacturing process. Biodegradable plastics derived from renewable biomass have become increasingly popular and bioplastics are currently produced on a scale of 4 million tons annually [9]. Globally, bioplastic production is expected to increase from 2.11 million tons in 2019 to 2.42 million tons by 2024. A major market for bioplastics is the packaging industry, which accounts for nearly 40% of global production [10]. Although many reviews discuss bioplastics, few address the positive and negative impacts of bioplastics on the environment comprehensively and simultaneously [11]. Nonetheless, not all polymers that are derived from bio-based sources are biodegradable, and not all polymers that are derived from fossil sources are non-biodegradable [12]. In nature, bioplastics are primarily composed of renewable resources, such as cellulose, starch, sugar, etc. [13]. In fact, biodegradation rates differ among bioplastics, and biopolymer properties depend on external environmental factors, intrinsic biopolymer properties, and filler properties in blends and composites [14]. In addition to their original source, production processes also have a great deal to do with degradation [15]. Moreover, many reports show that bioplastic composites and films degrade slowly in normal water and soil environments [16]. Due to this, there are concerns about their disposal in landfills and in soils at the end of their useful lives. Thus, composting bioplastics becomes an important tool for their effective environmental management at end-of-life.

Composting is considered more environmentally friendly and cost-effective than recycling or incineration. Specific microorganisms, such as Pseudomonaceae, Comamonadaceae, Erythrobacteraceae, Streptomycetaceae, Caulobacteraceae families, and Enterobacteriaceae, and enzymes, such as N-acetyl-β-glucosaminidase, esterase, β-glucosidase, acid phosphatase, alkaline, and phosphohydrolase, are involved in the degradation and microbial decomposition of bioplastics [17,18]. Specifically, enzymatic decomposition has been regarded as a means of minimizing environmental pollution. Microbiological degradation of bioplastics, particularly microbial enzymatic catalysis, has drawn attention as a means of reducing the amount of pollution in the environment.

The process of composting involves decomposing organic matter and turning it into humus, which can be used to strengthen soil structure and its fertility rate [19,20]. Bioplastic waste is typically disposed of in landfills, followed by recycling, incineration, and composting [16,21]. In contrast, landfilling produces greenhouse gases and creates environmental concerns. Landfilling not only produces greenhouse gases but also occupies and contaminates future agricultural land [22,23]. Therefore, composting would be a more profitable and desirable method for disposing of bioplastic waste. As a cost-effective and safe waste management solution, composting technology is being adopted by several industries [24]. In the literature, industrial composting of bioplastics has been demonstrated to be one of the most desirable methods for managing the material's end of life [25].

Compostable polymers are being developed as environmentally friendly alternatives, especially if they can be recycled organically and derived from renewable resources. Using lifecycle assessment techniques, ASTM D7075 and ISO 14000 have developed standards to evaluate biobased products and their environmental performance [26,27]. However, only some of the biopolymers are listed as compostable materials by ASTM. In order for a polymer to be considered compostable, it must convert 90% of its carbon content to carbon dioxide in accordance with ASTM International (D5338). An ASTM International (D5338) polymer can only be considered compostable if 90% of its carbon content is converted into carbon dioxide. This prepared polymer undergoes three primary steps in order to become biodegradable: biodeterioration, fragmentation, and assimilation [28]. In addition, plant-based polymers, thermoplastic starch, polyhydroxyalkanoates (PHAs), and polylactic acid or polylactide (PLA) are commonly reported as biopolymers [29]. It is important to know that a number of factors affect the biodegradation rate of biopolymers in nature, such as their chemical structures, functional groups, crystallinities, and polymer chains [8]. Furthermore, temperature, oxygen, and pH content play a significant role in polymer biodegradation [30]. It has been reported that PLA degradation in the soil is much slower than in compost medium because compost has a higher moisture content and temperature range encouraging PLA hydrolysis and the assimilation of PLA by thermophilic microorganisms. According to [31], Zn was used as catalyst in PLA depolymerization, but the problem with these catalysts was that they could not be recycled or re-used. However, ref. [32] reported that the degradation of PLA in soil takes much longer than in compost medium due to thermophilic bacteria which are able to hydrolyze and assimilate PLA with a higher temperature range and moisture content in the compost. After 47 days of composting, it was determined that the average rate of biodegradation for cellulose was $96.8 \pm 6.7\%$ [33] according to standard composting methods [34]. In addition, the composting of biobased polymers and the use of the compost in agriculture can result in significant emission and energy credits. Biobased polymers can be made even more sustainable through composting, which is an integral part of sustainable agriculture practices.

