Journal of Cleaner Production 312 (2021) 127816

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A review of biodegradable plastics to biodegradable microplastics: Another ecological threat to soil environments?

Meng Qin [1], Changya Chen [1], Biao Song, Maocai Shen, Weicheng Cao, Hailan Yang, Guangming Zeng [*], Jilai Gong [**]

College of Environmental Science and Engineering, Hunan University and Key Laboratory of Environmental Biology and Pollution Control (Hunan University), Ministry of Education, Changsha, 410082, PR China

ARTICLE INFO

Handling editorCecilia Maria Villas Bôas de Almeida

Keywords:
Biodegradable plastics
Microplastics
Soils
Ecological impacts
Biodegradable microplastics

ABSTRACT

Biodegradable plastics attract public attention as promising substitute for non-degradable plastics that trigger serious plastic pollution, and they are claimed to be environmentally harmless and biodegradable by microorganisms. However, not all biodegradable plastics are completely degradable under natural conditions. Some of them may be disintegrated into microplastics more rapidly than conventional plastics, emerging as another threat to soil environments. As a part of microplastics, biodegradable microplastics may pose stronger negative effects on several soil species than oil-based microplastics under some conditions. Currently, there is a fiercely increasing trend to replace nondegradable plastic commodities with biodegradable ones. Therefore, to discuss the ecological safety of biodegradable plastics is essential before promoting wide application of them during commercial use. This review provided a brief introduction on biodegradable plastics and summarized their deterioration behaviors in terrestrial environments, together with evidences on releases of additives and biodegradable microplastics. Then, potential adverse effects of biodegradable microplastics in soil ecosystems, including responses on soil properties, microbial communities, and several soil species were discussed, suggesting biodegradable microplastics as a potential threat to ecological safety of soil ecosystems. By this token, biodegradable plastics might not be a panacea to the existing "white pollution" and need further exploring.

1. Introduction

The wide application of plastic materials benefits all aspects of our daily life, including packaging, agricultural mulching, even construction and manufacture (Chae and An, 2018). However, the increasing consumption of fossil fuel resources, together with poor waste management of plastic wastes, are now posing ecological threats to various environments and even human health (Prata et al., 2020; Shen et al., 2019; Ye et al., 2019). After deposited into the environment, plastic wastes undergo decomposition by a series of natural forces like mechanical abrasion, ultraviolet (UV) degradation, oxidation, and biodegradation, disintegrating into smaller fragments. Those tiny plastic pieces smaller than 5 mm were defined as "microplastics (MPs)" by Thompson et al. (2004), emerging as a novel type of contaminant. MPs that enter into the environment with micron sizes are classified into "primary microplastics", whereas those undergo fragmentation from large debris are "secondary microplastics" (Akdogan and Guven, 2019).

Microplastic pollution has been detected in all types of environmental media (Liu et al., 2018; Scheurer and Bigalke, 2018; Wen et al., 2018). Among them, soil systems are gaining special concerns in the past few years, as researchers suggest that the content of MPs in soil environments may be 4–23 times greater than that in marine systems (Horton et al., 2017). Several main contributors have been identified as MPs sources in soils. High MPs concentrations were documented in agricultural lands due to fragmentation of plastic mulching films and reuse of sewage sludge for soil fertility improvement (Huang et al., 2020; Steinmetz et al., 2016; Ziajahromi et al., 2017). Landfill, surface runoff and atmospheric deposition introduce MPs into soil environments (Dris et al., 2016; Hurley and Nizzetto, 2018). Besides, improper waste management and other human activities also account for MPs pollution (Feng et al., 2020).

Once disseminated into soil systems, MPs interact with the ambient

* Corresponding author. College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China.
** Corresponding author. College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China.
E-mail addresses: zgming@hnu.edu.cn (G. Zeng), jilaigong@gmail.com (J. Gong).
[1] These authors contribute equally to this article.

https://doi.org/10.1016/j.jclepro.2021.127816
Received 6 February 2021; Received in revised form 27 May 2021; Accepted 31 May 2021
Available online 3 June 2021

environments. As exogenous input, MPs have been validated to exert influences on both abiotic and biotic components in soils, depending on their particle characteristics and environmental factors (Shen et al., 2020a; Xu et al., 2020). Some ecotoxicological studies documented the detrimental effects of MPs on soil properties, microbial communities, and soil biota, and some of them even triggered lethal effects (Guo et al., 2020; Wang et al., 2020a). Besides, due to the properties of persistency and large specific surface area, microplastic debris possess the ability to concentrate other environmental pollutants like heavy metals and persistent organic pollutants (POPs) following different mechanisms, potentially altering their distribution patterns and bioaccessibilities in soils (Hartmann et al., 2017; Tourinho et al., 2019).

Currently, the end-of-life treatments for plastic wastes are basically incineration, landfill disposal, and recycling, but each of them has huge limitations and remains uncontrolled (Walker and Rothman, 2020). To alleviate the current pollution status of both macro- and micro-plastics, researchers have been making great efforts searching for proper substitutes for conventional non-degradable plastic polymers (Rujnic-Sokele and Pilipovic, 2017). The appealing notion of "biodegradable plastics (BPs)" came into public attention as replacement for non-degradable plastic materials. It is claimed that BPs can be converted to CO_2 and H_2O as final products by naturally-occurring microorganism mineralization, providing new pathways for end-of-life treatment for plastic wastes like anaerobic digestion and composting (Lambert and Wagner, 2017; Tabone et al., 2010). Problematically, 100% degradation of biodegradable materials cannot be achieved under natural environments (Kubowicz and Booth, 2017; Viera et al., 2020). Evidences showed that BPs in natural environments also led to generation of biodegradable microplastics (BMPs) like conventional oil-based MPs did (Bagheri et al., 2017; Shruti and Kutralam-Muniasamy, 2019). In fact, since BPs are more vulnerable to degradation forces, more BMPs might be generated from BPs than MPs derived from non-degradable feedstocks within the same time frame, probably leading to more severe BMPs pollution among soil ecosystems (Fojt et al., 2020; Shruti and Kutralam-Muniasamy, 2019). Presently, most studies focus solely on oil-based non-degradable plastics, while overlooking the so-called BPs as potential threats due to their negligible output. Even fewer studies have paid attention to BMPs derived from BPs and their toxic impacts on soil species (Boots et al., 2019; Green et al., 2017). The market share of BPs is expanding at an unprecedented rate with the increasing public awareness of sustainable development (RameshKumar et al., 2020). Therefore, if we intend to replace conventional plastics with BPs in our daily life, to evaluate whether BPs and the generated BMPs would alleviate plastic pollution or induce greater ecological impacts is of great significance. A previous discussion article written by Shen et al. (2020b) demonstrated the potential risks of replacing non-degradable plastics with BPs. The article was conducted with the following aspects: the functionalities of BPs in practical use, end-of-life treatments, costs, public awareness, and the degradability of BPs in natural environments. Although the authors mentioned the generation of BMPs and their subsequent ecological impacts, the points were presented without further discussion on how BMPs were generated and their ecotoxic mechanisms compared with non-degradable MPs.

The objective of this paper is to provide an overview on the current situation of BPs and their potential threats to soil ecosystems as BMPs. The article conducts the review as follows (Fig. 1): (1) introduction of typical BPs and their applications; (2) generation of BMPs derived from large-sized BPs; (3) potential biological effects of BMPs including direct and indirect effects; (4) whether it is ecologically safe to replace conventional non-degradable plastics with BPs from the perspective of the generated MPs and BMPs; and (5) perspectives and future research needs. In this paper, BPs refer to plastic materials that can be broken down and mineralized by biotic (mainly microbial) forces. BMPs are micron-sized plastic debris generated from BPs. "MPs" or "conventional MPs" in this context, refer to nondegradable microplastics. The notion "conventional plastics" mentioned in this paper refers to plastics that cannot be mineralized by naturally-occurring biodegradation. Other types of degradable plastics that can be disintegrated by chemical and UV forces through adding photo- or chemical oxidants, such as oxo-degradable and photo-degradable plastics, are not within our scope.

2. Methodology

Firstly, we formulated our main questions of this paper both broadly

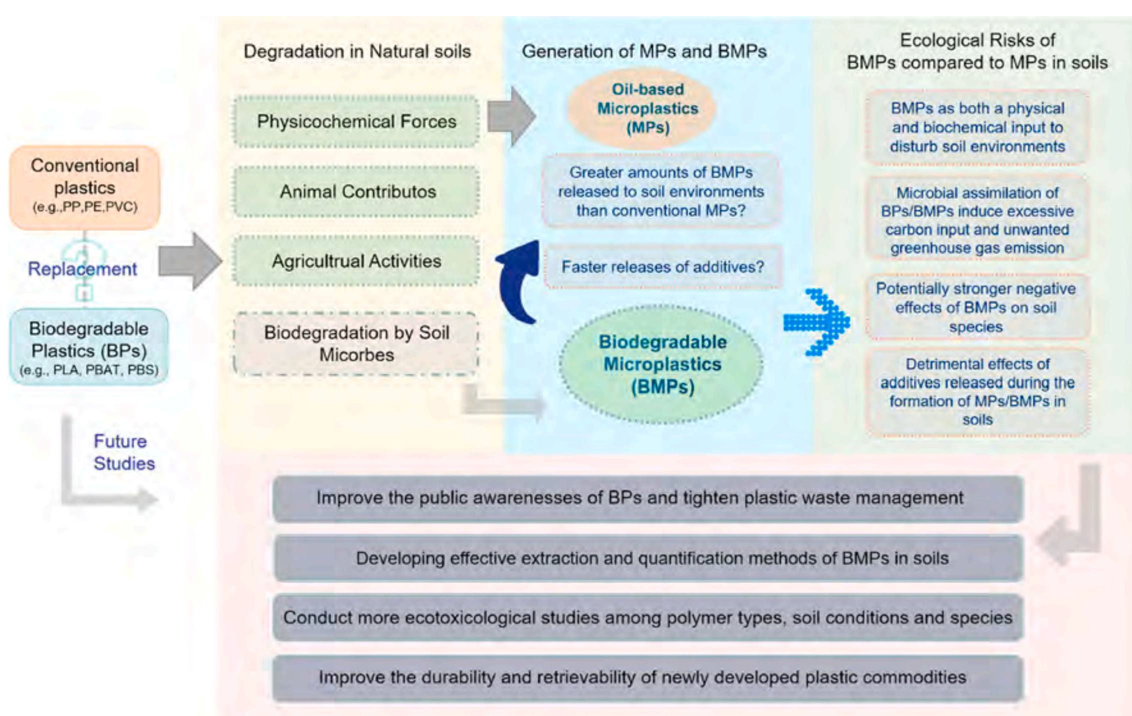

Fig. 1. Overview of the review structure.

and focally. Since replacing conventional plastics with BPs has been considered as a popular solution to the current MPs pollution by many researchers, we aim to discuss whether BPs are able to eliminate MPs without exerting negative effects on soil environments, from the generation of BMPs to their potential impacts in natural soils. We conducted our first screening using Web of Science, ResearchGate, ScienceDirect, Google Scholar, and SpringerLink databases with a combination of subject headings and keywords including "biodegradable microplastics", "biodegradable plastic degradability", "ecological impacts", "soil environments", "soil microbes", "soil plant", and "soil animal". The initial screening carried out 347 articles. Although several review articles have been published concerning BPs and MPs impacts on soil ecosystems respectively, we noticed that there is no critical review about the potential ecological impacts of BMPs on soil environments.

Next, 138 studies were selected after exclusion of duplicates and specific evaluation based on article types, research field, and relevance to our topic. Finally, they were divided into several categories for further discussion, including: current applications and market of BPs; the breakdown of large-sized BPs in natural soils; the generation of BMPs; and the direct and indirect ecological impacts of BMPs on soil ecosystems.

3. Typical BPs and their degradation in soils

3.1. Several typical biodegradable polymers and their applications

Up to now, clear notions and classification between "biodegradable plastics (BPs)", "bio-based plastics", and "bioplastics" have not yet been standardized, and that confusion usually occurs between BPs and bio-based plastics (Rujnic-Sokele and Pilipovic, 2017). According to Lambert and Wagner (2017), BPs are plastic materials containing high-molecular polymers that can be degraded by biological forces like enzymatic activities or microorganism metabolisms with the end-points of CO_2 and H_2O. Polylactic acid (PLA) and polyhydroxyalkanoate (PHA) are two typical biodegradable polymers derived from biogenic feedstocks. While petroleum-based poly(butylene adipate-co-terephthalate) (PBAT) and polycaprolactone (PCL) polymers also reveal biodegradability, indicating that the concept of "biodegradable" is not based on source materials, but on specific polymer structures that determine biodegradabilities. Contrastively, bio-based plastics are derived from renewable biological origins including animals, plants, and microorganisms instead of petroleum resources, but not necessarily biodegradable. Generally, they are made from bioethanol or biofuel, such as bio-polyethylene (bio-PE), bio-polyvinyl chloride (bio-PVC), and so on, providing insights to alleviate the shortage of oil resources and the related environmental pollution status (Siracusa and Blanco, 2020). The notion "bioplastics", refers to a sum of BPs and bio-based plastics. Within this context, we put special focus on BPs.

