Plastics of the Future? The Impact of Biodegradable Polymers on the Environment

Leicheng Zhao, Lili Rong, Longfei Zhao, Jintao Yang, Lei Wang, and Hongwen Sun

Contents

The original version of this chapter was revised. A correction to this chapter can be found at https://doi.org/10.1007/978-3-030-56271-7_466

L. Zhao, L. Rong, L. Zhao, J. Yang, L. Wang (✉), and H. Sun
MOE Key Laboratory of Pollution Processes and Environmental Criteria, College of Environmental Science and Engineering, Nankai University, Tianjin, China
e-mail: wang2007@nankai.edu.cn

Defu He and Yongming Luo (eds.), *Microplastics in Terrestrial Environments - Emerging Contaminants and Major Challenges*,
Hdb Env Chem (2020) 95: 423–446, DOI 10.1007/698_2020_462,

Abstract With the increasing reports on the environmental distribution and ecological risks of petrochemical plastics and microplastics, degradable plastics are considered as the optimal alternative to the traditional plastics. Compared with the traditional petrochemical plastics, the market of biodegradable plastics is still small but growing rapidly. At the same time, knowledge on the environmental distribution and ecological risks of biodegradable plastics is still limited, although their production and application continue to improve. Biodegradable plastics are divided into semi-biodegradable plastics and fully biodegradable plastics. Their ecological risks may show significant differences. In the soil environment, the particle size, shape, molecular weight of plastics, the type of functional groups in the molecular structure, and the additives added to plastics may play different roles in the biodegradation of biodegradable plastics. In current chapter, the available information of current researches on biodegradable plastics in the environment is reviewed. The environmental risk and future development of degradable plastics are also discussed.

Keywords Biodegradable plastics, Biodegradation, Ecological risks, Environmental distribution

1 The Concept, Composition, Application, and Output of Biodegradable Plastics

1.1 Definition and Classification of Biodegradable Plastics

Biodegradable plastics are defined as degradable plastics in which the degradation results from the action of naturally occurring microorganisms such as bacteria, fungi, and algae by the American Society for Testing and Materials [1]. Ammala et al. define biodegradable plastics as plastics that can be decomposed by the action of living organisms, usually microbes, into water, carbon dioxide, and biomass [2]. The national standard of the People's Republic of China defines biodegradable plastics as plastics degraded by the action of microorganisms in nature and eventually degraded into carbon dioxide and/or methane, water, and mineralized inorganic salts containing elements and new biomass [3].

According to the degradation degree of plastics under the action of microorganisms, biodegradable plastics can be divided into completely degradable plastics and semi-degradable plastics. The former can be completely degraded. In comparison, the semi-degradable plastics are a blend of non-biodegradable plastics with degradable polyesters or starch [4]. The purpose of destroying the structure of the copolymer is achieved by biodegradation of natural components.

Biodegradable plastics can also be classified into bio-based plastics and fossil-based plastics depending on the raw materials [5, 6]. Bio-based biodegradable plastics derived from renewable resources can be used in medical and pharmaceutical industries, such as polyhydroxyalkanoate (PHA) and polylactic acid (PLA). Fossil-based biodegradable plastics have been widely employed in the packaging

Table 1 Full name and abbreviation of target plastics

Full name	Abbreviation
Polyhydroxyalkanoate	PHA
Polylactic acid	PLA
Polyhydroxybutyrate	PHB
Polybutylene succinate	PBS
Polycaprolactone	PCL
Polyethersulfone resin	PES
Poly(butylene adipate-co-terephthalate)	PBAT
Polypropylene	PP
Polystyrene	PS
Polyethylene	PE
Polyvinyl chloride	PVC
Polyethylene terephthalate	PET
Polyurethane	PUR
Polyamide	PA
Polyurethane	PUR
Polyethylene furanoate	PEF
Acrylonitrile butadiene styrene	ABS
Polybutylene succinate-co-adipate	PBSA
Polyvinyl chloride	PVC
Polyoxymethylene (polyformaldehyde)	POM
Phthalate esters	PAEs
Hyperbranched aliphatic polyester and cellulose	HAPE-cell
Differential scanning calorimeter	DSC

industry, such as polyethersulfone resin (PES) and polycaprolactone (PCL). Abbreviations for common types of plastic polymers are shown in Table 1.

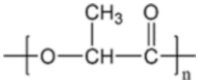
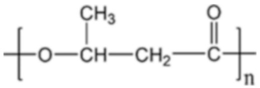
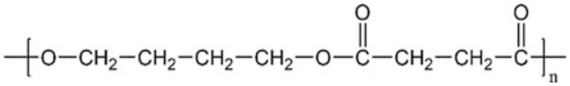
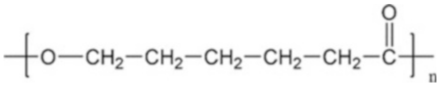
1.2 Representative Materials and Their Applications

Representative biodegradable plastics include PLA, PHA, polybutylene succinate (PBS), PCL, etc. The chemical structure and application of these plastics are shown in Table 2.

1.3 Production and Environmental Flux

Based on the latest market data compiled by *European Bioplastics* in cooperation with the research institute nova-Institute, the global production capacity of biodegradable plastics is 912 kt in 2018. The production capacities of biodegradable

Table 2 Representative biodegradable plastics and their applications

Plastics	Chemical structure	Application [6–8]
Polylactic acid (PLA)	 $\left[O-CH(CH_3)-C(=O) \right]_n$	Loose-fill packaging, compost bags, food packaging, disposable tableware, upholstery, disposable garments
Polyhydroxybutyrate (PHB)	 $\left[O-CH(CH_3)-CH_2-C(=O) \right]_n$	Disposable tableware, packaging materials, agricultural laminating films, coatings, fibers
Polybutylene succinate (PBS)	 $\left[O-CH_2-CH_2-CH_2-CH_2-O-C(=O)-CH_2-CH_2-C(=O) \right]_n$	Packaging, tableware, cosmetic bottles, pharmaceutical bottles, disposable medical supplies, agricultural films, biomedical applications
Polycaprolactone (PCL)	 $\left[O-CH_2-CH_2-CH_2-CH_2-CH_2-C(=O) \right]_n$	Drug carrier, cell or tissue culture rack, surgical suture, medical modeling materials, art modeling materials, toys, organic colorants

plastics with good development and industrial scale are PLA of ~218 kt, PBS of ~97 kt, and PHA of ~30 kt [9].

In China, the production capacity of biodegradable plastics has expanded rapidly in recent years. In 2018, China's biodegradable plastic industry was about 5.44 billion RMB (7.75 million $) with an increase of 21.13% compared with that in 2017 (4.941 billion RMB or 7.03 million $), which included 1.584 billion RMB for completely biodegradable plastics and 3.856 billion RMB for semi-degradable plastics. In 2018, China's biodegradable plastic industry produced about 650,000 tons, including 95,000 tons for completely biodegradable plastics and 555,000 tons for semi-degradable plastics.