This review aims to gather information about the biodegradation of bioplastics in diverse environments and to discuss it to examine the compostability rate of different types of bioplastics through composting. Finally, this review concludes by discussing the composting technology in the biodegradation of bioplastics as well as classifications of different bioplastics according to the degradation rate through home and industrial composting.

2. Types of Bioplastics

2.1. Starch-Based Bioplastic

Biopolymers made from starch are becoming increasingly popular due to their abundant availability, renewability, low-cost, and biodegradability. In addition, starch is regarded as a promising raw material for biopolymer production. After polylactic acid (PLA), starch-based plastics accounted for the second-highest share of the total bioplastics production [35]. There are two types of polymers involved in its composition: linear amylose and branched amylopectin [36]. An important feature of bioplastics is their elasticity, which is provided by linear amylose, while amylopectin has a branched structure that controls tensile strength and elongation [37]. Among the most promising biopolymers for producing edible films, starch is particularly popular because of its affordability.

2.2. PLA-Based Bioplastic

Polylactic acid is a commercial biodegradable thermoplastic based on lactic acid also called polylactide or PLA (also known as polylactic acid, lactic acid polymer). The most widely used biodegradable aliphatic polyester, PLA is a thermoplastic that is aliphatic non-cyclic, non-aromatic, derived from lactic acid and lactide, and formed by polymerizing sugars obtained from various agricultural biomass sources [38]. Polylactides are developed for degradable packaging materials, and polylactide decomposes within three weeks in industrial composting processes. Polylactide is the first synthetic polymer to be synthesized from renewable resources [39]. Moreover, polylactic acid exhibits a number of desirable characteristics, including being easy to fabricate, biocompatible, biodegradable, non-toxic, and having better thermal properties [40]. When polylactic acid biodegrades, it releases water, CO_2, and decomposed organic matter that green plants are able to utilize, which reduces greenhouse gas emissions. Additionally, when oxygen is added to polylactic acid, no toxic intermediates or byproducts are produced. In comparison with other synthetic polymers, polylactic acid emits relatively fewer greenhouse gases [41].

2.3. PHAs-Based Bioplastic

Several types of microalgae produce PHAs, which are biodegradable biopolymers [42,43]. In nutrient-limited environments, diverse prokaryotic microbes produce PHAs for carbon storage [44]. In PHAs, the carboxylate group of one monomer forms ester bonds with the hydroxyl group of the adjoining monomer to form polymers of 3 hydroxy-acid, sometimes called hydroxy alkanoic acids [45]. In terms of physical properties, PHAs can be compared to petro-chemical polymers, which makes them viable alternatives for the growing global bioplastic market [46]. In bioplastics, PHAs have not been widely applied, and this may be due to their high production and recovery costs [47]. Scientists are searching for cost-effective feedstocks to replace PHA. Approximately 90 percent of the microbes that degrade PHAs also breakdown starch as the biodegradation pathways are similar [48].