Currently, with more countries putting regulations on the production and marketing of non-degradable plastic products, the demand for BPs is increasing at an unprecedented rate, and the global BPs market is projected to reach $6.73 billion by 2025 (European Bioplastics, 2018; European Bioplastics, 2020). BPs have exhibited great potential replacing non-degradable plastics in many fields, such as agricultural activities, food industries, and medical treatments (Arrieta et al., 2017; Iwata, 2015; Viera et al., 2020). Among them, PLA, PHA, and starch-based materials act as main contributors in BPs market (do Val Siqueira et al., 2021; Rai et al., 2021). Different polymers reveal distinct properties and degradation behaviors. Taken PLA and PHA materials as examples, both plastic materials exhibit comparable properties with most non-degradable materials, making them applicable to replace nondegradable agricultural mulching films, grocery bags, and other commodities (Elsawy et al., 2017; Kasirajan and Ngouajio, 2012; Sharma et al., 2021). While another widely applied biodegradable materials, starch-based materials, being commercialized though, reveal relatively poor mechanical and hydrophilic properties, which hamper their practical use (do Val Siqueira et al., 2021; Gómez-Aldapa et al., 2020). Therefore, blending neat biodegradable polymers with other materials or adding additives during manufacture is of importance to obtain desired properties for different functions (Amulya et al., 2021; Gómez-Aldapa et al., 2020; Iwata, 2015). BPs during commercial use, such as Mater-Bi®, Ecoflex®, and co-polymer composites are synthesized by blending of different polymers and materials, making them comparable to conventional non-degradable plastics (Di Mola et al., 2021; Yang et al., 2020a). Adding photo- or chemical oxidants to accelerate disintegration is another pathway to achieve "degradability" of non-degradable plastics (Ojeda et al., 2009). However, it comes with a problem that the plastic products can be only disintegrated into small pieces, and the remaining "invisible", but non-degradable byproducts could be released or further leached into the groundwaters without being detected (Gómez and Michel, 2013). Also, the recycling of BPs since they require a new waste stream for compostable and BPs to be widely available.

3.2. Decomposition of BPs in soils

3.2.1. Factors determining the decomposition of BPs

Considering the incomplete degradation of BPs in natural soil environments, it is vital to discuss the degradation behaviors of BPs and generation of BMPs if we intend to investigate the ecological effects of BMPs in natural soil systems.

The main degradation processes of BPs were divided into fragmentation and biodegradation steps (Shen et al., 2020b). Non-degradable polymers like PE, polypropylene (PP), are mostly subject to fragmentation by physical and chemical weathering forces (e.g., physical abrasion, wind or water erosion and ultraviolet (UV) radiation), breaking into smaller pieces. Although some plastic-degrading microbes such as *Actinobacteria*, *Hyphomonadaceae*, *Bacteroidetes*, and *Proteobacteria* were detected enriched on the surfaces of MPs and the ambient soils, the degradation rate was slow enough to be ignored (Chai et al., 2020; Zettler et al., 2013). As for biodegradable materials, besides abiotic degradation forces, specific microorganisms could further mineralize the plastic fragments into CO_2 and H_2O as final products under specific laboratory conditions. Since complete degradation is rarely obtained, we summarized some main factors influencing BPs degradation under natural soil systems and made comparison with degradation behaviors of conventional plastics in soils (Fig. 2). Table 1 and Table 2 summarized some soil degradation studies of BPs and provided the possible explanations for their distinct degradation behaviors.

Polymer characteristics and composition are decisive factors determining biodegradation rate of BPs. Smaller sized BPs and BMPs have larger specific area to interact with various degradation factors, leading to more rapid deterioration in soil environments (Chinaglia et al., 2018; Tosin et al., 2019). The structural differences among different polymers lead to distinct degradation behaviors even under the same laboratory settings (Al Hosni et al., 2019; Bagheri et al., 2017; Sintim et al., 2020). For instance, crosslinking phenomena make PBAT polymers brittle and easily fragmentated in natural soil systems (Kijchavengkul et al., 2010a). To overcome the difficulties of PBAT materials during commercial use, blending them with other polymers including PLA, starch to enhance the durability is a common solution (Boyandin et al., 2013; Briassoulis, 2006). In line with the above conclusion, Weng et al. (2013) confirmed the slower erosion of PBAT-containing materials with the increasing PLA content in the biodegradable material blends. As demonstrated by extensive degradation studies, higher polymer crystallinity postponed the material biodegradation (Kanie et al., 2002; Mariani et al., 2007). And the amorphous region inside the material was more vulnerable to degradation forces than the crystalline part (Kijchavengkul et al., 2010b). Besides, plastic additives, even as minor components, can largely alter the degradation behaviors of BPs (Qi et al., 2021). For instance, mixing pro-degradants during plastic production, thereby enhancing the degradability of the materials, achieves faster

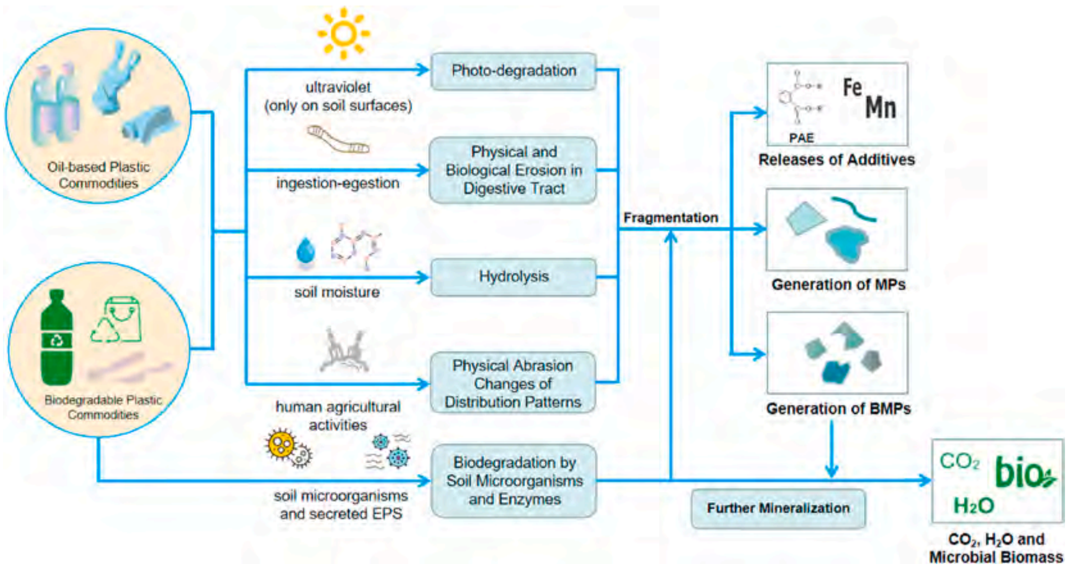

Fig. 2. Degradation of conventional plastics and BPs in soil environments.

degradation than the original materials (Schiavo et al., 2020). On the contrary, antioxidants are embedded during manufacture to prolong the lifespan of plastic commodities (Hahladakis et al., 2018).

Generally, faster biodegradation rate was observed under composting or microorganism-rich conditions, with higher temperature, humidity, and the help of specific microorganisms (Adhikari et al., 2016; Roohi et al., 2017). Zhang et al. (2019) identified functional bacteria including *Sphingomonas*, *Bacillus*, and *Streptomyces* as PBAT/PLA degrading species in two natural soil samples. Microbes themselves, together with secreted extracellular polymeric substance (EPS), break down the polymer chains of BPs and convert them into monomers, biomass, methane and finally CO_2 and H_2O. Laboratory studies that confirmed mineralization of BPs by incubating pure strains were extensive, while microorganisms that possessed the ability to degrade the specific polymer type might not exist extensively in natural soils (Apinya et al., 2015; Brodhagen et al., 2015). It is also noteworthy that environmental factors under natural environments also exert influences on the microbial activities, thereby disturbing the biodegradation of BPs (Hoshino et al., 2001; Sintim et al., 2020). Taken oxygen content as an example, the erosion of biodegradable polymers was slowed down under anaerobic conditions underneath soil profile than the soil surfaces (Cho et al., 2011; Napper and Thompson, 2019; Weng et al., 2013). In addition, temperature, soil moisture, soil structural component, and other environmental factors that stimulate or suppress the microbial activities possibly change the biodegradation rate (Borrowman et al., 2020; César et al., 2009; Shogren et al., 2003).

Likewise, abiotic processes, including pyrolysis, hydrolysis, and photo-degradation, contribute to BPs decomposition more rapidly. La Mantia et al. (2020) suggested that with the assistance of UV irradiation, the biodegradation of BPs was accelerated. Whereas, in natural soils, photo-degradation is largely hindered owing to soil burial of plastic wastes (Hayes et al., 2017). According to a PLA degradation study done by Karamanlioglu and Robson (2013), when environmental temperature was above the glass transition temperature (T_g) of the polymer, PLA materials became less stable with higher water absorption capacities, stimulating hydrolysis and microbial attachment. The above discussion indicates that abiotic forces help to disintegrate plastics into small fragments, thereby increasing specific surface area of the materials and the contact area of BPs with degradation contributors (Sintim et al., 2020).

The co-existence of BPs with other chemical substances in soils potentially triggers interactions, affecting their deterioration behaviors at the same time. One study validated the accelerated degradation rate of both oil-based PE and biodegradable PBAT plastic films by the amendment of a broad-spectrum fungicide, prothioconazole (Li et al., 2020b). Ingestion of MPs by soil organisms or microbial contributors within plant rhizosphere also accounted for BPs biodegradation (Janczak et al., 2018). Since tiny-sized MPs are easily mistaken for food, ingestion of plastic residues by soil animals, the subsequent degradation within digestive tracts, and the final egestion of the plastic materials accelerate BPs degradation in soils (Kwak and An, 2021; Sanchez-Hernandez et al., 2020).

3.2.2. Releases of additives and other substances during polymer decomposition

To obtain greater performances and other properties of plastic products during practical use, additives such as plasticizers, dyes, photostabilizers, and pro-oxidants are mixed with neat polymers during manufacture (Soroudi and Jakubowicz, 2013). Presently, common types of plastic modifiers are classified into stabilizers (to prolong lifespan of plastic products), plasticizers (to modify mechanical properties), antioxidants (to delay oxidation of plastics), pro-oxidants (to obtain faster degradation), surfactants (to promote surface properties), and other additives (to improve functionality) based on their different purposes (Gunaalan et al., 2020; Hahladakis et al., 2018). Releases of these potentially harmful chemicals probably occur during weathering processes of plastics under natural soil conditions, which is regarded as another challenge in plastic contamination control (Serrano-Ruíz et al., 2018; Shen et al., 2019). Heavy metals (like lead and chromium), pigments, phthalate acid esters (PAE), poly brominated diphenyl ethers (PBDE) and other biotoxic additives have been detected in leachates from both aged MPs and plastic films, posing biological threats as mixture of multicomponent pollutants (Bejgarn et al., 2015; Luo et al., 2020; Wang et al., 2016). Up to now, biotoxicity induced by leached chemicals from incubation of MPs and BMPs have been observed (Serrano-Ruíz et al., 2018; Zimmermann et al., 2020).

Similar problems arise in the case of BPs products (Balestri et al., 2019). Despite the existed knowledge gap, releases of additives from BPs in soils were recorded. A pile composting study conducted by Sintim et al. (2020) verified this concern on BPs. During the 18-week degradation test, the added carbon black, to retain mechanical properties and durability of the tested biodegradable mulching films (a PLA/PHA blend film and a co-polyester film containing PBAT polymers), were detected in leachates. Another water incubation study confirmed the releases of

Table 1
Degradation factors of BPs in soil environments.

Degradation factors		Testing Materials	Description	Environmental Conditions	Time	Degradation Results	Explanation	References
Soil biotic forces	Microbial biomass	PBS-starch, PBS, PLA	0.25% Soil burial; Different bacterial biomass	Different bacterial biomass; 25 °C	28 days, 2 years	Higher degradation ratio with higher bacterial biomass	Degradation closely related to soil microbial activities	Adhikari et al. (2016)
	Microbes	PLA coupons	With/without environmental microbes	Soil burial; Sterile soil extracts	12 months	Faster degradation in microorganism-rich soils	Direct role for microorganisms in PLA degradation	Karamanlioglu and Robson (2013)
	Plastic-degrading species	PLA sheets	Inoculated with/without several actinomycetes genera	ASTM D5988-12	90 days	Highest PLA degradability in soils inoculated with *Pseudonocardia* sp. RM423	Highest attachment and colonization of biofilms on PLA	Apinya et al. (2015)
	Plant Rhizosphere	PLA and PET films	Inoculated with 4 plant-promoting species	Pot incubated with planta and microbes	6 months	Accelerated PLA biodegradation by rhizosphere microbes	Efficient production of biof	Janczak et al. (2018)
	Animal activities	4 biodegradable plastic mulches	Weathering by soil burial	Earthworms feeding test	Weathering: 6, 12 months	Ingestion of soil-buried biodegradable mulches	Bioturbation and vermicomposting	Sanchez-Hernandez et al. (2020)
Soil abiotic forces	Depths	PHA/PLA blends with different ratio	20 and 40 cm underneath surfaces	20 ± 3 °C, watered, seeds planted	5 months	Faster PHA degradation at 20 cm but lower at 40 cm	Preferential PLA microbial degradation under aerobic conditions	Weng et al. (2013)
	Climate	Commercial BPs films	BioAgri, Naturecycle, Organix, PLA/PHA films	Field trials in two sites	36 months	Climate: Warmer > cooler; summer > winter	Promoted degradation under higher moisture and temperature	Sintim et al. (2020)
	Temperature	Biodegradable plastic sheets	PCL, PLA, PHB, and PBS	25, 37, and 50 °C	10 months	Higher degradation rate under higher temperatures	Melting temperatures, glass transition temperatures	Al Hosni et al. (2019)
		PBS plastics	pellets: 500–700 μm, 200–355 μm, 5–75 μm	28 ± 2 °C in dark, soil moisture 14.6%	138 days	Smaller sized samples degraded more rapidly	Biodegradation was related to total available surface area	Chinaglia et al. (2018)
		PLA coupons	Under 25, 37, 45, 50, and 55 °C	Soil burial	12 months	PLA degraded faster at higher temperature	High temperature favored PLA hydrolysis	Karamanlioglu and Robson (2013)

Table 2
Continued.