2 The Occurrence, Degradation Efficiency, and Environmental Impact of Semi-biodegradable Plastics

2.1 Environmental Distribution of Semi-Biodegradable Plastics

Most of the fossil-based and bio-based plastics, used nowadays, are non-biodegradable, such as polypropylene (PP), polystyrene (PS), polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polyurethane (PUR) [7]. These plastics are highly stable and do not readily enter into the degradation cycles of the biosphere. Most of the employed plastics are either non-biodegradable or their degradation rate is too slow to be disintegrated completely [10]. Therefore, these non-biodegradable plastics were accumulated in the soil environment in large quantities because of improper waste management and uncontrolled littering, posing a serious threat to our planet eventually [6].

The semi-biodegradable plastics are a blend of non-biodegradable plastics with biodegradable polyesters or starch [4]. The blending of biodegradable polymers is one approach of reducing the overall cost of the material and modifying the desired properties and apparent decomposition rate. Compared to the copolymerization method, blending may be a more efficient way to achieve the properties of plastic degradability. Former study has reported blend plastics by combining PCL with conventional plastics (such as low-density PE, PP, PET, and PS) [8]. The blends of PCL and low-density PE, PCL, and PP both retained the high biodegradability of PCL. On the contrary, the degradability of the PCL part in the blends of PCL and PS, PCL and PET both dropped off remarkably. In the case of blends of PCL and PS, the biodegradability of PCL did not change significantly [4].

The global distribution of bioplastics in 2014 and 2018 is shown in Fig. 1. Bio-based non-biodegradable plastics (semi-biodegradable plastics), including the drop-in solutions bio-based PE and bio-based PET and bio-based PA, account for around 53% (0.9 million tons) of the global bioplastic production capacities in 2014

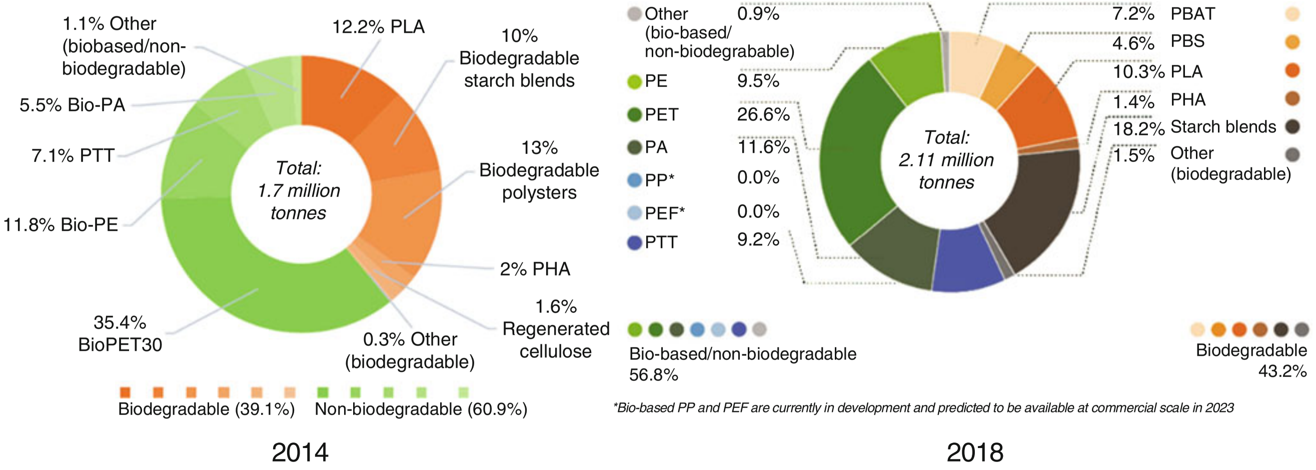


Fig. 1 Global distribution of bioplastics in 2014 [11, 12] and 2018 [9]

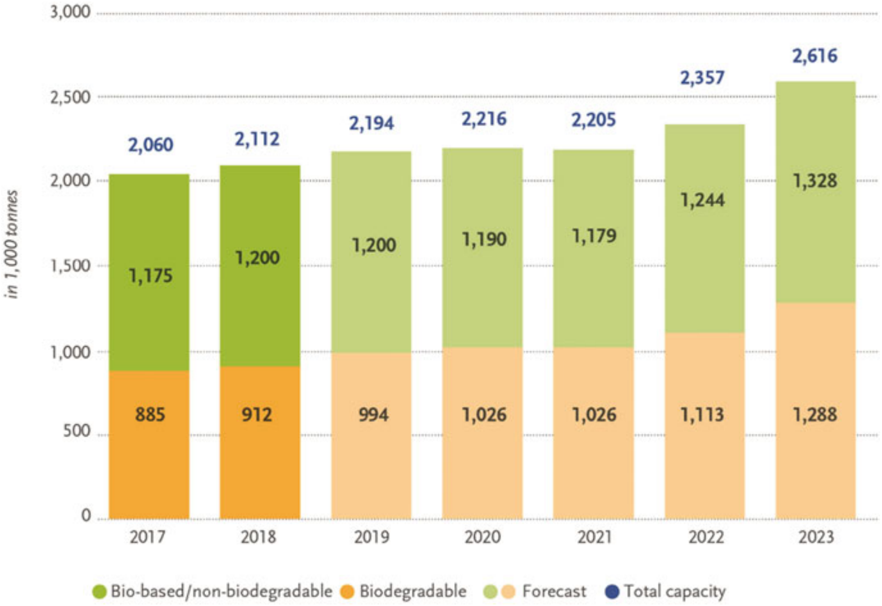


Fig. 2 Global production capacities of bioplastics from 2018 to 2023 [9]. Source: European Bioplastics, nova-Institute (2018). More information: www.european-bioplastics.org/market and www.bio-based.eu/markets

and 48% (1 million tons) in 2018, respectively. The proportion of semi-biodegradable plastic in the world was reduced from 60.9% in 2014 to 56.8% in 2018, indicating the demand for completely biodegradable plastics is gradually increased today.

The global production capacities of bioplastics from 2018 to 2023 are shown in Fig. 2. Currently, bioplastics represent roughly 1% of the 335 million tons of plastic produced annually. The global semi-biodegradable plastic production capacity is predicted to increase gradually from 2018 to 2023, increasing from around 1.20 million tons in 2018 to approximately 1.33 million tons in 2023 [9]. Specifically, the production of bio-based PE is predicted to continue to grow as new capacities are planned to come online in Europe in the coming years. The intention to increase production capacities for bio-based PET, however, has not been realized at the rate predicted in previous years [6]. Polyethylene furanoate (PEF), a new polymer, is expected to enter the market in 2023. PEF is 100% bio-based and is said to feature superior barrier and thermal properties, making it an ideal material for the packaging of drinks, food, and nonfood products. In 2023, bio-based PP is expected to enter the market at a commercial scale with a strong growth potential due to the widespread application of PP in a wide range of sectors. Additionally, bio-based PUR is another important group of polymers that have huge production capacities with a well-established market and is expected to grow faster than the conventional PUR market due to their versatility.

2.2 Degradation Characteristics of Semi-Biodegradable Plastics in the Environments

Non-biodegradable plastics mainly consist of conventional synthetic plastics such as PE, PS, PP, PET, and PVC, which have accumulated massively in the soil environment because of the randomly littering and poor waste management [6]. The biodegradation of major synthetic plastics in the soil environment is a very slow process that includes many environmental factors [2]. The basic mechanism for biodegradation of the high molecular weight plastics is the hydrolysis or oxidation by enzyme. Therefore, the main chains of plastics are biodegraded into polymer with feeble mechanical properties and low molecular weight, making it more convenient for further microbial assimilation [7]. The backbone of synthetic plastics is consisted of only long carbon chains. The characteristic structure makes polyolefins non-susceptible to degradation by microorganisms. However, a comprehensive study of polyolefin biodegradation has shown that some microorganisms could utilize polyolefins with low molecular weight [13].