2.4. Cellulose-Based Bioplastic

A variety of biomass can be used to produce cellulose, including wood, seed fibers, bast fibers, grass, marine animals (tunicates), algae, fungi, invertebrates, and bacteria [49]. Additionally, acetic acid bacteria can synthesize cellulose in addition to higher plants [50]. As with starch, cellulose consists of linear chains with glycosidic bonds that join a few hundred to more than ten thousand glucose units. Although starch and cellulose have the same monomer unit, they differ in how their polymeric chains are oriented [51]. In recent years, cellulose-based biopolymers have gained attention due to their strength, stiffness, high durability, and biodegradability [52]. In addition to being low-density, low-price, and nonabrasive, cellulose-based reinforced composites are also non-abrasive [1]. As cellulose-based bioplastics contain distant tenuous molecules with weak hydrogen bonds, they degrade rapidly. Conversely, bioplastics made from cellulose have weaker hydrogen bonds, and therefore have lower mechanical properties, such as strength and flexibility.

3. Biodegradation of Biopolymers in Soil and Aquatic Environments

In biodegradation, naturally occurring microorganisms, such as bacteria and fungi, mineralize materials through their action [53]. The degradation of bioplastics varies in three different surroundings (soil, aquatic system, and compost). In contrast, bioplastics derived from biological sources take significantly less time to degrade than petroleum-based plastics. Because plastics have a high molecular weight, chemical structure, low water solubility, and contain xenobiotics, their biodegradation is limited [54]. In previous studies in the literature, many scholars investigated the biodegradation of bioplastics which are listed in Table 1.

Bioplastic Degradation in Soil

Soil contains a wide diversity of microorganisms, making plastic biodegradation more feasible than in other environments such as water and air [55]. A number of microorganisms isolated from soil media utilized bioplastic as a carbon source. Actinobacteria species, such as Nonomuraea, Amycolatopsis, Streptomyces, Laceyella, Actinomadura, and Thermomactimyces species, were obtained from soil. However, among these the Streptomyces and Amycolatopsis were the most common species that play a crucial role in bioplastic degradation in soil environments. Bulkholderia, Pseudomonas, Paenibacillus, and Bacillus species were mainly isolated from different soil environments, and they were capable of degrading the bioplastics. Most commonly, Aspergillus, Fusarium, and Penicillium were identified as soil-isolated fungi responsible for bioplastic degradation [56]. In spite of the fact that cellulose, which was used as a positive control, was fully degraded, the biodegradation process was slow. Possibly, this is due to the lower temperature of the system under real conditions and the longer time span of the experiment. Consequently, these bioplastics required higher temperatures and longer degradation times to degrade effectively [57]. The biodegradation of polymers depends on the chemical nature of the polymer as well as on environmental factors, such as moisture, temperature, acidic nature, etc. [58]. Including these factors, bioplastics biodegrade differently in different soil compositions. Figure 1 depicts the biodegradation mechanism of biopolymers in soil environments. Starch-based plastics are found to reduce in weight and faster degradation were observed in field soil than PHAs and PLA, while PLA sustains its weight for a long period of time, about 12 weeks [59]. The highest biodegradability was found with cellulose-based bioplastics (80 to 100%) after 100 days [60,61]. Based on the kinetic constants of degradation of the three blends studied in soil, PHAs, blends showed the highest kinetic constant, followed by PLA blends [62]. Overall, the bioplastic-composted soil increases the soil fertility and increase the yield of crops. It is generally observed that microbiological content increases after biodegradable films are buried, as the organic mulch increases bacterial populations because of the different chemical compositions and decomposition rates of these materials [63]. However, in composting processes, the PHAs' films enrich the soil more than PLA since they increase the microbial population present in the soil [64]. In addition to an increase in Clostridia species and mesophilic aerobic bacteria, there was also a significant increase in fungi. There is no doubt that these changes were caused by the swift degradation of the protein-based bioplastic, which resulted in the release of carbon and nitrogen compounds, which served as food and increased the microbial population.

Table 1. Biodegradation of different types of bioplastics in soil and aquatic environments.