Degradation factors		Testing Materials	Description	Environmental Conditions	Time	Degradation Results	Explanation	References
Soil abiotic forces	Soil Texture	PCL/S blends	Burial in sandy and clayey soil	ASTM D5988-03[a]; 28 °C in dark	120 days	Faster degradation in clayey soils	Stronger microbial proliferation in finer soil texture	César et al. (2009)
	Soil moisture	PCL based polyurethane mulch	Two moisture, light levels, and soil types	Pot experiment; 19–25 °C	140 days	Soil moisture as the most important factor	Important role of moisture in bulk erosion of material	Borrowman et al. (2020)
	Co- existed chemicals	1% PBAT MPs (0.85–2.00 mm)	With/without pesticide prothioconazole	24 ± 1 °C; 12/12h light/dark cycle	6 weeks	Prothioconazole promoted MPs degradation	Need further studying	Li et al. (2020b)
BMPs characteristics	Material composition	PHA/PLA blending films	P(3HB,4HB)/PLA ratio from 100/0 to 0/100	20 ± 3 °C; seeds planted; regular watering	5 months	Faster degradation with increasing PHA content	Favorable in PHA microbial mineralization	Weng et al. (2013)
	Material composition	Two materials and their blends	PCL, AS-E, and PCL/AS-E	ASTM D5988-96[a]; 28 °C	90 days	Degradability: AS-E > PCL/AS-E > PCL	Preferential microbial attack on starch; Higher crystallinity in PCL	Mariani et al. (2007)
BPs characteristics	Polymer types	4 types of biodegradable materials	plastarch, co-polyester + corn-based plastics, starch-derived plastics, and PHA	ASTM D5988-03[a]; 20 ± 2 °C	660 days	Biodegradability: PHA > co-polyester + corn-based plastic > plastarch	Both enzymatic and chemical hydrolysis contribute to PHA degradation	Gómez and Michel (2013)
	Polymer structures	4 biodegradable plastic sheets	PCL, PLA, PHB, and PBS	25, 37, and 50 °C	10 months	PCL showed the fastest degradation	Polyesters (PCL) with side chains showed faster degradation	Al Hosni et al. (2019)
	Polymer structure	PBAT films		Soil burial at 0.3 m depth	39 weeks	Crosslinked structure delayed degradation	Crosslinked structures limited accessible water and microbes to polymer chain	Kijchavengkul et al. (2010a)
	Polymer structure	PHA specimens	PHBV, PHB	Environmental soil burial under 15 cm-depth	10–12 months	Increases in crystallinity in all PHA specimens	Preferential attack in amorphous regions inside the material	Boyandin et al. (2013)
	Particle sizes	Mater-Bi HF03V1	355–500 μm, 180–210 μm, 75–125 μm	28 ± 2 °C; pH 7.9; moisture: 14.6%	276 days	Smaller-sized materials degraded more rapidly	Larger available surface area	Tosin et al. (2019)
BPs characteristics	Particle sizes	PBS pellets	500–700 μm, 200–355 μm, 50–75 μm	28 ± 2 °C in dark; Moisture: 14.6%	140 days	Rapid degradation in smaller-sized pellets	Materials with larger surface area loaded with more microorganisms	Chinaglia et al. (2018)
	Material shapes	plastarch, co-polyester + corn-based plastics, starch-derived plastics, and PHA	Film samples; grounded samples	ASTM D5988-03[a]; 20 ± 2 °C	660 days	No distinct degradability among film and powder	Essential role of environmental conditions in BPs degradation	Gómez and Michel (2013)
	Material shapes	PHA specimens (PHB, PHBV)	Pellets and films	Buried at 15 cm	10–12 months	Faster degradation in films	Better attachment of microbes on the surfaces with PHA films	Boyandin et al. (2013)
	Additives	4 PBAT films	PBAT films + different additives	Soil burial	26 months	Fastest degradation in BMF containing PHA	PHA degradation accelerated disintegration	Qi et al. (2021)
	Additives	4 PBAT films	PBAT films + different additives	Soil burial	26 months	Addition of $CaCO_3$ delayed degradation	$CaCO_3$ proved physical properties and hindered surface cracking	Qi et al. (2021)

[a] ASTM D5988-03 and ASTM D5988-96 stand for Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil.

compounds from four commercial biodegradable plastic mulching films (including Mater-Bi®, Ecovio®, Bio-Flex®, and BioFilm®) even before biodegradation in soils (Serrano-Ruíz et al., 2020). Released compounds were mainly derived from partial hydrolysis of PBAT, PLA, and PHB in the blends of the commercial mulching films, potentially inducing negative impacts. Balestri et al. (2019) demonstrated similar leaching behaviors of the processing compounds from Mater-Bi® and high-density polyethylene (HDPE) bags after the ten-day natural weathering. The authors also observed adverse effects of plastic leachates on seedling growths of *Lepidium sativum* L., a garden cress species. The no differential phytotoxic effects on the early growth of the garden cress by conventional PE and biodegradable Mater-Bi® plastic leachates have also been confirmed (Menicagli et al., 2019).

So far, studies about ecotoxicological effects induced by plastic additives and leachates released from BPs have been poorly conducted. With less durability and faster biodegradation rate of BPs in soils, to what extent and under which condition the releases happen are vital problems that need long-term exploring. It is also worrying that whether the released chemicals during weathering could interact with the generated MPs and pose further ecological risks to natural soil environments (Serrano-Ruiz et al., 2021).

3.3. Evidences of MPs/BMPs released from large-sized plastics

Considering the technical difficulties in separation and the subsequent detection of MPs and BMPs from solid phases, there is very limited information available on the generation of MPs from large-sized plastics, let alone the generation of BMPs (Fojt et al., 2020; Viera et al., 2020). While the growing output of BPs and their increasingly important status urge us to explore whether BPs induce BMPs pollution like conventional ones do in natural ecosystems. A rapid degradation test on biodegradable PHA films in tap water and drinking water systems confirmed the generation of BMPs within the size range of 25 μm - 1 mm by epifluorescence microscopy (Shruti and Kutralam-Muniasamy, 2019). Scanning electron microscopy (SEM) observations further characterized the surface morphology of the generated MPs, revealing cracks and biofilm enrichment on the surfaces.

Since BPs are more vulnerable to various degradation factors than non-degradable plastics, the degradation rate of BPs seems to be more rapid than the conventional non-degradable plastic materials (Napper and Thompson, 2019; Wei et al., 2021). A study done by Lambert and Wagner (2016) demonstrated the releases of micron-sized fragments from several types of plastic materials, including conventional PP, PE, polystyrene (PS), polyethylene terephthalate (PET) commodities, and biodegradable PLA cup in a weathering chamber with UV exposure at 30 °C. The authors adopted nanoparticle tracking analysis for detection of particles between 30 and 2000 nm, and Coulter Counter techniques for 0.6–60 μm fragments. After 112 days, microscopic particles were detected increased in number among all plastic types, with PS plastic lid and PLA cup exhibiting the most increases in the concentrations of released micron-sized particles. Wei et al. (2021) compared the formation of BMPs and MPs from PBAT and LDPE materials in different aquatic environments, suggesting that PBAT BMPs were generated more readily from large-sized BPs than MPs from LDPE plastics. It was indicated that besides microbial mineralization, BPs also underwent UV degradation, oxidation, erosion, which jointly contributed to BMPs formation. The comparison of plastic deterioration was examined simultaneously under open-air, marine, and soil burial conditions, considering five types of plastic carrier bags (including biodegradable, oxo-biodegradable, compostable, and conventional plastics) (Napper and Thompson, 2019). The 27-month degradation experiment indicated higher fragmentation rate under the conditions with higher oxygen contents, humidity and ultraviolet (UV) radiation. Most of the detected fragments were in the size range of MPs, uncovering the no differential effects of natural weathering on generation of MPs/BMPs between biodegradable and non-biodegradable plastics. Similarly, Weinstein et al. (2020) compared the degradability of biodegradable PLA and Mater-Bi® plastics with conventional PET, HDPE, and PS commodities in a salt marsh. After 4 weeks of natural weathering, MPs and BMPs were produced and biofilms were detected among all plastic types, with single-use bags generating the most MPs during the incubation test. From the above discussion, we conclude that the degradability of BPs is not able to eliminate BMPs but have greater potential of BMPs accumulation in natural soils. Currently, due to the current negligible output and misunderstandings of BPs, little attention has been paid to BMPs in soil systems.

Incorporation of tiny sized BMPs, MPs, and even nanoplastics into soil profile make it more difficult to separate and evaluate their abundances and characteristics in soils. With the elevated awareness of potential risks posed by BPs, more efficient methods should be developed on quantifying BMPs and MPs in soils. Investigations, along with ecological risk assessments on BPs and BMPs should also be conducted. Common extraction procedures of conventional MPs from soil profile are based on density separation or flotation methods using saturated NaCl solution (density: 1.19 g cm^{-3}) (Li et al., 2020a). However, since most biodegradable polymers are denser than conventional plastic polymers (except for PVC), using NaCl solution as extraction solution is not appropriate for extracting BMPs from soil profile. Using saturated dense salt solution (such as NaBr, NaI, KI) may be more efficient in BMPs extraction (Li et al., 2021). In addition, special attention should be paid to the properties of the salt solution. For instance, saturated $ZnCl_2$ solution can dissolve cellulose, potentially interfering the extraction of BMPs containing cellulose. The oleophilic and non-conductive properties of MPs/BMPs could also be considered when it comes to separation of MPs/BMPs from environmental samples (Felsing et al., 2018; Scopetani et al., 2020). Use of chemicals to eliminate organic matter from MPs/BMPs surfaces is essential before further characterization, but since biodegradable polymers are more susceptible to many aggressive chemicals than conventional MPs, using solvents like chloroform seems to be a proper pathway (Krishnan et al., 2017). As for characterization of MPs and BMPs, common strategies, such as Fourier Transform infrared spectroscopy (FTIR) or Raman spectroscopies, and Pyrolysis gas chromatography-mass spectrometry are adopted (Fojt et al., 2020; Liang et al., 2021).

4. Can BMPs pose stronger negative effects to soil environments than conventional MPs?

4.1. Impacts on soil properties and soil biota

Considering that BMPs share some commonness with MPs, we first summarize some effects of conventional MPs on soil properties and organisms and possible mechanisms in this chapter, and then discuss the individualities of ecological effects posed by BMPs in soil environments. The objective of this part is to discuss whether it is ecologically safe to replace oil-based plastic commodities with BPs from the perspective of the generated and subsequent impacts of BMPs in soils.

4.1.1. Impacts on soil physicochemical properties

Soil properties play important roles in maintaining soil quality, crop production, nutrient cycling, and normal functioning in soil ecosystems (Mbachu et al., 2021). As xenobiotics, the presence of conventional MPs and BMPs in soil environments are able to change soil physicochemical properties and microbial activities (Boots et al., 2019; Liu et al., 2017; Qi et al., 2020b). Significant alterations in soil bulk density, total porosity, and soil aggregates were recorded due to the distinct characteristics of MPs/BMPs (densities, shapes, sizes, and surface properties) with natural soil particles, potentially related to soil erosion (Machado et al., 2018; Mbachu et al., 2021; Zhang and Liu, 2018). The random distribution of MPs in soils forms waterproof obstacles, blocking soil pores, and changing waterflow orientation (Jiang et al., 2017; Wan et al., 2019). One investigation study reported high coefficient of variation (CV) in soil property parameters vertically in a MPs-polluted agricultural field, indicating that the random distribution of MPs under realistic conditions exacerbated the heterogeneity in soil column (Jiang et al., 2017). Alterations in chemical composition and functional microbial groups in soils by conventional MPs intrusion were reported (Liu et al., 2017; Ren et al., 2020). From a long-term perspective, an investigation study in a cropped field contaminated by residual plastic films reported reductions in total nitrogen (TN) and soil organic matter (SOM), revealing negative effects of plastic residues on soil fertility and potential of soil impoverishment (Qian et al., 2018). Alterations in soil chemical components were generally provoked by indirect changes of biological activities, especially for those related to nutrient cycling.

Significant alterations in soil bulk density, porosity, as well as hydrological properties were recorded after the amendment of both LDPE and a starch-based microplastic debris under environmentally relevant concentrations from 0 to 2% (w/w) (Qi et al., 2020a). Changes in physicochemical and hydrological properties could further influence soil qualities and plant growths. Compared to conventional MPs that could be regarded as almost chemically inert intruders in soil environments, BMPs should be regarded as both physical and biochemical input. Qi et al. (2020b) reported distinct effects on soil pH, electrical conductivity, and soil C:N ratio between low-density polyethylene (LDPE) MPs-treatments and BMPs-treatments with similar sizes and doses. The possible explanation was attributed to the faster degradation rate and potential byproducts during BMPs degradation in soils. The mineralization of BMPs could further impact soil properties. For instance, depolymerization and hydrolysis of PLA have been reported to be accompanied by lactic acid generation and decreases in pH (Karamanlioglu and Robson, 2013).

Besides, BMPs could act as carbon sources for soil microorganisms, probably having legacy effects on microbial composition, activities, and functions in the long run. A study done by Chen et al. (2020) observed a faster ammonium transformation rate in PLA BMPs treatments compared than that in pure soils, demonstrating that PLA BMPs might act as potential carbon sources in soil ecosystems. Another pot experiment done by Zhou et al. (2021) studied the biochemical changes induced by BMPs amendment in a plant-soil system. PHBV, as one of the most common PHAs biodegradable materials, was chosen as BMPs specimens. Significant increases in microbial biomass C, as well as dissolved organic carbon (DOC) were documented, probably due to the microbial assimilation of BMPs. N immobilization was further confirmed by decreases in dissolved organic nitrogen (DON) but elevated content of microbial biomass N (MBN), demonstrating the direct impacts on carbon and nitrogen cycles by BMPs intrusion. Stronger rises in C:N ratio, as well as changes in N cycling induced by PLA samples than conventional ones were documented (Sanz-Lázaro et al., 2021). Apart from that, the presence of BMPs in soils may be exogenous carbon input, taking part in carbon cycles in ecosystems, and leading to emissions of unwanted greenhouse gases (Boots et al., 2019; Shen et al., 2020a, 2020c). If so, the promotion of BPs will become not a hope but a hidden risk, inducing more profound ecological impacts that have not been validated. From the point of this view, the rapid growth of BPs and their status as substitutes for non-degradable plastics could lead to BMPs accumulation in soil ecosystems, changes in soil biogeochemical cycles, and further climate changes.