PE is one of the non-biodegradable plastics with high hydrophobicity and high molecular weight. Hydro-biodegradation and oxo-biodegradation are two mechanisms of biodegradation of PE. These two mechanisms coincident with the modifications owing to starch and prooxidant are used as the two additives in the synthesis of biodegradable PE. Starch blend PE has a continuous starch phase that contributes to the hydrophilic of plastics, so it can be catalyzed by amylase enzymes. Microorganisms can easily access, attack, and remove the starch blend PE. Consequently, the hydrophilic PE with matrix is considered to be hydro-biodegraded [14]. Additionally, compatibilizer can also enhance the biodegradability of low molecular weight PE/starch blends. Generally, the blending of PE with additives enhances autooxidation and reduces the molecular weight of the plastics, leading microorganisms to degrade the low molecular weight plastics more easily. Although all these approaches can improve the biodegradation of PE blends, the biodegradability of PE part is still relatively low [2].

2.3 The Ecological Effect of Semi-biodegradable Plastics

Due to the growing volumes of semi-biodegradable plastics, a strong concern of the public opinion is about the environmental impact of persistent substances possibly released during the process of degradation and composting. Only the biodegradable components could be degraded in the environment. Therefore, the non-biodegradable components are broken up into smaller particles and diffuse into the environment [15]. Their ecological risk assessment can refer to that of non-degradable plastics. In addition, toxic degradation products or harmful compounds such as the additives in semi-biodegradable plastics will also release to the environment. Soil health is a key component of agroecosystem sustainability; thus there is a need to understand the effects of semi-biodegradable plastic on both crop productivity and soils [16]. Accordingly, more research about the ecological effects of semi-biodegradable should be done in the future.

3 The Occurrence, Degradation Efficiency, and Environmental Impact of Completely Biodegradable Plastics

3.1 Environmental Distribution of Completely Biodegradable Plastics

Completely biodegradable plastics mainly include bio-based and fossil-based polymers, which are advantageous in modern industrial applications because of their high degree of biodegradability and microbial assimilation [13]. Owing to maintain the advantages conferred through using plastic products without having the serious pollution burden of waste plastics, the attention of completely biodegradable plastics is continuously growing [6]. Compared to the majority of industrial plastics, completely biodegradable plastics are supposed to convert into carbon dioxide, water, and biomass once they end up in the environment. With the increasing awareness of plastic pollution, the demand for completely biodegradable plastics is urgent nowadays [17].

Figure 2 shows the global production capacity distribution of bioplastics. Based on the market data in 2018 compiled by European Bioplastics, the production capacity of global bioplastics is predicted to increase from 2.11 million tons in 2018 to approximately 2.62 million tons in 2023 [9]. Nevertheless, completely biodegradable plastics (0.91 million tons in 2018) are only accounted for less than 0.3% of the total plastic production (335 million tons in 2018) [9].

Completely biodegradable plastics mainly include bio-based and petroleum-based biodegradable plastics [7]. Bio-based completely biodegradable plastics are consisted of PHA and PLA. Petroleum-based completely biodegradable plastics mainly include PBS, PCL, and PBAT [13]. PLA and starch blends are two most contributors of the completely biodegradable plastics, accounting for 23.8 and 42.1% of the completely biodegradable plastics, respectively (Fig. 3). Compared to that in 2018, the production capacity of PLA is predicted to grow by 60% by 2023. It’s well known that PLA is a very versatile material that features significant barrier properties and is available in high-performance PLA grades that are one of significant replacements for PP, acrylonitrile butadiene styrene (ABS), and PS in more demanding applications [8]. Furthermore, polyhydroxybutyrate (PHB) as one of the completely biodegradable plastics has gradually attracted significant attention because of their biodegradation under both anaerobic and aerobic environments without releasing toxic contaminants into the environment [18].

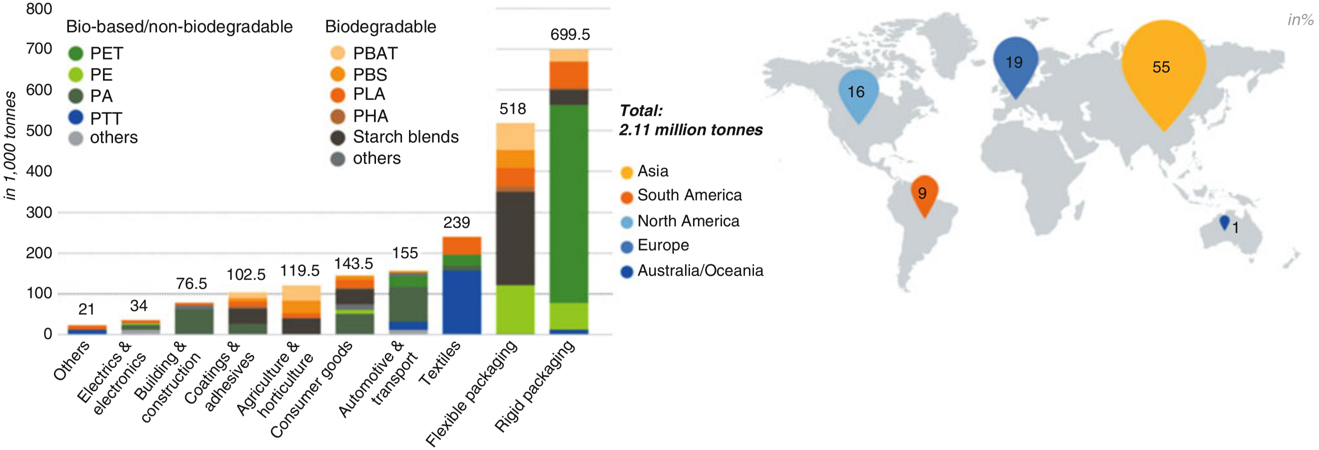


Fig. 3 The market and region distribution of completely biodegradable plastics in the environment [9]. Source: European Bioplastics, nova-Institute (2018). More information: www.european-bioplastics.org/market and www.bio-based.eu/markets

The market and region distribution of completely biodegradable plastics in the environment is provided in Fig. 3. Completely biodegradable plastics are applied to several application markets, mainly including flexible packaging, adhesives, agriculture, coatings, and textiles. Particularly in agriculture, demand for completely biodegradable plastics accounts for more than 60% of the total bioplastics. More than 50% of bioplastics were produced in Asia in 2018. In comparison, only approximately 20% of the global bioplastic production capacity is located in Europe.

3.2 Degradation Characteristic of Completely Biodegradable Plastics Entering the Environment

Biodegradation is the process of organic substances broken down by living organisms. Organic substances can degrade aerobically with oxygen or anaerobically without oxygen [7]. CO_2 and H_2O are released during aerobic biodegradation, while CO_2, H_2O, and CH_4 are produced accordingly during anaerobic biodegradation [19].