Bioplastics	Environment	Temperature/Moisture/pH	Biodegradability	Days Taken for Biodegradation	References
Starch-based	Soil	20 °C, 60%	14.2%	110	[54]
Starch-based blends	Sea water	25 °C	1.5%	90	[65]
Starch/chitosan (35/65)	Soil	Soil burial test method	96%	28	[66]
Starch-based	Sea water	Room temperature	1.5%	90	[67]
PLA	Soil	30%	10%	98	[68]
PLA	Soil	25 °C, 60%	13.8%	28	[69]
PLA (powdered)	Soil	25 °C, 60%	13.8%	28	[66]
PLA	Sea water	25 °C	8.4%	365	[70]
PHA	Soil	20 °C, 60%	48.5%	280	[54]
PHA	Compost/Soil (10/90%)	25 °C, 65%	50%	15	[71]
PHA	Soil	39% pH 6.8	75%	80	[72]
PHAs	Sea water	25 °C	8.5%	365	[73]
Cellulose	Soil	Undefined	100%	103	[60]
Sponge fibers	Compost containing synthetic soil	Aerobic, 58 °C	>80%	154	[74]
Cellulose	Municipal solid waste	Room temperature	44%	14	[75]

There is no doubt that the aquatic environment is the most susceptible to plastic contamination. However, bioplastic degradation in both seawater and fresh water generally appears to be slower than biodegradation in composting, anaerobic digestion, and soil environments. Specifically, this was related to the characteristics of aquatic environments that play a critical role in bioplastic degradation. In addition to bioplastics' properties, some environmental parameters, such as nutrients content, temperature, pH, microbial diversity, and microbial population density, have an important impact on bioplastic degradation in aquatic environments. As a result of the study in [76], the PHAs degraded in seawater, and temperature played a significant role in the degradation process. According to the authors, seasonal changes in water temperature led to the difference in degradation rates. There are a number of factors that could contribute to the slow biodegradation of bioplastics under aquatic environments, including low temperatures, nutrient levels, and microbe population density. Several bacteria species were capable of degrading bioplastics in aquatic environments, such as river water and marine environments; Bacillus, Lepthotrix, Tenacibaculum, Pseudomonas, Entrobacter, Variovorax Gracilibacillus, and Avanivorax were isolated from these environments as reported in several studies [55]. Figure 2 depicts the biodegradation mechanism of biopolymers in aquatic environments.

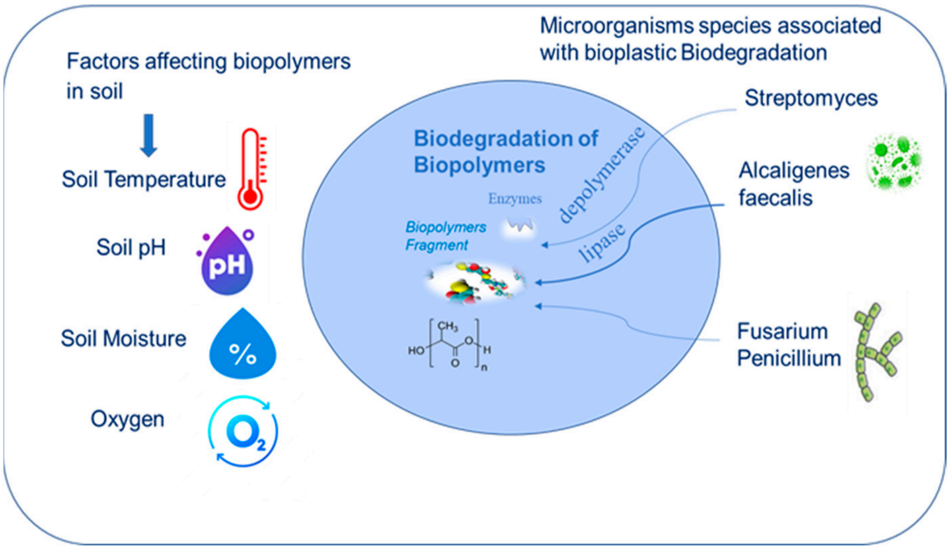

Figure 1. Interactions of microbes and environmental factors in microplastic-contaminated soils.