4.1.2. Impacts on soil microorganisms

Soil enzymes and microbial community structures, as important contributors in soil environments, are closely related to microbial activities and soil energy flow (Song et al., 2020). The impacts of conventional MPs and BMPs on soil enzymatic and microbial community shifts are largely induced by changes in soil physicochemical properties (Awet et al., 2018; Fei et al., 2020; Machado et al., 2018). MPs/BMPs-induced microbial alterations were highly variable considering polymer types, shapes, concentrations, and soil textures, but overall cropped areas suffered from long-term contamination of plastic residues displayed reductions in soil enzyme activities related to soil nutrient cycles (Qian et al., 2018; Wang et al., 2016). To better understand the in-depth mechanisms of MPs-induced shifts in microbial communities, we divided the changes into direct biochemical intrusions and indirect property-induced changes (Ye et al., 2019).

On the one hand, during natural weathering processes, MPs sometimes provide shelters for microbes and facilitate their survival even under adverse conditions, forming layers of biofilms as "plastisphere" (Keswani et al., 2016; Zettler et al., 2013). Unfortunately, such protective mechanism provides opportunities for some pathogens and potential harmful microbes to enrich. MPs associated with other environmental pollutants and potentially harmful microbes like faecal indicator organisms (FIO), pathogens, and some disease-causing bacteria, such as *Aeromonas*, *Arcobacter*, *Vibrio*, and *Pseudomonas*, may deteriorate the pollution status and pose stronger negative effects on ecological safety (McCormick et al., 2016; Miao et al., 2019; Wang et al., 2020e; Yang et al., 2020b). Meanwhile, Eckert et al. (2018) reported the inability of conventional wastewater treatments to wipe out MPs. Worse still, the microbial communities on the PS MPs surfaces in wastewater effluents after the incubation exhibited similarities to that on the untreated wastewater samples. Studies done by De Tender et al. (2015) and Wu et al. (2020) were in line with the above observations, suggesting that MPs, as microbial messengers between two different ecosystems, promoted bacterial migration, meanwhile weakening environmental variations, and facilitated the invasion of these pathogens, antibiotic resistance gene (ARGs) and harmful species into wider environments. Also, some plastic-degrading bacteria in *Actinobacteria*, *Hyphomonadaceae*, *Bacteroidetes* and *Proteobacteria* have been detected on MPs during soil incubation tests, providing insights for pollution control in the future (Chai et al., 2020; McCormick et al., 2014).

Compared to conventional MPs, disintegration and formation of biofilms were found more pronounced in BMPs, thereby posing stronger alterations in microbial community structures (Qi et al., 2020b; Wang et al., 2020b). In soil-plant systems, Qi et al. (2020b) performed comparative studies investigating the effects on bacterial composition in wheat rhizosphere between PLA BMPs and LDPE MPs. The differential abundance analysis revealed higher relative abundances on genera such as *Bacillus*, *Variovorax*, *Comamonadaceae* in PLA MPs treatments, potentially induced by distinct chemical composition and surface characteristics between LDPE MPs and PLA BMPs. In line with the observations, PLA BMPs were proved to induce more pronounced impacts on the diversity and community composition of arbuscular mycorrhizal fungi groups (probiotic microorganisms that symbiose with higher plants) than PE MPs did, subsequently affecting the plant performances (Wang et al., 2020b). An 28-day incubation study using PET and PHA pellets was conducted to explore their selection of ARGs recently (Sun et al., 2021a). Although relatively higher abundances of multidrug resistance genes were identified higher on PET surfaces, Shannon diversities and abundances of ARGs on PHA BMPs and non-degradable PET MPs were similar. The study illustrated that both conventional MPs and BMPs harbored ARGs, acting as hotspots for horizontal gene transfer, but with preferences. Nevertheless, the MPs-induced impacts in soil microbes are usually not significant and short-term under environmentally relevant concentrations due to the intrinsic robustness of natural soils (Wang et al., 2020d).

On the other hand, it is believed that changes in soil physicochemical properties could be related to soil microbial activities and community structures indirectly (Wang et al., 2020c; Xu et al., 2020). Changes in soil parameters and microbial communities were observed on both macro- and micro-sized biodegradable plastic fragments (Qi et al., 2020a). For example, the addition of PLA BMPs induced decreases in soil pH, which indirectly altered microbial communities in both bulk soils and the rhizospheres (Boots et al., 2019; Qi et al., 2020b). Pathan et al. (2020) further reported that MPs could pose indirect effects on cultivated plants through changing soil structure, nutrient immobilization, contaminant adsorption and diffusion, soil microbial community

Table 3
Recent comparative ecotoxicological studies on soil plants and animals between nondegradable MPs and BMPs.

Testing Species	Polymer types		Doses	Exposure	Effects	Comparison	Possible Explanation	References
	Conventional MPs	BMPs						
Earthworm, *Eisenia fetida*	PE	PLA, PPC	0–500 g kg^{-1}	Soil incubation	Avoidance, elevated mortality with the increasing rate	No significant differences	Effects of concentrations outweighing polymer types	Ding et al. (2021)
Earthworm, *Aporrectodea rosea*	HDPE	PLA	0.1% (w/w)	Soil-plant -earthworm system	Reduction in biomass	HDPE > PLA	Prolonged gut residence of the MPs altering the feeding activities	Boots et al. (2019)
Ryegrass, *Lolium perenne*					Fewer germination, Shorter shoots	PLA > HDPE	The toxic effects of degradation byproducts (e.g., lactic acid)	
Common bean, *Phaseolus vulgaris* L.	LDPE	PLA/ PBAT	0.5–2.5% (w/ w)	Soil-plant system	Reductions in shoot, root growth, and fruit biomass	BMPs > LDPE MPs	Degradation byproducts of PLA; Alterations in rhizosphere microbial communities;	Meng et al. (2021)
Wheat, *Triticum aestivum*	LDPE	Starch-based film residues (Bio)	1% (w/w)	Soil-plant system	Growth inhibition	Bio > LDPE	Faster degradation of BMPs leading to stronger alterations in soil structure, stability, and biological effects	Qi et al. (2018)
					Reductions in plant biomass; Shifts in wheat rhizosphere	Bio > LDPE	Faster degradation of BMPs; Releases of volatile compounds from BMPs	Qi et al. (2020b)
Maize, *Zea mays* L. var. Wannuoyihao	PE; PE + Cd	PLA; PLA + Cd	MPs: 0–10%; Cd: 5 mg kg^{-1}	MPs alone/ MPs-Cd exposure	Changes in soil pH; Reduction in biomass and chlorophyll content; Increases in DTPA-extracted Cd	PLA > PE	Potential toxic degradation byproducts of PLA	Wang et al. (2020b)
Lettuce, *Lactuca sativa* L., Tomato, *Lycopersicon esculentum* Mill.	PE film residues	7 types of Biodegradable film residues	Extracts from MPs/ BMPs	*In vitro* culture test	Reductions in germination, root growth; Variable responses to different types	BMPs extracts > PE extracts	Compounds and byproducts released from BMPs degradation	Serrano-Ruíz et al. (2018)
Maize, *Zea mays* L. var. Wannuoyihao	HDPE	PLA	MPs: 0–10%; ZnO NPs: 0–500 mg kg^{-1}	MPs alone/ MPs-ZnO NPs exposure	Inhibition in root and shoot growth under high-dose PLA BMPs treatment; Increased Zn accumulation under co-exposure;	PLA > HDPE	Releases of harmful secondary metabolites from PLA biodegradation	Yang et al. (2021)
Arbuscular Mycorrhizal Fungal (AMF) communities					Correlations between PLA dose and relative abundance of some AMF species; MP/BMPs + NPs alleviated reductions in microbial diversities induced by ZnO NPs	Not significant	Impacts on AMF communities by PLA and its metabolites; Protective role of MPs/BMPs against ZnO NPs toxicity	

root-associated microbiome, and root symbionts.

4.1.3. Impacts on soil animals and plants

Laboratory tests have demonstrated the adverse impacts of MPs and BMPs on soil organisms from cellular to trophic levels. Present studies mainly focus on higher plant species (e.g., wheat, ryegrass, garden cress, spring onion, etc.) and invertebrates (e.g., earthworms, nematodes, springtails, and snails, etc.) (Guo et al., 2020; Ju et al., 2019). The reported responses on soil animals induced by MPs included but not limited to decreases in survival, growth and reproductive rate, detrimental effects on digestive tracts, oxidative stress, gut microbiome dysbiosis, and even neurotoxicity (Jin et al., 2019; Rodriguez-Seijo et al., 2017; Setälä et al., 2016). In analogy to adverse impacts on animals, MPs in soils provoke phytotoxicity including growth inhibition, reduced seed germination, oxidative bursts, and genotoxicity (Pignattelli et al., 2020; Zou et al., 2017). The results were often accompanied by changes in soil properties that could also be one of the contributors to detrimental effects on plant health. (Jiang et al., 2019; Taylor et al., 2020). These reports implied that MPs in soils might exert influences on plant performances and further disturbances on normal functioning in soil ecosystems.

For a long time, BPs had been considered environmentally harmless. Unfortunately, since no differential adverse impacts of conventional MPs and BMPs on filter-feeding species, flat oysters (*Ostrea edulis*) and blue mussels (*Mytilus edulis*) were reported, researches began to lay eyes on the potential ecological risks of BMPs (Green et al., 2016, 2017; Klein et al., 2021). Up to now, there is still a paucity of information on environmental risk assessments of BMPs, especially in soil environments. And the contradictory results among different species and polymer types make it more difficult to elucidate the toxic mechanisms of BMPs in soil systems. Herein, we intend to provide a glimpse of potential ecotoxicological effects by BMPs.

On the one hand, as part of MPs, BMPs share some common features with MPs. Like conventional MPs, toxic effects of BMPs on animals and

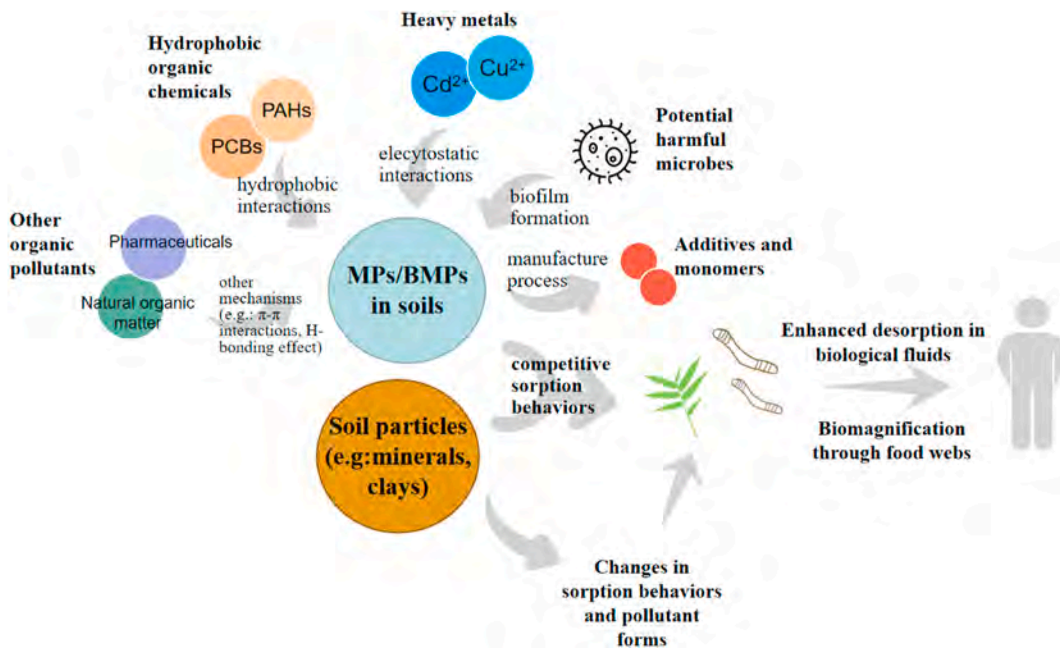

Fig. 3. MPs/BMPs as vectors of environmental pollutants in soils.

plants have also been recorded, leading to increases in intracellular reactive oxygen species (ROS) levels and impairment of membrane integrity (Gonzalez-Soto et al., 2019; Green et al., 2016; Zhang et al., 2021). Zimmermann et al. (2020) identified the particulate-induced toxicity of PLA BMPs on zebrafish *D. magna* by adding untreated BMPs, BMPs without extracted chemicals, and single extracted chemicals into culturing medium. On the other hand, due to the relatively rapid degradation of BPs and BMPs, releases of additives, monomers, and possibly noxious intermediates are more pronounced compared to non-degradable plastics (Serrano-Ruiz et al., 2021). For instance, Klein et al. (2021) conducted an 28-day sediment ecotoxicity study on freshwater oligochaete *Lumbriculus variegatus*, and identified chemicals originating from the PLA BMPs as the main driver of toxic effects in this study. Zhang et al. (2021) investigated the impact of virgin and UV-aged PLA BMPs on a zebrafish species. Sizes of the aged PLA BMPs reduced to half of the virgin ones (from ~25.56 to ~11.22 μm), and surface property changes such as introduction of O-containing surface groups and increase in hydrophilicity were also observed. Also, PLA BMPs after aging exerted stronger oxidative damages on zebrafish than virgin ones, indicating the elevated ecotoxicity of BMPs during natural weathering processes. More recently, an *in vitro* phytotoxic study of extracts from several types of biodegradable plastic fragments was conducted on two agricultural plant species (lettuce, *Lactuca satica* L., and tomato *Lycopersicon esculentum* Mill.) (Serrano-Ruíz et al., 2018). Several commercial BPs particles (Mater-Bi®, Ecovio®, Bio-Flex®, and BioFilm®) composed of PBAT, PLA, TPS, and PHB materials were chosen as representative for most BPs during agricultural use. Results showed that extracts from different types of BPs led to inhibitory effects on seed germination, plant growth, and root health, suggesting the potential adverse impacts of BMPs induced by released chemicals. While the effects of conventional MPs and BMPs on soil species were found largely dependent on polymer types and plastic composition (Huerta Lwanga et al., 2016; Qi et al., 2018; Rodriguez-Seijo et al., 2017). Back in 2013, Sinohara Souza et al. (2013) illustrated the inhibitory effects of aqueous extract from PLA films on cell division of the *Allium cepa* meristematic cells. While research conducted by Rychter et al. (2010) found it harmless of PBAT materials on radish, cress, and oats during the degradation test. Since soil ecosystems are composed of various abiotic and biotic components, the ecological impacts of BMPs and conventional MPs are results of multifactors. Therefore, it is not likely to consider the influencing factors individually when evaluating the ecological safety of plastic materials. Table 3 displayed some recent studies comparing ecotoxicological effects of MPs and BMPs on organisms in soils.