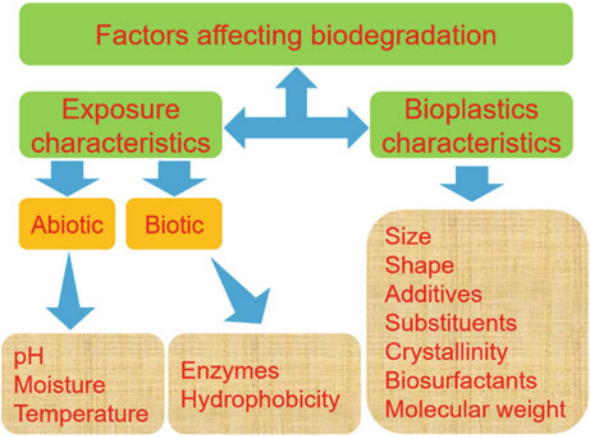
Biodegradation of bioplastics requires microorganisms to metabolize all organic components of bioplastics [20]. Specifically, the process of plastic biodegradation can be divided into three steps: (1) biodeterioration, the colonization of the polymer surfaces by soil microorganisms; (2) depolymerization, depolymerize the polymer into low molecular weight compounds by the secretion of extracellular microbial enzymes; and (3) bioassimilation, microbial uptake and utilization of these compounds, incorporating bioplastics carbon into biomass or releasing CO_2 [21–23].

Step 1: Microbial colonization of plastic surfaces. In this step, the formation of a microbial biofilm contributes to superficial degradation, fragmenting the polymeric material into smaller particles. Microbial colonization appears on the bioplastic surface through degrading soil fungi and bacteria. Factors that facilitate colonization can increase the contact area between bioplastics and microbial degraders, thus improving the biodegradation efficiency of plastics eventually [24].

Step 2: Enzymatic depolymerization of plastics. The microorganisms of the biofilm secrete extracellular enzymes, catalyzing the depolymerization of the bioplastic chain into low molecular weight oligomers, dimers, and monomers [25]. Ordinarily, the abiotic hydrolysis of these bonds is generally slower than enzymatic hydrolysis on the condition of pH and temperature that prevail in soil [21, 26]. Enzymatic depolymerization plays a role in limiting the rate of plastic biodegradation in soil. This is supported by much faster microbial utilization of oligomers, dimers, and monomers when directly added to soil than of the corresponding bioplastics in the same soil [23].

Step 3: Microbial utilization of plastic carbon. The last step in bioplastic biodegradation is the microbial assimilation and utilization of oligomers, dimers, and monomers released from bioplastics through enzymatic hydrolysis. The uptake of the small molecules produced into microbial cells and the following production of

Fig. 4 Factors affecting the biodegradation efficiency of biodegradable plastics



primary and secondary metabolites is a process recognized as assimilation. Microorganisms utilize the hydrolysis products as substrates for both respiration and synthesis of biomolecules. The most immediate solution to comprehend utilization is to follow the conversion of plastic-derived carbon into CO_2 and into microbial biomass [2]. Concomitantly, several simple and complex metabolites may be excreted and reach the extracellular surroundings (e.g., aldehydes, organic acids, and antibiotics). These metabolites are mineralized, and end products such as CO_2, H_2O, CH_4, and N_2 are formed and released into the soil environment eventually.

Figure 4 demonstrates several factors that influence the efficiency of biodegradation, mainly including plastic characteristics, type of organism, and nature of pretreatment [11]. The plastic characteristics such as size, shape, molecular weight, type of functional groups in molecular structure, and additives added to the bioplastics all play significant roles in plastic biodegradation [27].

Moisture: Moisture can influence the biodegradation of plastics in different ways because of the fundamental requirement of water for growth and the multiplication of microbes. Abundant moisture can increase the swift action of microbial; thus the efficiency of biodegradation is increased. Additionally, abundant moisture conditions can also influence the process of hydrolysis by generating more chain scission reactions [13].

pH: pH can modify the rate of hydrolysis reactions through controlling the acidic or basic conditions. For instance, the efficiency of hydrolysis of PLA capsules is optimal when the pH is controlled at 5. The pH conditions are altered during degradation products of various plastics, changing the rate of the degradation process and microbial growth eventually [11].

Temperature: Similarly, temperature can also have a significant influence on enzymatic biodegradation through the softening of bioplastics. Plastics with a higher melting point have less possibility of biodegradation, and potential enzymatic degradability decreases with the increase of temperature [11]. Furthermore, the efficiency of PHA biodegradation was not constant in various periods of the year from 1999 to 2000 owing to various weather temperatures [28].

Enzyme characteristics: Different enzymes possess unique active sites and have the ability to biodegrade various types of bioplastics. Depolymerases were obtained from bioplastic-degrading microorganisms, playing a significant role in controlling biodegradation of bioplastics [29]. Moreover, it was also shown that the extracellular enzymes were involved in the depolymerization of PHB, and the specific microbially produced depolymerase can influence the distinct mechanisms of degrading PHB [6].

Molecular weight: Molecular weight plays a significant role in controlling the efficiency of biodegradation of many bioplastics owing to it can influence many physical properties of bioplastics. Ordinarily, bioplastic degradability by microorganisms is a decline with the increase of the molecular weight of bioplastics. The degradability of higher molecular weight PCL (>4,000) by lipase of a strain R. Delmar was lower than that of the low molecular weight bioplastics [4]. It is convenient for microbial enzymes to attack a substrate low in molecular weight; this is maybe the reason for this phenomenon [30]. Furthermore, high molecular weights can lead to a sharp decrease in solubility, making them unfavorable for microbial attack owing to the substrate was required for the assimilation of bacteria, and then further degraded by cellular enzymes.

Shape and size: The shape and size of the bioplastics play a significant role in altering the biodegradation process [11]. The bioplastics having large surface areas can be degraded rapidly when compared to those with a small surface area [31]. It was reported that the PHA films are degraded faster than PHA pellets owing to their larger surface area. Additionally, a larger polymer/water interface can enhance the attachment of microorganisms to the surface of bioplastics.

Additives: The structure and the composition of bioplastics can significantly influence the efficiency of biodegradation. Modifying the composition of bioplastics, including the addition of additives with high soluble sugar content, and biodegradability may be enhanced accordingly [11]. Although bio-composite production from bioplastics may have some improved mechanical properties such as high tensile strength, the biodegradation process may not be favorable under certain circumstances or become interrupted at the same stage. Consequently, the optimization of the bio-composite additives can engender a more applicable and biodegradable product [6].

Biosurfactants: Biosurfactants are amphiphilic substances and mainly adhered to the living surfaces. The low toxicity and high biodegradability of biosurfactants can enhance the biodegradation of bioplastics [32]. Moreover, the presence of specific functional groups on biosurfactants can improve the biodegradation of bioplastics and can also enhance their activities even in the extreme pH, temperature, and salinity conditions as well [33].