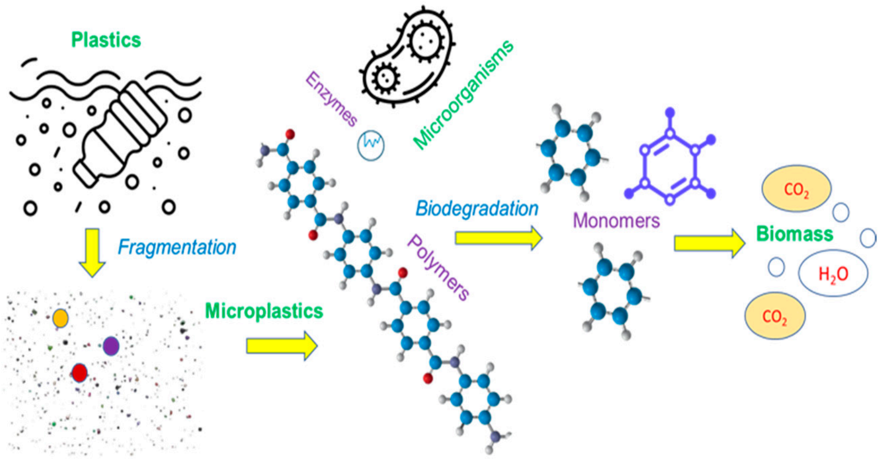

Figure 2. Bioplastic degradation in the aquatic environment.

In aquatic environments, PLA blends showed the slowest rate of degradation. There was an average estimated time of more than ten years for complete degradation. The degradation of starch-based blends in fresh water and seawater shows high variability. The authors of the study [65] concluded that the starch-based bioplastic obtain only a 1.5% degradation under marine and freshwater environments (25 °C, 90 days), while other studies have reported significantly higher degradation rates. The results of [67] showed that starch-based shoppers degraded by 69% (weight basis) within 236 days, probably due to both the material characteristics and the environmental conditions (sea water and sediment). In addition, aquatic environments are less likely to degrade bioplastics than soil environments due to the lack of microbial diversity.

Recently, microscale plastics have entered the marine environment through wastewater discharges, which have caught the attention of researchers. In the current literature, however, no information was found about wastewater discharges releasing and/or shedding bioplastics.

4. Biodegradation of Bioplastics in Compost

There is a significant amount of plastic waste disposed in landfills, which eventually generates greenhouse gases and leachate. Recycling or composting are generally regarded as more suitable ways of recovering plastic from solid waste. Composting occurs when microorganisms convert organic matter into CO_2 and humus by consuming it [58,77]. A number of modern techniques have been introduced to detect the presence of microorganisms, among them, polymerase chain reaction (PCR) and next-generation sequencing (NGS) are two well-known techniques that can be used to analyze and sequence in depth the specific microbial communities involved in the degradation of plastics [78,79]. In accordance with the ASTM's definition of compostable plastics [80], the decomposition of such polymers produces CO_2, water, inorganic compounds, and biomass without leaving behind any visible or toxic residues. The composting process is particularly appropriate for dealing with food-contaminated packaging, as recycling facilities cannot deal with food-contaminated plastics, and the compost formed can be used for soil improvement [81]. A biodegradable plastic is not necessarily a bio-based plastic, as degradability depends on the structure and polymer chemical composition, as well as its interaction with its surroundings [82]. In addition to reducing our global ecological footprint, composting is an excellent end-of-life option. It has been extensively studied over the past decade how compost can be used to biodegrade different types of bioplastics (Table 2).