Despite the scarcity of related reports in soils, the results of toxicological studies between conventional MPs and BMPs were worrying. A laboratory study investigating biotoxicity of PLA BMPs, polypropylene carbonate (PPC) BMPs, and non-degradable PE MPs on earthworms *Eisenia fetida* concluded that PLA and PPC BMPs displayed comparable biotoxicity compared to PE MPs (Ding et al., 2021). In a soil-plant system, stronger reductions in shoot, root growth, and fruit biomass of common bean (*Phaseolus vulgaris* L.) induced by PBAT/PLA BMPs were recorded, while LDPE MPs only triggered negative effects under high concentrations (Meng et al., 2021). The negative effects of degradation compounds and alterations in rhizosphere bacterial community induced by BMPs might account for the results. Another pot experiment conducted to explore the effects of micron-sized LDPE and starch-based plastic film residues concluded that biodegradable film residues exhibited more severe inhibition on wheat growth than LDPE did (Qi et al., 2018). Wang et al. (2020b) demonstrated that 10% PLA MPs amendment in soils decreased maize biomass and chlorophyll contents in leaves in soils, while PE showed no discernible impacts. Similar results such as stronger inhibitory effects on the growth of *L. perenne*, lower root and shoot biomass, together with significant lower leaf chlorophyll content on common bean (*Phaseolus vulgaris* L.) by BMPs compared to conventional MPs questioned the environmental safety of the so-called "environmentally harmless" BPs (Boots et al., 2019).

By comparing the ecotoxicological studies of conventional MPs and BMPs in soils, it is worrying that BMPs pose no differential, sometimes even greater negative effects on soil animals and plants, which should be taken into consideration when we regard BPs as substitutes for conventional non-degradable plastics.

4.2. Interactions between BMPs and environmental chemicals

4.2.1. BMPs alter the distribution patterns of environmental pollutants in soils

Due to high specific surface area, hydrophobicity and persistence, MPs possess the ability to concentrate environmental pollutants, including organic and inorganic chemicals, and subsequently alter their environmental behaviors as "vectors" (Dobaradaran et al., 2018; Syberg et al., 2015). Meanwhile, with the increasing awareness of potential risks by BPs and BMPs, some researches have demonstrated no differential impacts between BMPs with conventional MPs on concentrating and changing distribution patterns of environmental pollutants (Černá et al., 2021; Torres et al., 2021). Mechanisms participating in sorption of BMPs and MPs are mainly attributed to hydrophobic interactions, electrostatic, π-π, hydrogen bonding, and some other effects (Hartmann et al., 2017; Shen et al., 2021). Fig. 3 displayed the ability of concentrating environmental pollutants by both conventional MPs and BMPs, acting as vectors for pollutants in soils.

Despite the paucity of field investigations, experimental studies have confirmed similar sorption behaviors and mechanisms between conventional MPs and BMPs, and sometimes BMPs even presented higher affinities to chemical substances with BMPs. For example, PBAT MPs revealed the highest affinity to phenanthrene in aqueous solution among PBAT, PE and PS MPs, owing to the low crystallinity of PBAT materials (Zuo et al., 2019). The calculated K_d value of the PBAT MPs was even higher than some of the carbonaceous geosorbents like biochars and black carbons, indicating BMPs as vectors for phenanthrene even in natural environments. Jiang et al. (2020) investigated sorption abilities of PBS, PVC, and PS MPs towards two triazole fungicides-triadimefon, and difenoconazole. PBS BMPs presented the highest sorption capacity for triadimefon (104.2 ± 4.8 μg g^{-1}) and difenoconazole (192.8 ± 2.3 μg g^{-1}), and the sorption behaviors were barely affected by environmental factors like pH, salinity, and dissolved organic matter like PVC and PS MPs did. The branched aliphatic composition of polymers contributed to the strong affinities. Tubić et al. (2019) demonstrated a relatively stronger affinity of PLA BMPs to 4-chlorophenol (4-CP) (85–101 μg g^{-1}) than conventional PP and PE MPs, following the pseudo-second order equation, indicating the contribution of different binding sites during the sorption. Heterogeneous sorption of pesticides fipronil to BMPs (polybutylene succinate (PBS) and PLA) was indicated by the well fitted Freundlich model, revealing greater concentrating abilities of BMPs for the pesticides than conventional MPs (Gong et al., 2019). As another main organic pollutants, antibiotics exhibited affinities to MPs and BMPs (Atugoda et al., 2021; Torres et al., 2021; Verdú et al., 2021). Fan et al. (2021) investigated the sorption behaviors of two common antibiotics-tetracycline (TC) and ciprofloxacin (CIP), on conventional PVC MPs and PLA BMPs in original and aged forms. It was indicated that the multi-layer adsorption of PLA BMPs displayed higher adsorption capacity for antibiotics than single-layer adsorption of PVC MPs. More importantly, since PLA BMPs were proved more susceptible to UV aging than PVC MPs, sorption capacities of aged PLA BMPs towards TC and CIP were greatly enhanced, potentially inducing combined effects under co-exposure. The more susceptible properties of BMPs in natural environments also lead to higher adsorption abilities to chemicals. Similar observations were documented in oxytetracycline (OTC) adsorption on PLA BMPs under different environmental conditions (Sun et al., 2021b). It was confirmed that biofilm-formed PLA BMPs exhibited much stronger affinity to OTC due to increased surface area, the generated oxygen-containing functional groups, stronger hydrogen bonding, and interactions with biofilms. Also, the OTC desorption behavior was also more pronounced on biofilm-formed PLA BMPs. These studies highlighted the environmental risks of BMPs in actual environmental conditions.

Under natural soil environments where BPs are more vulnerable to weathering than conventional plastics, BMPs present smaller sizes, rougher surfaces, along with generation of cracks and hydroxyl and carboxyl functional groups. The experimental results by Li et al. (2020b) illustrated that the weathered PBAT MPs presented distinctly higher sorption capacities to heavy metals than PE MPs had during the soil incubation tests, especially for Cu. In this study, the more rapid degradation rate of biodegradable PBAT than non-degradable PE materials possibly contributed to the results. More recently, Černá et al. (2021) investigated the PAHs (anthracene, benzo[a]anthracene, and benzo[a]pyrene) accumulation onto MPs and BMPs in both aged and unaged forms in a PAHs-contaminated soil incubation test. Significant higher PAHs accumulation on BMPs than conventional MPs was observed, and the driving factors for PAHs sorption was the rubbery or glassy state of the particles. Within this study, aging process did not lead to significant changes.

From the above discussion, it is suggested that the chemical compositions and relative vulnerability of BMPs make them more readily to concentrate environmental chemical substances than oil-based MPs. However, there is still a dearth of experimental data to validate whether BMPs could act as vectors for environmental chemicals, changing their fate and distribution patterns to a larger extent than conventional MPs do in natural soil systems.

4.2.2. Biological effects of co-exposure of BMPs and contaminants

With the complexity under realistic soil environments, the combined effects of MPs with associated chemical substances on organisms and their mechanisms are ongoing concerns. The uptake of MPs by soil organisms provides a pathway for MPs-associated contaminants to enter animal tissues and thereby inducing detrimental effects on animal health. The problem whether MPs can act as vectors for environmental pollutants, leading to elevated bioaccumulation in organisms is under intense discussion (Syberg et al., 2015; Yang et al., 2019). Presently, studies concerning the co-transport of MPs with sorbed contaminants (mainly focused on persistent organic pollutants, including model polycyclic aromatic hydrocarbons (PAHs) (benzo[a]pyrene, fluoranthene), PBDEs, perfluorooctanesulfonate (PFOS), etc.) have documented higher bioaccumulation of contaminants in animal and plant tissues, and biological toxic effects (Chua et al., 2014; Gonzalez-Soto et al., 2019; O'Donovan et al., 2018). One possible explanation for the elevated bioaccumulation of chemicals by MPs-ingestion lies with the possible stronger desorption behaviors of chemicals inside animal digestive fluids (Liu et al., 2020; Rochman et al., 2013). Taken earthworms as an example, Hodson et al. (2017) reported that the Zn desorption abilities from MPs and Zn bioaccessibility inside gut fluids in earthworms were elevated than that in soils. Ma et al. (2020) studied the combined effect of MPs and antibiotics tetracycline (TC) in the gut microbiota of *Enchytraeus crypticus*, revealing significant higher abundances of ARGs in gut microbial communities in MPs-TC treatments than MPs or TC alone treatment groups.

Little information is available when it comes to co-exposure of environmental pollutants with BMPs and the subsequent ecological impacts in soil environments. An *in-vitro* human digestive model compared the desorption abilities of heavy metals from PE, PP, PVC, PS and PLA MPs. It was noteworthy that in the simulated human digestive tracts, Cr (VI) desorption rate and Cr bioaccessibility in PLA BMPs treatments presented to be the highest among all the tested materials, posing higher noncarcinogenic risks to human health (Liao and Yang, 2020). A soil-plant incubation study done by Wang et al. (2020b) documented higher DTPA-extractable Cd in soils after the amendment of PLA BMPs compared to PE MPs under their co-exposure with Cd, possibly due to the indirect effects of BMPs on soil properties and microbial community structures. Nanoparticles (NPs), as another emerging contaminant, is gaining concerns recently. Yang et al. (2021) explored the toxic impacts on maize (*Zea mays* L. var. Wannuoyihao) by single and co-exposure of conventional MPs and BMPs with ZnO NPs, as one of the most common engineered NPs. Increased Zn accumulation in maize was observed under the co-exposure of ZnO NPs with MPs/BMPs. Meanwhile, the amendment of MPs and BMPs were found to alleviate the negative effects of ZnO NPs on arbuscular mycorrhizal fungal communities, which might exert more profound impacts on soil microbial communities and plant growth.

According to recent studies, however, contribution of MPs or BMPs to the bioaccumulation of pollutants was not comparable to other exposure pathways such as dietary and dermal exposure (Rosato et al., 2020; Wang et al., 2019). Considering relatively low abundances of MPs compared to other natural organic materials, the effect is negligible under realistic concentrations. For instance, Wang et al. (2019) exposed the earthworm, *E. fetida* under MPs or MPs-polychlorinated biphenyls (PCB) treatments in soils, and indicated that under environmentally relevant exposure, neither MPs-induced oxidative stress, nor enhanced bioaccumulation of PCB would exert detrimental effect on the earthworms. While the hypothesis has only been tested among very limited species and polymer types, it remains uncertain whether co-exposure of MPs and environmental pollutants would induce stronger impacts on soil organisms and even human health. The more profound impacts of BPs and BMPs on both soil abiotic and biotic components bring great uncertainty to the consequences of contaminant-MPs co-exposure. Moreover, compared to MPs/BMPs associated with chemicals sorbed from the ambient environments, more focus should be put on the inherent releases of potentially harmful chemicals, along with their following association with generated MPs. Since the releases of both intermediates, additives and byproducts are more pronounced in BPs and BMPs, future studies should put emphasis on the topic.

5. Perspectives and future research needs

In this paper, we conducted discussions on the ecological impacts of BMPs from their generation in natural soil environments to their single and combined effects on soil organisms and environments. In all, there is now a paucity of recognition on ecological safety of both BPs and BMPs. Clearly more experimental data and in-depth explanations are in urgent need to illustrate the ecological effects on soil environments posed by so-called harmless BPs.

As far as we are concerned, to consider current BPs as substitutes for conventional plastic commodities is not a wise choice, considering the potential ecological threats of BMPs. The reasons are stated as follows:

1) Due to the faster but incomplete degradation of BPs than conventional plastics in natural soil environments, larger amounts of BMPs may be released into soils in the same time frame than conventional non-degradable plastics, causing greater BMPs pollution;
2) BMPs in soil environments exert no differential ecological impacts on soil abiotic and biotic components with conventional MPs, following similar mechanisms. Besides, the presence of BMPs in soils may further lead to excessive carbon input, together with releases of degradation byproducts (such as monomers and possibly noxious intermediates), posing more profound impacts that need further investigating;
3) The existing ecotoxicological studies of BPs and BMPs are in lack. Under some conditions, BMPs generated from the so-called environmentally friendly BPs exhibit stronger, and more profound negative effects on soil abiotic and biotic components, emerging as a hidden threat. Clearly more experimental studies should be conducted to explore the biotoxicity of BMPs and their behind reasons;
4) The ecotoxicity studies of BMPs should not be limited to single particle impacts, and releases of chemicals from BPs and BMPs during natural weathering and their co-exposure with environmental pollutants should also be paid attention to;
5) The public misconceptions that BPs are totally environmental-friendly should be corrected, otherwise it may cause littering and improper waste management practices;

Considering the above limitations at present, great caution should be exercised in promoting BPs. We also suggest that future researches should lay eyes on the following aspects:

1) At present, detection and quantification methods of MPs, especially for BMPs, are in extreme shortage. Therefore, to accurately recognize the pollution status of MPs/BMPs in terrestrial environments, developing simple, effective, and cost-saving separation and extraction standards of MPs/BMPs from soil profile are in urgent need. For instance, in density separation procedures, denser salt solutions should be adopted in separating BMPs in soil profile than that in conventional MPs. Methods considering other distinct properties of MPs/BMPs from soil particles should also be considered;
2) In our opinions, the point of solving MPs pollution lies not in developing new biodegradable polymers with excellent performances, but rather in improving plastic recycling processes and tightening regulations on plastic waste disposal. To improve the public awareness and correct understanding of BPs, bio-based, and bioplastics are also priorities;
3) Ecotoxicological studies on BPs and BMPs in soil ecosystems are now very limited, and mainly focused on PLA and PBAT materials. Clearly, discussions on the generation, environmental behaviors, and ecological impacts of BMPs and whether BMPs pose stronger negative effects than conventional MPs do need further uncovering. Also, investigations on BPs and BMPs with more polymer types, sizes, and more species should be conducted if we aim to consider BPs as substitutes for conventional plastic products;
4) Guidelines should be set and popularized on the classification of biodegradable materials according to their biodegradabilities under different environmental conditions. Specifically, we recommend developing degradation models of biodegradable polymers with different soil parameters, like soil moisture, soil organic matter, and nutrient contents, providing references for native agricultural activities;
5) To alleviate the current plastic pollution status, we recommend improving the durability and retrievability of newly developed plastic commodities. From our views, adding pro-oxidants to prove chemical degradation of plastic materials is not a wise move, but probably leading to higher MPs accumulation in natural environments. Instead, we prefer improving the flexibility and retrievability of BPs for cyclic utilization and further modification; If disposal is unavoidable, it is suggested to conduct biodegradation in pile composting conditions during centralized processing and monitor to ensure no toxic substances are released.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful for the financial supports from National Natural Science Foundation of China (U20A20323, 51521006, 51579095, 51378190), the Program for Changjiang Scholars and Innovative Research Team in University (IRT-13R17), and the China National Postdoctoral Program for Innovative Talents (BX20200119).