3.3 The Ecological Effect of Completely Biodegradable Plastics[1]

In order to assess the ecological effect of completely biodegradable plastics, ecotoxicity tests have been conducted under controlled laboratory conditions using model organisms [21]. The choice of the test organisms depends on the specific ecosystem. The most commonly used test species for terrestrial ecosystems are soil microorganisms, soil fauna, and terrestrial plant. For aquatic ecosystems, algae, crustaceans, and fish are generally investigated for their response to completely biodegradable plastics. From a toxicology standpoint, the fragments of completely biodegradable plastics incorporated into the soil are generally considered to be safe [16]. In theory, completely biodegradable plastics should be completely catabolized by soil microorganisms, converted to microbial biomass, CO_2, and water. However, complete breakdown in a reasonable amount of time is not always observed in practice [34].

Table 3 shows the reported ecological effects of completely biodegradable plastics. Most completely biodegradable plastics did not show adverse effects on the selected organisms except PLA and PBAT. Souza et al. found cytotoxic and genotoxic effects of PLA degradation products after 76 days of incubation in the compost on the common onion (*Allium cepa*) [37]. Likewise, the negative effect on the activities of both ammonium and nitrite-oxidizing bacteria caused by PLA mulch films after 84 days of incubation in the soil was also detected [39]. PLA granules can affect the health and behavior of lugworms and directly or indirectly reduce primary productivity of these habitats after 31 days of incubation in the sand [40]. Zhang et al. have shown that the four kinds of field-weathered biodegradable plastic mulch (PLA/PHA, Organix, BioAgri, Naturecycle) could be dragged into the burrows of earthworms when earthworms are foraging for food [44].

Although these studies measured the effects of degradation products at a specific time, they did not provide enough information on the components of the product, which are responsible for the toxicity. Identification of toxic degradation products can help to further understand the toxic mechanisms and produce safe biodegradable plastics.

4 Interaction of Biodegradable Plastics with Other Contaminants

4.1 Interaction with Heavy Metals

Some polymers are designed as sorbents. In order to improve the adsorption capacity of polymers, the surface of many polymer matrix composites can interact with the target chemicals [45]. For example, on a degradable polymer made of hyperbranched aliphatic polyester and cellulose (HAPE-Cell) [46], the adsorption capacity of

---

[1] Parts of this text are reused with permission from [21].

Table 3 Ecological effects of completely biodegradable plastics. Reused with permission from [21]

Polymer	Test material preparation	Test medium	Test system	Effect	Reference
Mater-BiDF04P (starch blend)	Powdered mulch film in the soil (10 g/800 g), incubation for 528 days	Aerobic agricultural soil	Nitrification test based on ISO 14238	No inhibition of the nitrification potential; biodegradable carbon source in soil potentially elicited microbial growth	[35]
Mater-Bi, DF04A,EF04P, AF05S0 (starch blend)	Powdered films in the soil (10 g/800 g), incubation for 6 months	Soil aqueous extracts	Set of acute and chronic bioassays with bacteria, protozoa, algae, plants, crustaceans, and earthworms	No adverse effects	[36]
PLA	PLA, nanocomposites of PLA and organoclays Cloisite 20A and Cloisite 30B in compost (50 g/300 g), incubation for 76 days	Compost aqueous extracts	*Allium cepa* (cytotoxicity, genotoxicity, mutagenicity)	Cytotoxic and genotoxic effects of PLA degradation products (not for the organoclays)	[37]
	Plastic films (0.3 mm thickness, 1 cm^2) in the soil, incubation for 8 months	Soil aqueous extracts	*Allium cepa* (phytotoxicity, cytotoxicity, genotoxicity, mutagenicity)	No adverse effects	[38]
	Plastic films (3 cm × 3 cm) in agricultural soil, incubation for 84 days	Agricultural soil	Microbial activity (nitrogen circulation activity)	Negative effect on the activities of both ammonium and nitrite-oxidizing bacteria	[39]
	Plastic granules (1.4–707 μm) in sand, incubation for 31 days	Sand sediments	Lugworms (biological activity, nutrient cycling, and primary productivity)	Affect the health and behavior of lugworms and directly or indirectly reduce primary productivity of these habitats	[40]
PBAT (Ecoflex®)	Plastic films (0.3 mm thickness, 1 cm^2) in the soil, incubation for 8 months	Soil aqueous extracts	*Allium cepa* (phytotoxicity, cytotoxicity, genotoxicity, mutagenicity)	No adverse effects	[38]
	Polymer granules (100–250 μm) in aqueous medium (350 mg/80 mL) with the actinomycete	Aqueous medium	Luminescent bacteria (light emission), crustacean Daphnia magna (mobility)	No adverse effects	[41]

(continued)

Table 3 (continued)

Polymer	Test material preparation	Test medium	Test system	Effect	Reference
	Thermomonospora fusca, incubation for 21 days				
	Plastic granules (2 mm × 20 mm) in sandy soil (1,000 mg/kg), incubation for 4, 10, 16, and 22 months	Sandy soil	Plant growth tests	No adverse effects	[42]
	Plastic films (3 cm × 3 cm) in agricultural soil (1.8 g/300 g), incubation for 7 months	Andosol soil	Soil microbiota and plant growth	Affected the growth of specific fungal species; little influence on the growth of *Brassica rapa* var. *Chinensis*	
PBS	Plastic films (3 cm × 3 cm) in agricultural soil, incubation for 84 days	Agricultural soil	Microbial activity (nitrogen circulation activity)	No adverse effects	[39]
PBS-starch	Plastic films (3 cm × 3 cm) in agricultural soil, incubation for 84 days	Agricultural soil	Microbial activity (nitrogen circulation activity)	No adverse effects	[15]
Modified starch-cellulose fiber composites	Microbial activity (nitrogen circulation activity)	Aqueous medium	Luminescent bacteria (light emission)	No adverse effects	[43]
PLA/PHA, Organix, BioAgri, Naturecycle	Plastic films (1.5 cm × 1.5 cm) in agricultural soil, incubation for 2 weeks	Aqueous medium; Skagit silt loam	Earthworms (*Lumbricus terrestris*) interaction with plastic mulches	Dragged plastic mulch into their burrows; plastic mulch was partially ingested, but only after weathering occurred	[44]

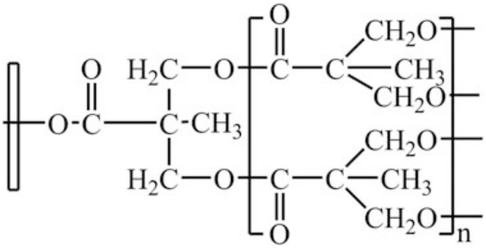


Fig. 5 The chemical structure of HAPE-Cell [47]

HAPE-Cell to Cu^{2+}, Hg^{2+}, Zn^{2+}, and Cd^{2+} was much higher when compared with cellulose. Gao et al. measured the adsorption capability of PVC, PP, PA, PE, and POM to Cu^{2+} and Cd^{2+}. The adsorption capacities of those non-degradable plastics to Cu^{2+} and Cd^{2+} are below 1 mg/g, which were much lower than that of HAPE-Cell (Fig. 5) [47]. Compared with commercial synthetic polymers, HAPE-Cell is degradable and will not cause secondary pollution. Thus HAPE-Cell is proposed as a promising sorbent for removal of the heavy metals.