4.1. Degradation of PLA through Composting

PLA is one of the latest materials to be commercialized for use in organic food packaging, such as bags, containers, and films, and it has been proven to decompose under composting conditions [32,83]. PLA degradation in compost occurs only in high-temperature, humid environments containing relevant microorganisms [84]. In the process of biodegradation of PLA, it undergoes two stages: first, hydrolysis or oxidation into monomers and oligomers, and then finally metabolization by microorganisms that produce CO_2 and H_2O [85]. During degradation, PLA is chemically hydrolyzed in thermophilic conditions to reduce its molecular weight, and then microorganisms assimilate lactic acid oligomers as an energy source. A number of enzymes play an important role in the depolymerization of PLA, including carboxylesterase, cutinase, lipase, and serine protease [86]. Serine protease has been identified as the most important enzyme involved in PLA degradation by actinobacteria of the genus amycolatopsis [87]. Moreover, enzymes encoded by a multitude of bacteria and fungi can partially degrade plastics; enzymes are crucial to the depolymerization of polymers, even those that are considered resistant [88]. The enzymes in this group mostly include carboxylesterases, lipases, cutinases, and proteases as well as several other enzyme groups (i.e., laccases, oxidoreductases, manganese peroxidases, and alkane hydroxylases monooxygenases) [89] involved in the degradation of plastics. Despite this, little information exists on the characterization of PLA-degrading enzymes in previous studies. Figure 3 shows the biodegradation mechanism of biopolymers in compost. In terms of chemical and biological degradation, temperature is considered the important restraining parameter, as the increased flexibility of the chains occurs only above the PLA glass transition temperature of 55 °C [32]. Another relevant parameter is the PLA amount in the composting pile: in a mixture of 70:30 wt% garden waste/PLA, the chemical hydrolysis of PLA lowers the pH due to the large amounts of lactic acid that are produced, reducing the degrading action of compost microorganisms [90]. According to a study, ref. [91], poly lactic acid (PLA) bioplastics degrade completely through industrial composting within four to six weeks. This makes PLA incompatible with home composting as the moisture-rich environments favor chemical hydrolysis [92].

4.2. Degradation of PHAs through Composting

Although PHA is not as well-known as PLA, its easy disposal makes it more popular among the environmental community [93]. In low-temperature or low-pH home composting conditions, PHAs show minimal or no biodegradation. Biodegradation is improved by higher temperatures in industrial composting [94]. Ref. [95] studied the biodegradation of PHAs when exposed to temperatures between 8 and 30 °C for 152 days, and PHB, PHBV (10% HV), and PHBV (20% HV) degraded at 4%, 6–17%, and 67%, respectively. Ref. [96] reported that PHBV (HV26%) had fifty-nine-percent mass loss in 186 days, suggesting that it is biodegrading more slowly even though the temperature ranged from 40 to 63 degrees Celsius throughout the study. Probably, the differences in inoculum and temperature profiles resulted in PHB degrading by 50% in 84 days at 34–66 °C and 74–89% humidity in organic waste home compost [97]. It was observed that degradation rates for PHBV were increased more rapidly than those for PHBA, PHBHHx, and PHB when a medium with PHA depolymerase was used. According to their hypothesis, PHAs with longer side chains, including PHBA and PHBHHx, have a lower degradation rate than PHAs with shorter side chains because their side chains slow down depolymerase degradation (Wang et al., 2018). According to Danimer Scientific, PHAS produced by the company are compostable in backyard and industrial composting systems. They have obtained third-party certification from Vinçotte that demonstrates that their products are compostable both in home and industrial composting systems [98].