References

Adhikari, D., Mukai, M., Kubota, K., Kai, T., Kaneko, N., Araki, K., Kubo, M., 2016. Degradation of bioplastics in soil and their degradation effects on environmental microorganisms. J. Agric. Chem. Environ. 5, 23–34.
Akdogan, Z., Guven, B., 2019. Microplastics in the environment: a critical review of current understanding and identification of future research needs. Environ. Pollut. 254, 113011.
Al Hosni, A.S., Pittman, J.K., Robson, G.D., 2019. Microbial degradation of four biodegradable polymers in soil and compost demonstrating polycaprolactone as an ideal compostable plastic. Waste Manag. 97, 105–114.
Amulya, K., Katakojwala, R., Ramakrishna, S., Venkata Mohan, S., 2021. Low carbon biodegradable polymer matrices for sustainable future. Composites Part C: Open Access 4, 100111.
Apinya, T., Sombatsompop, N., Prapagdee, B., 2015. Selection of a *Pseudonocardia* sp. RM423 that accelerates the biodegradation of poly(lactic) acid in submerged cultures and in soil microcosms. Int. Biodeterior. Biodegrad. 99, 23–30.
Arrieta, M.P., Samper, M.D., Aldas, M., López, J., 2017. On the use of PLA-PHB blends for sustainable food packaging applications. Materials 10.

Atugoda, T., Vithanage, M., Wijesekara, H., Bolan, N., Sarmah, A.K., Bank, M.S., You, S., Ok, Y.S., 2021. Interactions between microplastics, pharmaceuticals and personal care products: implications for vector transport. Environ. Int. 149, 106367.
Awet, T.T., Kohl, Y., Meier, F., Straskraba, S., Gruen, A.L., Ruf, T., Jost, C., Drexel, R., Tunc, E., Emmerling, C., 2018. Effects of polystyrene nanoparticles on the microbiota and functional diversity of enzymes in soil. Environ. Sci. Eur. 30.
Bagheri, A.R., Laforsch, C., Greiner, A., Agarwal, S., 2017. Fate of so-called biodegradable polymers in seawater and freshwater. Global Challenges 1.
Balestri, E., Menicagli, V., Ligorini, V., Fulignati, S., Galletti, A.M.R., Lardicci, C., 2019. Phytotoxicity assessment of conventional and biodegradable plastic bags using seed germination test. Ecol. Indicat. 102, 569–580.
Bejgarn, S., MacLeod, M., Bogdal, C., Breitholtz, M., 2015. Toxicity of leachate from weathering plastics: an exploratory screening study with *Nitocra spinipes*. Chemosphere 132, 114–119.
Bioplastics, European, 2018. Bioplastics Market Data 2018. Global Production Capacities of Bioplastics 2018 vs. 2023.
Bioplastics, European, 2020. What Are Bioplastics?.
Boots, B., Russell, C.W., Green, D.S., 2019. Effects of microplastics in soil ecosystems: above and below ground. Environ. Sci. Technol. 53, 11496–11506.
Borrowman, C.K., Johnston, P., Adhikari, R., Saito, K., Patti, A.F., 2020. Environmental degradation and efficacy of a sprayable, biodegradable polymeric mulch. Polym. Degrad. Stabil. 175, 109126.
Boyandin, A.N., Prudnikova, S.V., Karpov, V.A., Ivonin, V.N., Đỗ, N.L., Nguyễn, T.H., Lê, T.M.H., Filichev, N.L., Levin, A.L., Filipenko, M.L., Volova, T.G., Gitelson, I.I., 2013. Microbial degradation of polyhydroxyalkanoates in tropical soils. Int. Biodeterior. Biodegrad. 83, 77–84.
Briassoulis, D., 2006. Mechanical behaviour of biodegradable agricultural films under real field conditions. Polym. Degrad. Stabil. 91, 1256–1272.
Brodhagen, M., Peyron, M., Miles, C., Inglis, D.A., 2015. Biodegradable plastic agricultural mulches and key features of microbial degradation. Appl. Microbiol. Biotechnol. 99, 1039–1056.
Černá, T., Pražanová, K., Beneš, H., Titov, I., Klubalová, K., Filipová, A., Klusoň, P., Cajthaml, T., 2021. Polycyclic aromatic hydrocarbon accumulation in aged and unaged polyurethane microplastics in contaminated soil. Sci. Total Environ. 770, 145254.
César, M.E.F., Mariani, P.D.S.C., Innocentini-Mei, L.H., Cardoso, E.J.B.N., 2009. Particle size and concentration of poly(ϵ-caprolactone) and adipate modified starch blend on mineralization in soils with differing textures. Polym. Test. 28, 680–687.
Chae, Y., An, Y.J., 2018. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: a review. Environ. Pollut. 240, 387–395.
Chai, B., Li, X., Liu, H., Lu, G., Dang, Z., Yin, H., 2020. Bacterial communities on soil microplastic at Guiyu, an E-Waste dismantling zone of China. Ecotoxicol. Environ. Saf. 195.
Chen, H., Wang, Y., Sun, X., Peng, Y., Xiao, L., 2020. Mixing effect of polylactic acid microplastic and straw residue on soil property and ecological function. Chemosphere 243.
Chinaglia, S., Tosin, M., Degli-Innocenti, F., 2018. Biodegradation rate of biodegradable plastics at molecular level. Polym. Degrad. Stabil. 147, 237–244.
Cho, H.S., Moon, H.S., Kim, M., Nam, K., Kim, J.Y., 2011. Biodegradability and biodegradation rate of poly(caprolactone)-starch blend and poly(butylene succinate) biodegradable polymer under aerobic and anaerobic environment. Waste Manag. 31, 475–480.
Chua, E.M., Shimeta, J., Nugegoda, D., Morrison, P.D., Clarke, B.O., 2014. Assimilation of polybrominated diphenyl ethers from microplastics by the marine amphipod, *allorchestes compressa*. Environ. Sci. Technol. 48, 8127–8134.
De Tender, C.A., Devriese, L.I., Haegeman, A., Maes, S., Ruttink, T., Dawyndt, P., 2015. Bacterial community profiling of plastic litter in the Belgian part of the north sea. Environ. Sci. Technol. 49, 9629–9638.
Di Mola, I., Ventorino, V., Cozzolino, E., Ottaiano, L., Romano, I., Duri, L.G., Pepe, O., Mori, M., 2021. Biodegradable mulching vs traditional polyethylene film for sustainable solarization: chemical properties and microbial community response to soil management. Appl. Soil Ecol. 163, 103921.
Ding, W., Li, Z., Qi, R., Jones, D.L., Liu, Q., Liu, Q., Yan, C., 2021. Effect thresholds for the earthworm Eisenia fetida: toxicity comparison between conventional and biodegradable microplastics. Sci. Total Environ., 146884
do Val Siqueira, L., Arias, C.I.L.F., Maniglia, B.C., Tadini, C.C., 2021. Starch-based biodegradable plastics: methods of production, challenges and future perspectives. Current Opinion in Food Science 38, 122–130.
Dobaradaran, S., Schmidt, T.C., Nabipour, I., Khajeahmadi, N., Tajbakhsh, S., Saeedi, R., Javad Mohammadi, M., Keshtkar, M., Khorsand, M., Faraji Ghasemi, F., 2018. Characterization of plastic debris and association of metals with microplastics in coastline sediment along the Persian Gulf. Waste Manag. 78, 649–658.
Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104, 290–293.
Eckert, E.M., Di Cesare, A., Kettner, M.T., Arias-Andres, M., Fontaneto, D., Grossart, H.-P., Corno, G., 2018. Microplastics increase impact of treated wastewater on freshwater microbial community. Environ. Pollut. 234, 495–502.
Elsawy, M.A., Kim, K.-H., Park, J.-W., Deep, A., 2017. Hydrolytic degradation of polylactic acid (PLA) and its composites. Renew. Sustain. Energy Rev. 79, 1346–1352.
Fan, X., Zou, Y., Geng, N., Liu, J., Hou, J., Li, D., Yang, C., Li, Y., 2021. Investigation on the adsorption and desorption behaviors of antibiotics by degradable MPs with or without UV ageing process. J. Hazard Mater. 401, 123363.
Fei, Y., Huang, S., Zhang, H., Tong, Y., Wen, D., Xia, X., Wang, H., Luo, Y., Barcelo, D., 2020. Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil. Sci. Total Environ. 707.
Felsing, S., Kochleus, C., Buchinger, S., Brennholt, N., Stock, F., Reifferscheid, G., 2018. A new approach in separating microplastics from environmental samples based on their electrostatic behavior. Environ. Pollut. 234, 20–28.
Feng, S., Lu, H., Tian, P., Xue, Y., Lu, J., Tang, M., Feng, W., 2020. Analysis of microplastics in a remote region of the Tibetan Plateau: implications for natural environmental response to human activities. Sci. Total Environ. 739, 140087.
Fojt, J., David, J., Prikryl, R., Rezacova, V., Kucerik, J., 2020. A critical review of the overlooked challenge of determining micro-bioplastics in soil. Sci. Total Environ. 745.
Gómez, E.F., Michel, F.C., 2013. Biodegradability of conventional and bio-based plastics and natural fiber composites during composting, anaerobic digestion and long-term soil incubation. Polym. Degrad. Stabil. 98, 2583–2591.
Gómez-Aldapa, C.A., Velazquez, G., Gutierrez, M.C., Rangel-Vargas, E., Castro-Rosas, J., Aguirre-Loredo, R.Y., 2020. Effect of polyvinyl alcohol on the physicochemical properties of biodegradable starch films. Mater. Chem. Phys. 239, 122027.
Gong, W., Jiang, M., Han, P., Liang, G., Zhang, T., Liu, G., 2019. Comparative analysis on the sorption kinetics and isotherms of fipronil on nondegradable and biodegradable microplastics. Environ. Pollut. 254.
Gonzalez-Soto, N., Hatfield, J., Katsumiti, A., Duroudier, N., Maria Lacave, J., Bilbao, E., Orbea, A., Navarro, E., Cajaraville, M.P., 2019. Impacts of dietary exposure to different sized polystyrene microplastics alone and with sorbed benzo a pyrene on biomarkers and whole organism responses in mussels *Mytilus galloprovincialis*. Sci. Total Environ. 684, 548–566.
Green, D.S., 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, 426–434.
Green, D.S., Boots, B., O'Connor, N.E., Thompson, R., 2017. Microplastics affect the ecological functioning of an important biogenic habitat. Environ. Sci. Technol. 51, 68–77.
Gunaalan, K., Fabbri, E., Capolupo, M., 2020. The hidden threat of plastic leachates: a critical review on their impacts on aquatic organisms. Water Res. 184.
Guo, J.-J., Huang, X.-P., Xiang, L., Wang, Y.-Z., Li, Y.-W., Li, H., Cai, Q.-Y., Mo, C.-H., Wong, M.-H., 2020. Source, migration and toxicology of microplastics in soil. Environ. Int. 137, 105263.
Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard Mater. 344, 179–199.
Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H.S., Schmidt, S.N., Mayer, P., Meibom, A., Baun, A., 2017. Microplastics as vectors for environmental contaminants: exploring sorption, desorption, and transfer to biota. Integrated Environ. Assess. Manag. 13, 488–493.
Hayes, D.G., Wadsworth, L.C., Sintim, H.Y., Flury, M., English, M., Schaeffer, S., Saxton, A.M., 2017. Effect of diverse weathering conditions on the physicochemical properties of biodegradable plastic mulches. Polym. Test. 62, 454–467.
Hodson, M.E., Duffus-Hodson, C.A., Clark, A., Prendergast-Miller, M.T., Thorpe, K.L., 2017. Plastic bag derived-microplastics as a vector for metal exposure in terrestrial invertebrates. Environ. Sci. Technol. 51, 4714–4721.
Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci. Total Environ. 586, 127–141.
Hoshino, A., Sawada, H., Yokota, M., Tsuji, M., Fukuda, K., Kimura, M., 2001. Influence of weather conditions and soil properties on degradation of biodegradable plastics in soil. Soil Sci. Plant Nutr. 47, 35–43.
Huang, Y., Liu, Q., Jia, W., Yan, C., Wang, J., 2020. Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environ. Pollut. 260, 114096.
Huerta Lwanga, E., Gertsen, H., Gooren, H., Peters, P., Salanki, T., van der Ploeg, M., Besseling, E., Koelmans, A.A., Geissen, V., 2016. Microplastics in the terrestrial ecosystem: implications for *Lumbricus terrestris* (Oligochaeta, lumbricidae). Environ. Sci. Technol. 50, 2685–2691.
Hurley, R.R., Nizzetto, L., 2018. Fate and occurrence of micro(nano)plastics in soils: knowledge gaps and possible risks. Current Opinion in Environmental Science & Health 1, 6–11.
Iwata, T., 2015. Biodegradable and bio-based polymers: future prospects of eco-friendly plastics. Angew. Chem. Int. Ed. 54, 3210–3215.
Janczak, K., Hrynkiewicz, K., Znajewska, Z., Dąbrowska, G., 2018. Use of rhizosphere microorganisms in the biodegradation of PLA and PET polymers in compost soil. Int. Biodeterior. Biodegrad. 130, 65–75.
Jiang, X.J., Liu, W., Wang, E., Zhou, T., Xin, P., 2017. Residual plastic mulch fragments effects on soil physical properties and water flow behavior in the Minqin Oasis, northwestern China. Soil Tillage Res. 166, 100–107.
Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M., Klobucar, G., 2019. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant *Vicia faba*. Environ. Pollut. 250, 831–838.
Jiang, M., Hu, L., Lu, A., Liang, G., Lin, Z., Zhang, T., Xu, L., Li, B., Gong, W., 2020. Strong sorption of two fungicides onto biodegradable microplastics with emphasis on the negligible role of environmental factors. Environ. Pollut. 267, 115496.
Jin, Y., Lu, L., Tu, W., Luo, T., Fu, Z., 2019. Impacts of polystyrene microplastic on the gut barrier, microbiota and metabolism of mice. Sci. Total Environ. 649, 308–317.
Ju, H., Zhu, D., Qiao, M., 2019. Effects of polyethylene microplastics on the gut microbial community, reproduction and avoidance behaviors of the soil springtail, Folsomia candida. Environ. Pollut. 247, 890–897.