PLA has been recognized as an eco-friendly alternative polymer for packing, clothing, and biomedical [48]. The degradation of the PLA is divided into two steps. Firstly, under suitable temperature and humidity, the PLA would become oligomers due to the hydrolysis of ester group. Then the smaller fragments could be degraded by microorganisms [49]. The elements of Bi, Pb, Zn, and Cd are often used as catalysts in PLA synthesis [50, 51]. When the polymers are degraded, these heavy metals may be transferred to soils, which could cause some ecological risks.

4.2 Interaction with Organic Contaminants

Many researches showed that PLA fibers had higher sorption capacity to dyes since they had more D-lactide units. Yang et al. used different disperse dyes to dye PLA and PET. PLA had higher color strength compared to PET since PLA had a lower refractive index under similar dyeing conditions [52]. Many studies have investigated the influence factor about the sorption of dyes on PLA. Karst et al. studied the effects of the structure of dyes on their sorption onto PLA [53]. The interaction energies between dyes and PLA showed a negative correlation with the percentage sorption of dyes on PLA. The functional groups $–N(C_2H4OCOCH_3)_2$ and $(CO)_2NC_3H_6OCH_3$ could form stronger interaction with PLA, while the functional groups –Br and –Cl could form weaker interaction with PLA. An investigation on the effects of dyeing on melting behavior of PLA using differential scanning calorimeter (DSC) was conducted. It was concluded that dyeing progress could decrease the restricting force and the crystallites became more perfect in the dyeing progress [54]. It was also reported that the rate of dyeing PLA was positively correlated with temperature, and the percentage exhaustion of dye reached 90% at 100°C [55].

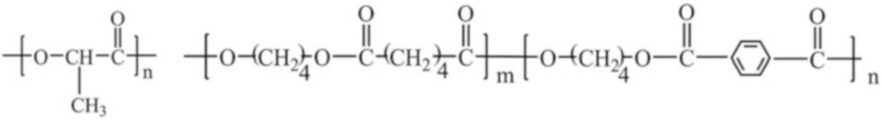


Fig. 6 The chemical structure of PLA (left) and PBAT (right)

PBAT was another typical biodegradable plastic (Fig. 6). When the sorption behavior of phenanthrene on PBAT, PE, and PS was investigated [56], the K_d values on PBAT, PE, and PS were measured to be 54,800, 15,600 and 1,340 L/kg, respectively. Much higher K_d of phenanthrene on PBAT mainly attributes to the rubbery subfraction of PBAT [56]. More researches need to be conducted since biodegradable plastics had various functional groups and their interaction with pollutants may be complicated.

4.3 Additives and Functional Monomers

Phthalate esters (PAEs) are plasticizers and additives that are also widely used in degradable plastic production [57, 58]. Polyolefins such as polyethylene and polypropylene are usually not accessible to direct microbial attack. Starch, as a natural polymer, can be degraded by microorganisms. When starch was mixed with polyolefins, the blends were easier to be degraded, if microorganisms can contact starch.

On the research of Siotto et al., aerobic biodegradation efficiency of ten biodegradable plastic monomer, adipic acid, azelaic acid, 1,4-butanediol, 1,2-ethanediol, 1,6-hexanediol, lactic acid, glucose, sebacic acid, succinic acid, and terephthalic acid, in soil was tested according to standard respirometric test, by measuring the carbon dioxide evolution [59]. During the 27–45 days of experiment, it was found that 1,4-butanediol, lactic acid, succinic acid, and glucose were completely biodegraded and the degradation efficiency of terephthalic acid was only 60%. The results showed that the degradation efficiency of the plastic monomer had a positive correlation with the percent of carbon converted to biomass.

5 Conclusions

5.1 Ecological Risks of Biodegradable Plastics

Plastics with very high molecular weights are not directly available to the living cells and therefore difficult to be harmless generally. However, low molecular weight additives can be toxic. Intermediates formed during incomplete biodegradation can accumulate in the surrounding soil, temporarily or permanently. These degradation intermediates can be monomers, oligomers, or metabolic derivatives and can interact with the living organisms. It is, therefore, important to assess the possible ecotoxic effects of the biodegradable plastics introduced into the soil.

To date, biodegradable plastics are a promising alternative to conventional plastic. Although there are a few studies on the effects of biodegradable plastic on the soil ecosystem, considerable gaps in our understanding of biodegradable plastics and their ecological risks on soil ecosystems are still present. First, while several studies have focused on short-term effects or acute toxicity of biodegradable plastics, and their long-term effects are unexplored. Second, the relationship between plastic composition and soil organism responses needs to be identified, because the parent polymer composition and breakdown products may lead to different risk. Third, biodegradable plastic effects on soil nutrient biogeochemistry are largely unexplored [16].

5.2 Development Prospect of Biodegradable Plastics

Currently, the biodegradable polymers have offered a possible solution to the disposal of plastic waste produced from various sources associated with traditional petroleum-derived plastics. Most biodegradable plastics are used in the packaging industry, agriculture, and specialized biomedical applications. Among these biodegradable plastics, PLA is the most promising candidate to replace current plastics, because of its good mechanical strength and low toxicity [60]. Nevertheless, biodegradable plastic represents just a tiny market as compared with the conventional petrochemical plastics, and their production has not reached the level of conventional plastics [61]. Although degradable plastics meet the environmental requirements, they have some limitations in heat resistance, barrier, and mechanical properties.

Next-generation biodegradable plastics should be biodegraded and recycled in a balanced way to make their reuse possible [61]. Consequently, we must understand the degradation mechanism and degradation products of biodegradable plastics under real environmental conditions. The effect of additives also needs to be considered in a life cycle assessment of biodegradable alternatives. Researchers related to different disciplines (chemistry, engineering, materials science, biogeochemistry, and climate science) should design more environment-friendly biodegradable plastics and develop more application individually or in collaboration, to make the society more sustainable [21, 61].

Similar to the plastics we currently use, the production of new materials must take into account their raw materials and service life, as well as the basic standards of production scalability and material performance. It will take time and the key multidisciplinary developments will be required. However, biodegradable plastics are the only known choice for the future development of plastics.

Acknowledgments The authors gratefully acknowledge the financial support by the Natural Science Foundation of China (41722304; 41773109) and the 111 Program, Ministry of Education, China (T2017002).