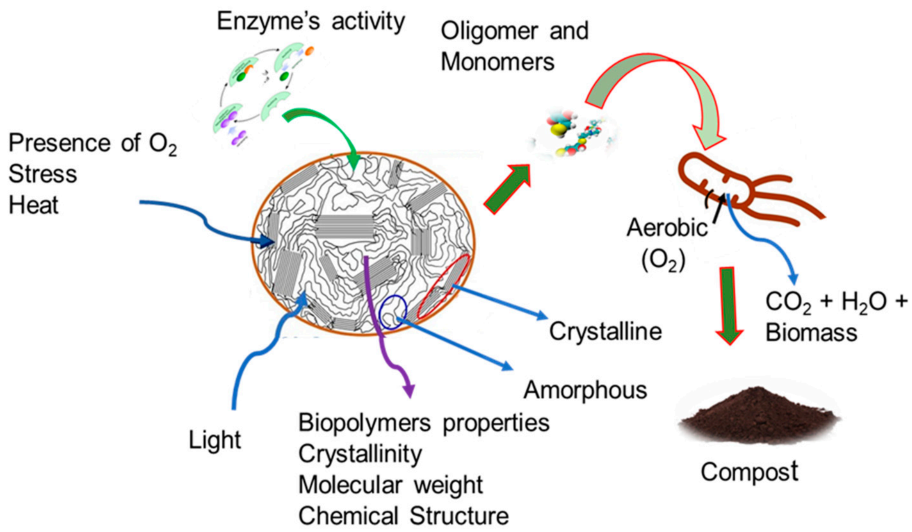

Figure 3. Mechanism of biodegradation of bioplastics through composting.

4.3. Degradation of Starch-Based Bioplastic through Composting

In bioplastic production, starch is used frequently because of its abundance in nature (especially agricultural products) and low cost [99]. Additionally, starch has been reported in the literature to be a good compostable material for plastic films, bags, and agricultural mulching films [100]. Microorganisms can directly attack starch and cellulose molecules since they are capable of producing enzymes to depolymerize or cleave the polymer physical structure. This can result in molecular weight abatement outside the microbial cells [53]. For example, the mineralization of corn starch at 58 °C took 44 days under aerobic conditions [34]. The pH range of 7.0–8.0 and 50% moisture facilitate the biodegradation of starch films in organic compost obtained from different crops. In the first stage of degradation, mainly caused by plasticizer leaching, around 30% of the weight was lost within 24 h. In the second stage, primarily due to biological activity and glycosidic bond scission, weight slowly decreased until 90% of the original weight in approximately 20 days [101]. Interestingly, several papers reported on starch-based blends' decomposition during mesophilic composting (23–25 °C) and found that under aerobic conditions, temperature also played a key role in bioplastic degradation. Ref. [65] reported starch-based bioplastic degradation in non-industrial composting conditions after about 9 weeks of composting [102].

4.4. Degradation of Cellulose-Based Bioplastic through Composting

Just like starch, cellulose is a polysaccharide arising from glucose monomers. However, in cellulose structures, these monomers are bound with stronger glycosidic bonds, making them more resistant to decomposition. Plant cell walls, which are made of cellulose, contain high levels of natural cellulose [103]. Among biopolymers, cellulose is considered relatively fast-degrading in compost environments [54]. A 47-day composting experiment found that 97 + 7% of cellulose mineralized after standard composting methods were applied [34]. Ref. [104] studied the degradation of cellulose powder through a composter bin at lab scale. During the composting process, the maximum temperature was above 60 °C for at least one week. This shows that cellulose powder biodegrades at a rate of 69% after 65 days. Furthermore, the degradation of cellulose-based products may be dependent on a favorable environment for microorganisms in terms of temperature, moisture, and oxygen. In some cases, however, adding other substances (salts, pigments) can inhibit cellulose decomposition [54].

Bioplastic degradation in composting environments is influenced by a number of factors, with temperature and the chemical composition of bioplastics playing major roles [27]. In composting, maximum temperatures (above 55 °C) allow the most common bioplastics to reach their glass transition temperature, resulting in amorphous polymers that are more hydrophilic [105], increased hydrolyzation, and enhanced bioplastic degradation kinetics. The conditions for industrial composting are adequately standardized and controlled. Comparatively, home composting conditions tend to be much more variable, and temperatures tend to be lower. Thus, composting at home is less effective and slower than composting in industrial settings. In composting, biodegradable mulch by itself does not provide sufficient nutrients to compost. However, polymer carbon must be accounted for in determining the appropriate ratio of carbon to nitrogen.