Kanie, O., Ishikawa, H., Ohta, S., Kitaoka, T., Tanaka, H., 2002. Study on characteristics of paper laminated with biodegradable plastics, 1. Burial test in soil. J. Fac. Agric. Kyushu Univ. 47, 89–96.
Karamanlioglu, M., Robson, G.D., 2013. The influence of biotic and abiotic factors on the rate of degradation of poly(lactic) acid (PLA) coupons buried in compost and soil. Polym. Degrad. Stabil. 98, 2063–2071.
Kasirajan, S., Ngouajio, M., 2012. Polyethylene and biodegradable mulches for agricultural applications: a review. Agron. Sustain. Dev. 32, 501–529.
Keswani, A., Oliver, D.M., Gutierrez, T., Quilliam, R.S., 2016. Microbial hitchhikers on marine plastic debris: human exposure risks at bathing waters and beach environments. Mar. Environ. Res. 118, 10–19.
Kijchavengkul, T., Auras, R., Rubino, M., Alvarado, E., Camacho Montero, J.R., Rosales, J.M., 2010a. Atmospheric and soil degradation of aliphatic-aromatic polyester films. Polym. Degrad. Stabil. 95, 99–107.
Kijchavengkul, T., Auras, R., Rubino, M., Selke, S., Ngouajio, M., Fernandez, R.T., 2010b. Biodegradation and hydrolysis rate of aliphatic aromatic polyester. Polym. Degrad. Stabil. 95, 2641–2647.
Klein, K., Piana, T., Lauschke, T., Schweyen, P., Dierkes, G., Ternes, T., Schulte-Oehlmann, U., Oehlmann, J., 2021. Chemicals associated with biodegradable microplastic drive the toxicity to the freshwater oligochaete Lumbriculus variegatus. Aquat. Toxicol. 231, 105723.
Krishnan, S., Chinnadurai, G.S., Perumal, P., 2017. Polyhydroxybutyrate by Streptomyces sp.: production and characterization. Int. J. Biol. Macromol. 104, 1165–1171.
Kubowicz, S., Booth, A.M., 2017. Biodegradability of plastics: challenges and misconceptions. Environ. Sci. Technol. 51, 12058–12060.
Kwak, J.I., An, Y.-J., 2021. Microplastic digestion generates fragmented nanoplastics in soils and damages earthworm spermatogenesis and coelomocyte viability. J. Hazard Mater. 402, 124034-124034.
La Mantia, F.P., Ascione, L., Mistretta, M.C., Rapisarda, M., Rizzarelli, P., 2020. Comparative investigation on the soil burial degradation behaviour of polymer films for agriculture before and after photo-oxidation. Polymers 12.
Lambert, S., Wagner, M., 2016. Formation of microscopic particles during the degradation of different polymers. Chemosphere 161, 510–517.
Lambert, S., Wagner, M., 2017. Environmental performance of bio-based and biodegradable plastics: the road ahead. Chem. Soc. Rev. 46, 6855–6871.
Li, J., Song, Y., Cai, Y., 2020a. Focus topics on microplastics in soil: analytical methods, occurrence, transport, and ecological risks. Environ. Pollut. 257, 113570.
Li, R., Liu, Y., Sheng, Y., Xiang, Q., Zhou, Y., Cizdziel, J.V., 2020b. Effect of prothioconazole on the degradation of microplastics derived from mulching plastic film: apparent change and interaction with heavy metals in soil. Environ. Pollut. 260.
Li, C., Cui, Q., Zhang, M., Vogt, R.D., Lu, X., 2021. A commonly available and easily assembled device for extraction of bio/non-degradable microplastics from soil by flotation in NaBr solution. Sci. Total Environ. 759, 143482.
Liang, C., Niu, H.-Y., Guo, H., Niu, C.-G., Yang, Y.-Y., Liu, H.-Y., Tang, W.-W., Feng, H.-P., 2021. Efficient photocatalytic nitrogen fixation to ammonia over bismuth monoxide quantum dots-modified defective ultrathin graphitic carbon nitride. Chem. Eng. J. 406, 126868.
Liao, Y.-l., Yang, J.-y., 2020. Microplastic serves as a potential vector for Cr in an *in-vitro* human digestive model. Sci. Total Environ. 703.
Liu, H., Yang, X., Liu, G., Liang, C., Xue, S., Chen, H., Ritsema, C.J., Geissen, V., 2017. Response of soil dissolved organic matter to microplastic addition in Chinese loess soil. Chemosphere 185, 907–917.
Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., Zhou, W., Cao, C., Shi, H., Yang, X., He, D., 2018. Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. Environ. Pollut. 242, 855–862.
Liu, P., Wu, X., Liu, H., Wang, H., Lu, K., Gao, S., 2020. Desorption of pharmaceuticals from pristine and aged polystyrene microplastics under simulated gastrointestinal conditions. J. Hazard Mater. 392.
Luo, H., Li, Y., Zhao, Y., Xiang, Y., He, D., Pan, X., 2020. Effects of accelerated aging on characteristics, leaching, and toxicity of commercial lead chromate pigmented microplastics. Environ. Pollut. 257.
Ma, J., Sheng, G.D., O'Connor, P., 2020. Microplastics combined with tetracycline in soils facilitate the formation of antibiotic resistance in the *Enchytraeus crypticus* microbiome. Environ. Pollut. 264.
Machado, A.A.d.S., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R., Rillig, M.C., 2018. Impacts of microplastics on the soil biophysical environment. Environ. Sci. Technol. 52, 9656–9665.
Mariani, P., Neto, A., Silva Junior, J., Cardoso, E., Esposito, E., Innocentini-Mei, L., 2007. Mineralization of poly(ϵ-caprolactone)/adipate modified starch blend in agricultural soil. J. Polym. Environ. 15, 19–24.
Mbachu, O., Jenkins, G., Kaparaju, P., Pratt, C., 2021. The rise of artificial soil carbon inputs: reviewing microplastic pollution effects in the soil environment. Sci. Total Environ. 780, 146569.
McCormick, A., Hoellein, T.J., Mason, S.A., Schluep, J., Kelly, J.J., 2014. Microplastic is an abundant and distinct microbial habitat in an urban river. Environ. Sci. Technol. 48, 11863–11871.
McCormick, A.R., Hoellein, T.J., London, M.G., Hittie, J., Scott, J.W., Kelly, J.J., 2016. Microplastic in surface waters of urban rivers: concentration, sources, and associated bacterial assemblages. Ecosphere 7.
Meng, F., Yang, X., Riksen, M., Xu, M., Geissen, V., 2021. Response of common bean (Phaseolus vulgaris L.) growth to soil contaminated with microplastics. Sci. Total Environ. 755, 142516.
Menicagli, V., Balestri, E., Lardicci, C., 2019. Exposure of coastal dune vegetation to plastic bag leachates: a neglected impact of plastic litter. Sci. Total Environ. 683, 737–748.
Miao, L., Wang, P., Hou, J., Yao, Y., Liu, Z., Liu, S., Li, T., 2019. Distinct community structure and microbial functions of biofilms colonizing microplastics. Sci. Total Environ. 650, 2395–2402.
Napper, I.E., Thompson, R.C., 2019. Environmental deterioration of biodegradable, oxo-biodegradable, compostable, and conventional plastic carrier bags in the sea, soil, and open-air over a 3-year period. Environ. Sci. Technol. 53, 4775–4783.
O'Donovan, S., Mestre, N.C., Abel, S., Fonseca, T.G., Carteny, C.C., Cormier, B., Keiter, S. H., Bebianno, M.J., 2018. Ecotoxicological effects of chemical contaminants adsorbed to microplastics in the clam *Scrobicularia plana*. Frontiers in Marine Science 5.
Ojeda, T.F.M., Dalmolin, E., Forte, M.M.C., Jacques, R.J.S., Bento, F.M., Camargo, F.A.O., 2009. Abiotic and biotic degradation of oxo-biodegradable polyethylenes. Polym. Degrad. Stabil. 94, 965–970.
Pathan, S.I., Arfaioli, P., Bardelli, T., Ceccherini, M.T., Nannipieri, P., Pietramellara, G., 2020. Soil pollution from micro- and nanoplastic debris: a hidden and unknown biohazard. Sustainability 12.
Pignattelli, S., Broccoli, A., Renzi, M., 2020. Physiological responses of garden cress (*L. sativum*) to different types of microplastics. Sci. Total Environ. 727.
Prata, J.C., da Costa, J.P., Lopes, I., Duarte, A.C., Rocha-Santos, T., 2020. Environmental exposure to microplastics: an overview on possible human health effects. Sci. Total Environ. 702, 134455.
Qi, Y., Yang, X., Mejia Pelaez, A., Huerta Lwanga, E., Beriot, N., Gertsen, H., Garbeva, P., Geissen, V., 2018. Macro- and micro- plastics in soil-plant system: effects of plastic mulch film residues on wheat (*Triticum aestivum*) growth. Sci. Total Environ. 645, 1048–1056.
Qi, Y., Beriot, N., Gort, G., Lwanga, E.H., Gooren, H., Yang, X., Geissen, V., 2020a. Impact of plastic mulch film debris on soil physicochemical and hydrological properties. Environ. Pollut. 266.
Qi, Y., Ossowicki, A., Yang, X., Lwanga, E.H., Dini-Andreote, F., Geissen, V., Garbeva, P., 2020b. Effects of plastic mulch film residues on wheat rhizosphere and soil properties. J. Hazard Mater. 387.
Qi, R., Jones, D.L., Liu, Q., Liu, Q., Li, Z., Yan, C., 2021. Field test on the biodegradation of poly(butylene adipate-co-terephthalate) based mulch films in soil. Polym. Test. 93, 107009.
Qian, H., Zhang, M., Liu, G., Lu, T., Qu, Q., Du, B., Pan, X., 2018. Effects of soil residual plastic film on soil microbial community structure and fertility. Water Air Soil Pollut. 229.
Rai, P., Mehrotra, S., Priya, S., Gnansounou, E., Sharma, S.K., 2021. Recent advances in the sustainable design and applications of biodegradable polymers. Bioresour. Technol. 325, 124739.
RameshKumar, S., Shaiju, P., O'Connor, K.E., P, R.B., 2020. Bio-based and biodegradable polymers - state-of-the-art, challenges and emerging trends. Current Opinion in Green and Sustainable Chemistry 21, 75–81.
Ren, X., Tang, J., Liu, X., Liu, Q., 2020. Effects of microplastics on greenhouse gas emissions and the microbial community in fertilized soil. Environ. Pollut. 256.
Rochman, C.M., Hoh, E., Kurobe, T., Teh, S.J., 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci. Rep. 3.
Rodriguez-Seijo, A., Lourenco, J., Rocha-Santos, T.A.P., da Costa, J., Duarte, A.C., Vala, H., Pereira, R., 2017. Histopathological and molecular effects of microplastics in *Eisenia andrei* Bouché. Environ. Pollut. 220, 495–503.
Roohi Bano, K., Kuddus, M., Zaheer, M.R., Zia, Q., Khan, M.F., Ashraf, G.M., Gupta, A., Aliev, G., 2017. Microbial enzymatic degradation of biodegradable plastics. Curr. Pharmaceut. Biotechnol. 18, 429–440.
Rosato, A., Barone, M., Negroni, A., Brigidi, P., Fava, F., Xu, P., Candela, M., Zanaroli, G., 2020. Microbial colonization of different microplastic types and biotransformation of sorbed PCBs by a marine anaerobic bacterial community. Sci. Total Environ. 705.
Rujnic-Sokele, M., Pilipovic, A., 2017. Challenges and opportunities of biodegradable plastics: a mini review. Waste Manag. Res. 35, 132–140.
Rychter, P., Kawalec, M., Sobota, M., Kurcok, P., Kowalczuk, M., 2010. Study of aliphatic-aromatic copolyester degradation in sandy soil and its ecotoxicological impact. Biomacromolecules 11, 839–847.
Sanchez-Hernandez, J.C., Capowiez, Y., Ro, K.S., 2020. Potential use of earthworms to enhance decaying of biodegradable plastics. ACS Sustain. Chem. Eng. 8, 4292–4316.
Sanz-Lázaro, C., Casado-Coy, N., Beltrán-Sanahuja, A., 2021. Biodegradable plastics can alter carbon and nitrogen cycles to a greater extent than conventional plastics in marine sediment. Sci. Total Environ. 756, 143978.
Scheurer, M., Bigalke, M., 2018. Microplastics in Swiss floodplain soils. Environ. Sci. Technol. 52, 3591–3598.
Schiavo, S., Oliviero, M., Chiavarini, S., Manzo, S., 2020. Adverse effects of oxo-degradable plastic leachates in freshwater environment. Environ. Sci. Pollut. Control Ser. 27, 8586–8595.
Scopetani, C., Chelazzi, D., Mikola, J., Leiniö, V., Heikkinen, R., Cincinelli, A., Pellinen, J., 2020. Olive oil-based method for the extraction, quantification and identification of microplastics in soil and compost samples. Sci. Total Environ. 733, 139338.
Serrano-Ruíz, H., Martín-Closas, L., Pelacho, A.M., 2018. Application of an in vitro plant ecotoxicity test to unused biodegradable mulches. Polym. Degrad. Stabil. 158, 102–110.
Serrano-Ruíz, H., Eras, J., Martín-Closas, L., Pelacho, A.M., 2020. Compounds released from unused biodegradable mulch materials after contact with water. Polym. Degrad. Stabil. 178, 109202.
Serrano-Ruiz, H., Martin-Closas, L., Pelacho, A.M., 2021. Biodegradable plastic mulches: impact on the agricultural biotic environment. Sci. Total Environ. 750, 141228.