References

1. ASTM D 883-17 Standard Terminology Relating to Plastics. https://www.astm.org/DATABASE.CART/HISTORICAL/D883-17.htm
2. Ammala A, Bateman S, Dean K, Petinakis E, Sangwan P, Wong S, Yuan Q, Yu L, Patrick C, Leong KH (2011) An overview of degradable and biodegradable polyolefins. Prog Polym Sci 36(8):1015–1049. https://doi.org/10.1016/j.progpolymsci.2010.12.002
3. GBT 20197-2006 Define, classify, marking and degradability requirement of degradable plastic. http://openstd.samr.gov.cn/bzgk/gb/newGbInfo?hcno=97FCB8AB9135BC8B636253071C1AA6C2
4. Tokiwa Y, Calabia BP, Ugwu CU, Aiba S (2009) Biodegradability of plastics. Int J Mol Sci 10(9):3722–3742. https://doi.org/10.3390/ijms10093722
5. Song JH, Murphy RJ, Narayan R, Davies GB (2009) Biodegradable and compostable alternatives to conventional plastics. Philos Trans R Soc Lond Ser B Biol Sci 364(1526):2127–2139. https://doi.org/10.1098/rstb.2008.0289
6. Ahmed T, Shahid M, Azeem F, Rasul I, Shah AA, Noman M, Hameed A, Manzoor N, Manzoor I, Muhammad S (2018) Biodegradation of plastics: current scenario and future prospects for environmental safety. Environ Sci Pollut Res Int 25(8):7287–7298. https://doi.org/10.1007/s11356-018-1234-9
7. Shah AA, Hasan F, Hameed A, Ahmed S (2008) Biological degradation of plastics: a comprehensive review. Biotechnol Adv 26(3):246–265. https://doi.org/10.1016/j.biotechadv.2007.12.005
8. Madhavan Nampoothiri K, Nair NR, John RP (2010) An overview of the recent developments in polylactide (PLA) research. Bioresour Technol 101(22):8493–8501. https://doi.org/10.1016/j.biortech.2010.05.092
9. Bioplastics Market Data 2018; European Bioplastics: 2019. https://www.european-bioplastics.org/market/
10. Zhang S, Wang J, Liu X, Qu F, Wang X, Wang X, Li Y, Sun Y (2019) Microplastics in the environment: a review of analytical methods, distribution, and biological effects. Trends Anal Chem 111:62–72. https://doi.org/10.1016/j.trac.2018.12.002
11. Emadian SM, Onay TT, Demirel B (2017) Biodegradation of bioplastics in natural environments. Waste Manag 59:526–536. https://doi.org/10.1016/j.wasman.2016.10.006
12. Bioplastics Market Data 2014; European Bioplastics: 2015. https://www.european-bioplastics.org/market/
13. Sander M (2019) Biodegradation of polymeric mulch films in agricultural soils: concepts, knowledge gaps, and future research directions. Environ Sci Technol 53(5):2304–2315. https://doi.org/10.1021/acs.est.8b05208
14. Restrepo-Flórez J-M, Bassi A, Thompson MR (2014) Microbial degradation and deterioration of polyethylene – a review. Int Biodeterior Biodegradation 88:83–90. https://doi.org/10.1016/j.ibiod.2013.12.014
15. Iwata T (2015) Biodegradable and bio-based polymers: future prospects of eco-friendly plastics. Angew Chem Int Ed 54(11):3210–3215. https://doi.org/10.1002/anie.201410770
16. Bandopadhyay S, Martin-Closas L, Pelacho AM, DeBruyn JM (2018) Biodegradable plastic mulch films: impacts on soil microbial communities and ecosystem functions. Front Microbiol 9:819. https://doi.org/10.3389/fmicb.2018.00819

17. Zhang GS, Liu YF (2018) The distribution of microplastics in soil aggregate fractions in southwestern China. Sci Total Environ 642:12–20. https://doi.org/10.1016/j.scitotenv.2018.06.004
18. Dahman Y, Ugwu CU (2014) Production of green biodegradable plastics of poly (3-hydroxybutyrate) from renewable resources of agricultural residues. Bioprocess Biosyst Eng 37(8):1561–1568. https://doi.org/10.1007/s00449-014-1128-2
19. Thakur S, Chaudhary J, Sharma B, Verma A, Tamulevicius S, Thakur VK (2018) Sustainability of bioplastics: opportunities and challenges. Curr Opinion Green Sustain Chem 13:68–75. https://doi.org/10.1016/j.cogsc.2018.04.013
20. Slomkowski S, Penczek S, Duda A (2014) Polylactides-an overview. Polym Adv Technol 25 (5):436–447. https://doi.org/10.1002/pat.3281
21. Haider TP, Voelker C, Kramm J (2019) Plastics of the future? The impact of biodegradable polymers on the environment and on society. Angew Chem Int Ed 58(1):50–62. https://doi.org/10.1002/ange.201805766
22. Fahim IS, Chbib H, Mahmoud HM (2019) The synthesis, production & economic feasibility of manufacturing PLA from agricultural waste. Sustain Chem Pharm 12:100142. https://doi.org/10.1016/j.scp.2019.100142
23. Zumstein MT, Schintlmeister A, Nelson TF, Baumgartner R, Woebken D, Wagner M, Kohler-H-PE, McNeill K, Sander M (2018) Biodegradation of synthetic polymers in soils: tracking carbon into CO_2 and microbial biomass. Sci Adv 4(7):eaas9024. https://doi.org/10.1126/sciadv.aas9024
24. Chinaglia S, Tosin M, Degli-Innocenti F (2018) Biodegradation rate of biodegradable plastics at molecular level. Polym Degrad Stab 147:237–244. https://doi.org/10.1016/j.polymdegradstab.2017.12.011
25. Weiss MS, Abele U, Weckesser J, Welte W, Schiltz E, Schulz GE (1991) Molecular architecture and electrostatic properties of a bacterial porin. Science 254(5038):1627–1630. https://doi.org/10.1126/science.1721242
26. Lucas N, Bienaime C, Belloy C, Queneudec M, Silvestre F, Nava-Saucedo J-E (2008) Polymer biodegradation: mechanisms and estimation techniques. Chemosphere 73(4):429–442. https://doi.org/10.1016/j.chemosphere.2008.06.064
27. Sintim HY, Bandopadhyay S, English ME, Bary AI, DeBruyn JM, Schaeffer SM, Miles CA, Reganold JP, Flury M (2019) Impacts of biodegradable plastic mulches on soil health. Agric Ecosyst Environ 273:36–49. https://doi.org/10.1016/j.agee.2018.12.002
28. Volova TG, Gladyshev MI, Trusova MY, Zhila NO (2007) Degradation of polyhydroxyalkanoates in eutrophic reservoir. Polym Degrad Stab 92(4):580–586. https://doi.org/10.1016/j.polymdegradstab.2007.01.011
29. Tokiwa Y, Calabia BP (2004) Degradation of microbial polyesters. Biotechnol Lett 26 (15):1181–1189. https://doi.org/10.1023/B:BILE.0000036599.15302.e5
30. Auras R, Harte B, Selke S (2004) An overview of polylactides as packaging materials. Macromol Biosci 4(9):835–864. https://doi.org/10.1002/mabi.200400043
31. Kijchavengkul T, Auras R (2008) Perspective compostability of polymers. Polym Int 57 (6):793–804. https://doi.org/10.1002/pi.2420
32. Orr IG, Hadar Y, Sivan A (2004) Colonization, biofilm formation and biodegradation of polyethylene by a strain of Rhodococcus ruber. Appl Microbiol Biotechnol 65(1):97–104. https://doi.org/10.1007/s00253-004-1584-8
33. Kawai F, Watanabe M, Shibata M, Yokoyama S, Sudate Y, Hayashi S (2004) Comparative study on biodegradability of polyethylene wax by bacteria and fungi. Polym Degrad Stab 86 (1):105–114. https://doi.org/10.1016/j.polymdegradstab.2004.03.015
34. Li C, Moore-Kucera J, Miles C, Leonas K, Lee J, Corbin A, Inglis D (2014) Degradation of potentially biodegradable plastic mulch films at three diverse U.S. locations. Agroecol Sustain Food Syst 38(8):861–889. https://doi.org/10.1080/21683565.2014.884515