In general, PLA-, PAHs-, starch-, and cellulose-based bioplastics which are easy to hydrolyze are considered an end-of-life option by biodegradation, but it should only be performed under controlled industrial conditions to ensure complete digestion and prevent side effects that are uncontrollable, such as the formation of microplastics or the leakage of contaminants on the site. Moreover, composting requires chemical compounds to fully degrade the bioplastics, but on the other hand these chemical compounds or approaches have a heavy load on the environment. For a sustainable approach, some studies [106] reported that some metal compounds and enzymes are commonly used as catalysts to degrade bioplastics, such as PLA-, PHAs-, starch-, and cellulose-based bioplastics, from the environment.

Table 2. Biodegradation of different types of bioplastics in compost.

Bioplastics	Feedstock	Temperature/Moisture Contents	Biodegradability in Percentage	Composting Time Frame (Days)	References
Starch-based (potato almidon)	Compost	Aerobic, 58 °C	85%	90	[107]
Plastarch	Compost	Aerobic, 55 °C, 60%	50%	85	[54]
Starch-based blends	Compost/Food waste	45–65 °C	60%	90	[108]
PLA	Compost	58 °C, 60%	60%	30	[109]
PLA +Clay film	Compost	Aerobic, 58 °C, 55%	34%	130	[110]
PLA	Compost	65 °C, pH = 8.5, 63%	84%	58	[111]
PHA-based	Compost	55 °C, 70%	80%	28	[112]
PHAs blends	Compost/Cow manure	50 °C	30%	60	[113]
Cellulose-based	Compost containing synthetic material	Aerobic, 58 °C	>80%	154	[74]
Sponge cloth (Cellulose-based)	Compost	Aerobic, 58 °C	80%	154	[74]
Nylon4 (polyamides, bio-based)	Composted soil	25 °C, pH 7.5–7.6, 80%	100%	120	[61]

5. Current Gaps and Future Research Directions

There is a need for further research on the degradation of bioplastics in backyard compost piles as well as in industrial compost piles. In spite of the fact that there are many composability standards for bioplastics, data from the literature showed good performance in industrial composting when proper conditions were followed. In addition, compost is the most suitable environment for biodegradation, followed by soil and aquatic environments. Compost or anaerobic digestion can easily degrade some biodegradable plastics, but soil may not. It is therefore important that biodegradable plastics have clearly defined end-of-life targets. Aquatic environments may degrade some biodegradable polymers, but they should never be used as end-of-life disposal. Biodegradation is less feasible in aquatic environments due to the lower temperatures and less microbial activity than in compost and soil.

The information here can help industrial companies to categorize the current limits of bioplastic degradation and identify potential growth areas. In a way, it will boost the food packaging industry's sustainable progress toward producing cleaner, environmentally friendly packaging, meeting consumer and industry expectations for the future of this important sector. In terms of research, it is also important to look at the relationship between the biopolymer's chemical structure and its composability in industrial plants. Therefore, the understanding of biodegradation processes is progressing and the advancement from a technological point of view makes this approach an actual opportunity within a certain maturity level. There are some problems that need to be addressed, such as pollution from non-compostable plastics, the accumulation of plastics with long degradation times, and confusion about how additives affect biodegradation rates. A compostable material is the perfect solution for some applications, such as food waste bags, where organic matter cannot be separated from plastics. In addition, there is a need to introduce biocatalysts, such as enzymes and microorganisms, to selectively depolymerize bioplastic waste into its constituent monomers or other value-added products.

6. Conclusions

Bioplastics are emerging as a sustainable alternative to traditional plastics. The identification and biodegradation of bioplastics have been developed through various methods in recent years. Bioplastics have been reported to biodegrade in various studies. In the studies, bioplastics were studied in their production as well as their environmental persistence. A variety of standard biodegradation test methods were described in aerobic biodegradation. The current knowledge about the degradation of bioplastics through composting, soil, and aquatic environments is summarized in this review paper. A composting process can only degrade compostable polymers, and mineralization can begin within the composting period for other biodegradable materials. With the help of industrial composting, the volume of bioplastic waste can be reduced in a sustainable way. Therefore, it is important to identify the conditions that result in safe compost production.

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