Setälä, O., Norkko, J., Lehtiniemi, M., 2016. Feeding type affects microplastic ingestion in a coastal invertebrate community. Mar. Pollut. Bull. 102, 95–101.
Sharma, V., Sehgal, R., Gupta, R., 2021. Polyhydroxyalkanoate (PHA): properties and modifications. Polymer 212, 123161.
Shen, M., Zhang, Y., Zhu, Y., Song, B., Zeng, G., Hu, D., Wen, X., Ren, X., 2019. Recent advances in toxicological research of nanoplastics in the environment: a review. Environ. Pollut. 252, 511–521.
Shen, M., Huang, W., Chen, M., Song, B., Zeng, G., Zhang, Y., 2020a. (Micro)plastic crisis: un-ignorable contribution to global greenhouse gas emissions and climate change. J. Clean. Prod. 254.
Shen, M., Song, B., Zeng, G., Zhang, Y., Huang, W., Wen, X., Tang, W., 2020b. Are biodegradable plastics a promising solution to solve the global plastic pollution? Environ. Pollut. 263.
Shen, M., Ye, S., Zeng, G., Zhang, Y., Xing, L., Tang, W., Wen, X., Liu, S., 2020c. Can microplastics pose a threat to ocean carbon sequestration? Mar. Pollut. Bull. 150, 110712.
Shen, M., Song, B., Zeng, G., Zhang, Y., Teng, F., Zhou, C., 2021. Surfactant changes lead adsorption behaviors and mechanisms on microplastics. Chem. Eng. J. 405, 126989.
Shogren, R.L., Doane, W.M., Garlotta, D., Lawton, J.W., Willett, J.L., 2003. Biodegradation of starch/polylactic acid/poly(hydroxyester-ether) composite bars in soil. Polym. Degrad. Stabil. 79, 405–411.
Shruti, V.C., Kutralam-Muniasamy, G., 2019. Bioplastics: missing link in the era of microplastics. Sci. Total Environ. 697.
Sinohara Souza, P.M., Corroque, N.A., Morales, A.R., Marin-Morales, M.A., Innocentini Mei, L.H., 2013. PLA and organoclays nanocomposites: degradation process and evaluation of ecotoxicity using *Allium cepa* as test organism. J. Polym. Environ. 21, 1052–1063.
Sintim, H.Y., Bary, A.I., Hayes, D.G., Wadsworth, L.C., Anunciado, M.B., English, M.E., Bandopadhyay, S., Schaeffer, S.M., DeBruyn, J.M., Miles, C.A., Reganold, J.P., Flury, M., 2020. In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. Sci. Total Environ. 727.
Siracusa, V., Blanco, I., 2020. Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly(ethylene Terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications. Polymers 12.
Song, B., Gong, J., Tang, W., Zeng, G., Chen, M., Xu, P., Shen, M., Ye, S., Feng, H., Zhou, C., Yang, Y., 2020. Influence of multi-walled carbon nanotubes on the microbial biomass, enzyme activity, and bacterial community structure in 2,4-dichlorophenol-contaminated sediment. Sci. Total Environ. 713.
Soroudi, A., Jakubowicz, I., 2013. Recycling of bioplastics, their blends and biocomposites: a review. Eur. Polym. J. 49, 2839–2858.
Steinmetz, Z., Wollmann, C., Schaefer, M., Buchmann, C., David, J., Tröger, J., Muñoz, K., Frör, O., Schaumann, G.E., 2016. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Sci. Total Environ. 550, 690–705.
Sun, Y., Cao, N., Duan, C., Wang, Q., Ding, C., Wang, J., 2021a. Selection of antibiotic resistance genes on biodegradable and non-biodegradable microplastics. J. Hazard Mater. 409, 124979.
Sun, Y., Wang, X., Xia, S., Zhao, J., 2021b. New insights into oxytetracycline (OTC) adsorption behavior on polylactic acid microplastics undergoing microbial adhesion and degradation. Chem. Eng. J. 416, 129085.
Syberg, K., Khan, F.R., Selck, H., Palmqvist, A., Banta, G.T., Daley, J., Sano, L., Duhaime, M.B., 2015. Microplastics: addressing ecological risk through lessons learned. Environ. Toxicol. Chem. 34, 945–953.
Tabone, M.D., Cregg, J.J., Beckman, E.J., Landis, A.E., 2010. Sustainability metrics: life cycle assessment and green design in polymers. Environ. Sci. Technol. 44, 8264–8269.
Taylor, S.E., Pearce, C.I., Sanguinet, K.A., Hu, D., Chrisler, W.B., Kim, Y.-M., Wang, Z., Flury, M., 2020. Polystyrene nano- and microplastic accumulation at Arabidopsis and wheat root cap cells, but no evidence for uptake into roots. Environmental Science-Nano 7, 1942–1953.
Thompson, R., Olsen, Y., Mitchell, R., Davis, A., Rowland, S., John, A., McGonigle, D.F., Russell, A., 2004. Lost at sea: where is all the plastic? Science (Washington, D.C.) 304, 838.
Torres, F.G., Dioses-Salinas, D.C., Pizarro-Ortega, C.I., De-la-Torre, G.E., 2021. Sorption of chemical contaminants on degradable and non-degradable microplastics: recent progress and research trends. Sci. Total Environ. 757, 143875.
Tosin, M., Pischedda, A., Degli-Innocenti, F., 2019. Biodegradation kinetics in soil of a multi-constituent biodegradable plastic. Polym. Degrad. Stabil. 166, 213–218.
Tourinho, P.S., Koci, V., Loureiro, S., van Gestel, C.A.M., 2019. Partitioning of chemical contaminants to microplastics: sorption mechanisms, environmental distribution and effects on toxicity and bioaccumulation. Environ. Pollut. 252, 1246–1256.
Tubić, A., Loncarski, M., Maletic, S., Jazic, J.M., Watson, M., Trickovic, J., Agbaba, J., 2019. Significance of chlorinated phenols adsorption on plastics and bioplastics during water treatment. Water 11.
Verdú, I., González-Pleiter, M., Leganés, F., Rosal, R., Fernández-Piñas, F., 2021. Microplastics can act as vector of the biocide triclosan exerting damage to freshwater microalgae. Chemosphere 266, 129193.
Viera, J.S.C., Marques, M.R.C., Nazareth, M.C., Jimenez, P.C., Castro, Í.B., 2020. On replacing single-use plastic with so-called biodegradable ones: the case with straws. Environ. Sci. Pol. 106, 177–181.
Walker, S., Rothman, R., 2020. Life cycle assessment of bio-based and fossil-based plastic: a review. J. Clean. Prod. 261.
Wan, Y., Wu, C., Xue, Q., Hui, X., 2019. Effects of plastic contamination on water evaporation and desiccation cracking in soil. Sci. Total Environ. 654, 576–582.
Wang, J., Lv, S., Zhang, M., Chen, G., Zhu, T., Zhang, S., Teng, Y., Christie, P., Luo, Y., 2016. Effects of plastic film residues on occurrence of phthalates and microbial activity in soils. Chemosphere 151, 171–177.
Wang, J., Coffin, S., Sun, C., Schlenk, D., Gan, J., 2019. Negligible effects of microplastics on animal fitness and HOC bioaccumulation in earthworm *Eisenia fetida* in soil. Environ. Pollut. 249, 776–784.
Wang, F., Zhang, X., Zhang, S., Zhang, S., Adams, C.A., Sun, Y., 2020a. Effects of Co-contamination of microplastics and Cd on plant growth and Cd accumulation. Toxics 8.
Wang, F., Zhang, X., Zhang, S., Zhang, S., Sun, Y., 2020b. Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. Chemosphere 254.
Wang, J., Huang, M., Wang, Q., Sun, Y., Zhao, Y., Huang, Y., 2020c. LDPE microplastics significantly alter the temporal turnover of soil microbial communities. Sci. Total Environ. 726, 138682.
Wang, W., Ge, J., Yu, X., Li, H., 2020d. Environmental fate and impacts of microplastics in soil ecosystems: progress and perspective. Sci. Total Environ. 708, 134841.
Wang, Z., Wang, H., Zeng, Z., Zeng, G., Xu, P., Xiao, R., Huang, D., Chen, X., He, L., Zhou, C., Yang, Y., Wang, Z., Wang, W., Xiong, W., 2020e. Metal-organic frameworks derived Bi2O2CO3/porous carbon nitride: a nanosized Z-scheme systems with enhanced photocatalytic activity. Appl. Catal. B Environ. 267.
Wei, X.-F., Bohlén, M., Lindblad, C., Hedenqvist, M., Hakonen, A., 2021. Microplastics generated from a biodegradable plastic in freshwater and seawater. Water Res., 117123
Weinstein, J.E., Dekle, J.L., Leads, R.R., Hunter, R.A., 2020. Degradation of bio-based and biodegradable plastics in a salt marsh habitat: another potential source of microplastics in coastal waters. Mar. Pollut. Bull. 160, 111518-111518.
Wen, X., Du, C., Xu, P., Zeng, G., Huang, D., Yin, L., Yin, Q., Hu, L., Wan, J., Zhang, J., Tan, S., Deng, R., 2018. Microplastic pollution in surface sediments of urban water areas in Changsha, China: abundance, composition, surface textures. Mar. Pollut. Bull. 136, 414–423.
Weng, Y.-X., Wang, L., Zhang, M., Wang, X.-L., Wang, Y.-Z., 2013. Biodegradation behavior of P(3HB,4HB)/PLA blends in real soil environments. Polym. Test. 32, 60–70.
Wu, N., Zhang, Y., Zhao, Z., He, J., Li, W., Li, J., Xu, W.a., Ma, Y., Niu, Z., 2020. Colonization characteristics of bacterial communities on microplastics compared with ambient environments (water and sediment) in Haihe Estuary. Sci. Total Environ. 708.
Xu, B., Liu, F., Cryder, Z., Huang, D., Lu, Z., He, Y., Wang, H., Lu, Z., Brookes, P.C., Tang, C., Gan, J., Xu, J., 2020. Microplastics in the soil environment: occurrence, risks, interactions and fate – a review. Crit. Rev. Environ. Sci. Technol. 50, 2175–2222.
Yang, Y., Liu, G., Song, W., Ye, C., Lin, H., Li, Z., Liu, W., 2019. Plastics in the marine environment are reservoirs for antibiotic and metal resistance genes. Environ. Int. 123, 79–86.
Yang, Y., Li, P., Jiao, J., Yang, Z., Lv, M., Li, Y., Zhou, C., Wang, C., He, Z., Liu, Y., Song, S., 2020a. Renewable sourced biodegradable mulches and their environment impact. Sci. Hortic. 268, 109375.
Yang, Y., Zeng, G., Huang, D., Zhang, C., He, D., Zhou, C., Wang, W., Xiong, W., Song, B., Yi, H., Ye, S., Ren, X., 2020b. In situ grown single-atom cobalt on polymeric carbon nitride with bidentate ligand for efficient photocatalytic degradation of refractory antibiotics. Small 16.
Yang, W., Cheng, P., Adams, C.A., Zhang, S., Sun, Y., Yu, H., Wang, F., 2021. Effects of microplastics on plant growth and arbuscular mycorrhizal fungal communities in a soil spiked with ZnO nanoparticles. Soil Biol. Biochem. 155, 108179.
Ye, S., Zeng, G., Wu, H., Liang, J., Zhang, C., Dai, J., Xiong, W., Song, B., Wu, S., Yu, J., 2019. The effects of activated biochar addition on remediation efficiency of co-composting with contaminated wetland soil. Resour. Conserv. Recycl. 140, 278–285.
Zettler, E.R., Mincer, T.J., Amaral-Zettler, L.A., 2013. Life in the "plastisphere": microbial communities on plastic marine debris. Environ. Sci. Technol. 47, 7137–7146.
Zhang, G.S., Liu, Y.F., 2018. The distribution of microplastics in soil aggregate fractions in southwestern China. Sci. Total Environ. 642, 12–20.
Zhang, M., Jia, H., Weng, Y., Li, C., 2019. Biodegradable PLA/PBAT mulch on microbial community structure in different soils. Int. Biodeterior. Biodegrad. 145.
Zhang, X., Xia, M., Su, X., Yuan, P., Li, X., Zhou, C., Wan, Z., Zou, W., 2021. Photolytic degradation elevated the toxicity of polylactic acid microplastics to developing zebrafish by triggering mitochondrial dysfunction and apoptosis. J. Hazard Mater. 413, 125321.
Zhou, J., Gui, H., Banfield, C.C., Wen, Y., Zang, H., Dippold, M.A., Charlton, A., Jones, D. L., 2021. The microplastisphere: biodegradable microplastics addition alters soil microbial community structure and function. Soil Biol. Biochem. 156, 108211.
Ziajahromi, S., Neale, P.A., Rintoul, L., Leusch, F.D.L., 2017. Wastewater treatment plants as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. Water Res. 112, 93–99.
Zimmermann, L., Göttlich, S., Oehlmann, J., Wagner, M., Völker, C., 2020. What are the drivers of microplastic toxicity? Comparing the toxicity of plastic chemicals and particles to Daphnia magna. Environ. Pollut. 267, 115392.
Zou, X., Niu, W., Liu, J., Li, Y., Liang, B., Guo, L., Guan, Y., 2017. Effects of residual mulch film on the growth and fruit quality of tomato (*Lycopersicon esculentum* Mill.). Water Air Soil Pollut. 228.
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.