35. Ardisson GB, Tosin M, Barbale M, Degli-Innocenti F (2014) Biodegradation of plastics in soil and effects on nitrification activity. A laboratory approach. Front Microbiol 5(2–3):710. https://doi.org/10.3389/fmicb.2014.00710
36. Sforzini S, Oliveri L, Chinaglia S, Viarengo A (2016) Application of biotests for the determination of soil ecotoxicity after exposure to biodegradable plastics. Front Environ Sci 4:68. https://doi.org/10.3389/fenvs.2016.00068
37. Souza PMS, Corroqué NA, Morales AR, Marin-Morales MA, Mei LHI (2013) PLA and organoclays nanocomposites: degradation process and evaluation of ecotoxicity using Allium cepa as test organism. J Polymers Environ 21(4):1052–1063. https://doi.org/10.1007/s10924-013-0604-0
38. Palsikowski PA, Roberto MM, Sommaggio LRD, Souza PMS, Morales AR, Marin-Morales MA (2017) Ecotoxicity evaluation of the biodegradable polymers PLA, PBAT and its blends using Allium cepa as test organism. J Polymers Environ 26:1–8. https://doi.org/10.1007/s10924-017-0990-9
39. Adhikari D, Mukai M, Kubota K, Kai T, Kaneko N, Araki KS, Kubo M (2016) Degradation of bioplastics in soil and their degradation effects on environmental microorganisms. J Agric Chem Environ 05:23–34. https://doi.org/10.4236/jacen.2016.51003
40. Green DS, Boots B, Sigwart J, Jiang S, Rocha C (2016) Effects of conventional and biodegradable microplastics on a marine ecosystem engineer (Arenicola marina) and sediment nutrient cycling. Environ Pollut 208(Pt B):426–434. https://doi.org/10.1016/j.envpol.2015.10.010
41. Witt U, Einig T, Yamamoto M, Kleeberg I, Deckwer WD, Müller RJ (2001) Biodegradation of aliphatic-aromatic copolyesters: evaluation of the final biodegradability and ecotoxicological impact of degradation intermediates. Chemosphere 44(2):289–299. https://doi.org/10.1016/S0045-6535(00)00162-4
42. Piotr R, Micha K, Micha S, Piotr K, Marek K (2010) Study of aliphatic-aromatic copolyester degradation in sandy soil and its ecotoxicological impact. Biomacromolecules 11(4):839. https://doi.org/10.1021/bm901331t
43. Rudnik E, Milanov N, Matuschek G, Kettrup A (2008) Ecotoxicity of biocomposites based on renewable feedstock – preliminary studies. Chemosphere 70(2):337–340. https://doi.org/10.1016/j.chemosphere.2007.06.026
44. Zhang L, Sintim HY, Bary AI, Hayes DG, Wadsworth LC, Anunciado MB, Flury M (2018) Interaction of Lumbricus terrestris with macroscopic polyethylene and biodegradable plastic mulch. Sci Total Environ 635:1600–1608. https://doi.org/10.1016/j.scitotenv.2018.04.054
45. Zhao X, Lv L, Pan B, Zhang W, Zhang S, Zhang Q (2011) Polymer-supported nanocomposites for environmental application: a review. Chem Eng J 170(2):381–394. https://doi.org/10.1016/j.cej.2011.02.071
46. Liu P (2007) A novel degradable adsorbent of the hyperbranched aliphatic polyester grafted cellulose for heavy metal ions. Turk J Chem 31(4):457–462
47. Gao F, Li J, Sun C, Zhang L, Jiang F, Cao W, Zheng L (2019) Study on the capability and characteristics of heavy metals enriched on microplastics in marine environment. Mar Pollut Bull 144:61–67. https://doi.org/10.1016/j.marpolbul.2019.04.039
48. Tsiropoulos I, Faaij APC, Lundquist L, Schenker U, Briois JF, Patel MK (2015) Life cycle impact assessment of bio-based plastics from sugarcane ethanol. J Clean Prod 90:114–127. https://doi.org/10.1016/j.jclepro.2014.11.071
49. Hussain T, Tausif M, Ashraf M (2015) A review of progress in the dyeing of eco-friendly aliphatic polyester-based polylactic acid fabrics. J Clean Prod 108:476–483. https://doi.org/10.1016/j.jclepro.2015.05.126
50. Hua J-J, Yang J, Hu Y-F, Wei J, Li S-M (2008) Synthesis of polylactide with low-toxic zinc catalysts. Acta Chim Sin 66(24):2730–2734
51. Lebedev SM (2019) Manufacturing poly(lactic acid)/metal composites and their characterization. Int J Adv Manuf Technol 102(9–12):3213–3216. https://doi.org/10.1007/s00170-019-03420-y

52. Yang Y, Huda S (2003) Comparison of disperse dye exhaustion, color yield, and colorfastness between polylactide and poly(ethylene terephthalate). J Appl Polym Sci 90(12):3285–3290. https://doi.org/10.1002/app.13062
53. Karst D, Nama D, Yang Y (2007) Effect of disperse dye structure on dye sorption onto PLA fiber. J Colloid Interface Sci 310(1):106–111. https://doi.org/10.1016/j.jcis.2007.01.037
54. Mogi K, Kubokawa H, Hatakeyama T (2002) Effect of dyeing on melting behavior of poly (lactic acid) fabric. J Therm Anal Calorim 70(3):867–875. https://doi.org/10.1023/a:1022216622433
55. Wu J, Guo H, Ke J, Fan J (2013) Studies on kinetic and thermodynamic parameters of natural dye curcumin on PLA fibre. Indian J Fibre Textile Res 38(4):424–426
56. Zuo L-Z, Li H-X, Lin L, Sun Y-X, Diao Z-H, Liu S, Zhang Z-Y, Xu X-R (2019) Sorption and desorption of phenanthrene on biodegradable poly(butylene adipate co-terephtalate) microplastics. Chemosphere 215:25–32. https://doi.org/10.1016/j.chemosphere.2018.09.173
57. Wang J, Luo Y, Teng Y, Ma W, Christie P, Li Z (2013) Soil contamination by phthalate esters in Chinese intensive vegetable production systems with different modes of use of plastic film. Environ Pollut 180:265–273. https://doi.org/10.1016/j.envpol.2013.05.036
58. Wang J, Chen G, Christie P, Zhang M, Luo Y, Teng Y (2015) Occurrence and risk assessment of phthalate esters (PAEs) in vegetables and soils of suburban plastic film greenhouses. Sci Total Environ 523:129–137. https://doi.org/10.1016/j.scitotenv.2015.02.101
59. Siotto M, Sezenna E, Saponaro S, Innocenti FD, Tosin M, Bonomo L, Mezzanotte V (2012) Kinetics of monomer biodegradation in soil. J Environ Manag 93(1):31–37. https://doi.org/10.1016/j.jenvman.2011.08.018
60. Luckachan GE, Pillai CKS (2011) Biodegradable polymers – a review on recent trends and emerging perspectives. J Polym Environ 19(3):637–676. https://doi.org/10.1007/s10924-011-0317-1
61. Ahmed T, Shahid M, Azeem F, Rasul I, Shah AA, Noman M, Hameed A, Manzoor N, Manzoor I, Muhammad S (2018) Biodegradation of plastics: current scenario and future prospects for environmental safety. Environ Sci Pollut Res 25(8):7287–7298. https://doi.org/10.1007/s11356-018-1234-9