

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/374235093>

Microplastic Pollution in Terrestrial Ecosystems: Global Implications and Sustainable Solutions

Article in *Journal of Hazardous Materials* · January 2024

DOI: 10.1016/j.jhazmat.2023.132636

CITATIONS

11

READS

413

11 authors, including:



Aurang Zeb

Nankai University

35 PUBLICATIONS 1,701 CITATIONS

SEE PROFILE



Weitao Liu

Nankai University

77 PUBLICATIONS 3,697 CITATIONS

SEE PROFILE



Shi Ruiying

Nankai University

18 PUBLICATIONS 286 CITATIONS

SEE PROFILE



Qi Wang

Nankai University

25 PUBLICATIONS 473 CITATIONS

SEE PROFILE



Review

Microplastic pollution in terrestrial ecosystems: Global implications and sustainable solutions

Aurang Zeb^{a,b}, Weitao Liu^{a,b,*}, Nouman Ali^{a,b}, Ruiying Shi^{a,b}, Qi Wang^{a,b},
Jianling Wang^{a,b}, Jiantao Li^{a,b}, Chuan Yin^{a,b}, Jinzheng Liu^{a,b}, Miao Yu^{a,b}, Jianv Liu^{a,b}

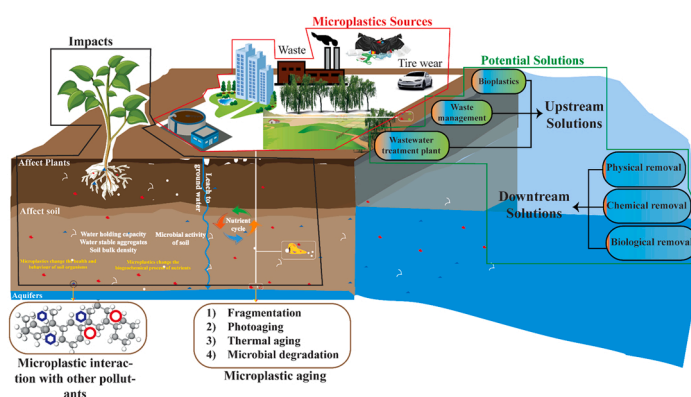
^a MOE Key Laboratory of Pollution Processes and Environmental Criteria, College of Environmental Science and Engineering, Nankai University, Tianjin 300350, China

^b Tianjin Engineering Research Center of Environmental Diagnosis and Contamination Remediation, Tianjin 300350, China

HIGHLIGHTS

- Distribution and behavior of microplastics (MPs) in soil-plant systems are reviewed.
- MPs can influence the physio-biochemical parameters of soil and plants.
- MPs can serve as vectors for other soil contaminants, leading to co-toxicity.
- MPs can age naturally or artificially and may be influenced by various factors.
- MPs research gaps are identified, and future perspectives are proposed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Teresa Rocha-Santos

Keywords:
Microplastics
Soil
Plants
Aging
Additives
Mitigation

ABSTRACT

Microplastic (MPs) pollution has become a global environmental concern with significant impacts on ecosystems and human health. Although MPs have been widely detected in aquatic environments, their presence in terrestrial ecosystems remains largely unexplored. This review examines the multifaceted issues of MPs pollution in terrestrial ecosystem, covering various aspects from additives in plastics to global legislation and sustainable solutions. The study explores the widespread distribution of MPs worldwide and their potential antagonistic interactions with co-occurring contaminants, emphasizing the need for a holistic understanding of their environmental implications. The influence of MPs on soil and plants is discussed, shedding light on the potential consequences for terrestrial ecosystems and agricultural productivity. The aging mechanisms of MPs, including photo and thermal aging, are elucidated, along with the factors influencing their aging process. Furthermore, the review provides an overview of global legislation addressing plastic waste, including bans on specific plastic items and levies on single-use plastics. Sustainable solutions for MPs pollution are proposed, encompassing

* Corresponding author at: MOE Key Laboratory of Pollution Processes and Environmental Criteria, College of Environmental Science and Engineering, Nankai University, Tianjin 300350, China.

E-mail address: lwt@nankai.edu.cn (W. Liu).

¹ Present Address: No. 38 Tongyan Road, College of Environmental Science and Engineering, Nankai University, Tianjin 300350, China

² ORCID : 0000-0003-1352-0243

upstream approaches such as bioplastics, improved waste management practices, and wastewater treatment technologies, as well as downstream methods like physical and biological removal of MPs. The importance of international collaboration, comprehensive legislation, and global agreements is underscored as crucial in tackling this pervasive environmental challenge. This review may serve as a valuable resource for researchers, policymakers, and stakeholders, providing a comprehensive assessment of the environmental impact and potential risks associated with MPs.

1. Introduction

Plastics are widely used in modern life due to their desirable characteristics such as high stability, lightweight nature, ease of production, thermal and electrical insulation, and versatility [156]. Materials like polystyrene (PS), polyethylene (PE), poly(ethylene terephthalate) (PET), poly(vinyl chloride) (PVC), polycarbonate (PC), etc are produced in large quantities and extensively utilized [243]. Despite efforts to improve plastic recycling and management, plastic misuse remains a global problem, leading to unregulated proliferation [15]. Plastics in the environment undergo fragmentation due to factors like biological metabolism, UV radiation, and water forces, forming microplastics (MPs) with sizes ranging from 1 μm to 5 mm, as well as nanoplastics (NPs) with sizes ranging from 1 nm to 1 μm [67,258].

MPs are found extensively across various ecosystems, including terrestrial environments, freshwater systems, marine ecosystems, and even in the air [168,188]. Unfortunately, a significant portion of plastic waste goes unrecycled, resulting in its accumulation in the environment [6,73]. The presence of MPs raises concerns due to their potential adverse effects on organisms. Additives and monomers leached from MPs can be harmful, with some possessing carcinogenic or

endocrine-disrupting properties [135,157,22,23]. MPs also have the capacity to absorb organic pollutants [221] and heavy metals from the surrounding environment. Additionally, they serve as vectors for pathogenic microorganisms or antibiotic-resistant bacteria, posing risks to human health and other soil organisms [189,259].

MPs undergo significant aging processes in the natural environment, involving physical, chemical, and biological transformations [281]. These aging processes cause notable changes in the physicochemical properties of MPs, which subsequently affect their environmental behavior. For instance, aged MPs exhibit altered hydrophilicity, surface charge, and oxygen-containing groups, influencing their interaction with co-existing contaminants [129] (Fig. 1). To investigate the effects of diverse environmental stresses on MPs, researchers have simulated natural aging processes in the laboratory, including photo and thermal aging, and biodegradation [106,2,87]. However, there is a lack of comprehensive reviews on the characterization technology and aging mechanisms of MPs under various conditions. Understanding the aging process of MPs and the factors that affects the aging process is crucial for reducing uncertainty in hazard and risk assessments.

The current understanding of the risks and impacts of MPs on terrestrial ecosystems is limited and fragmented, highlighting significant

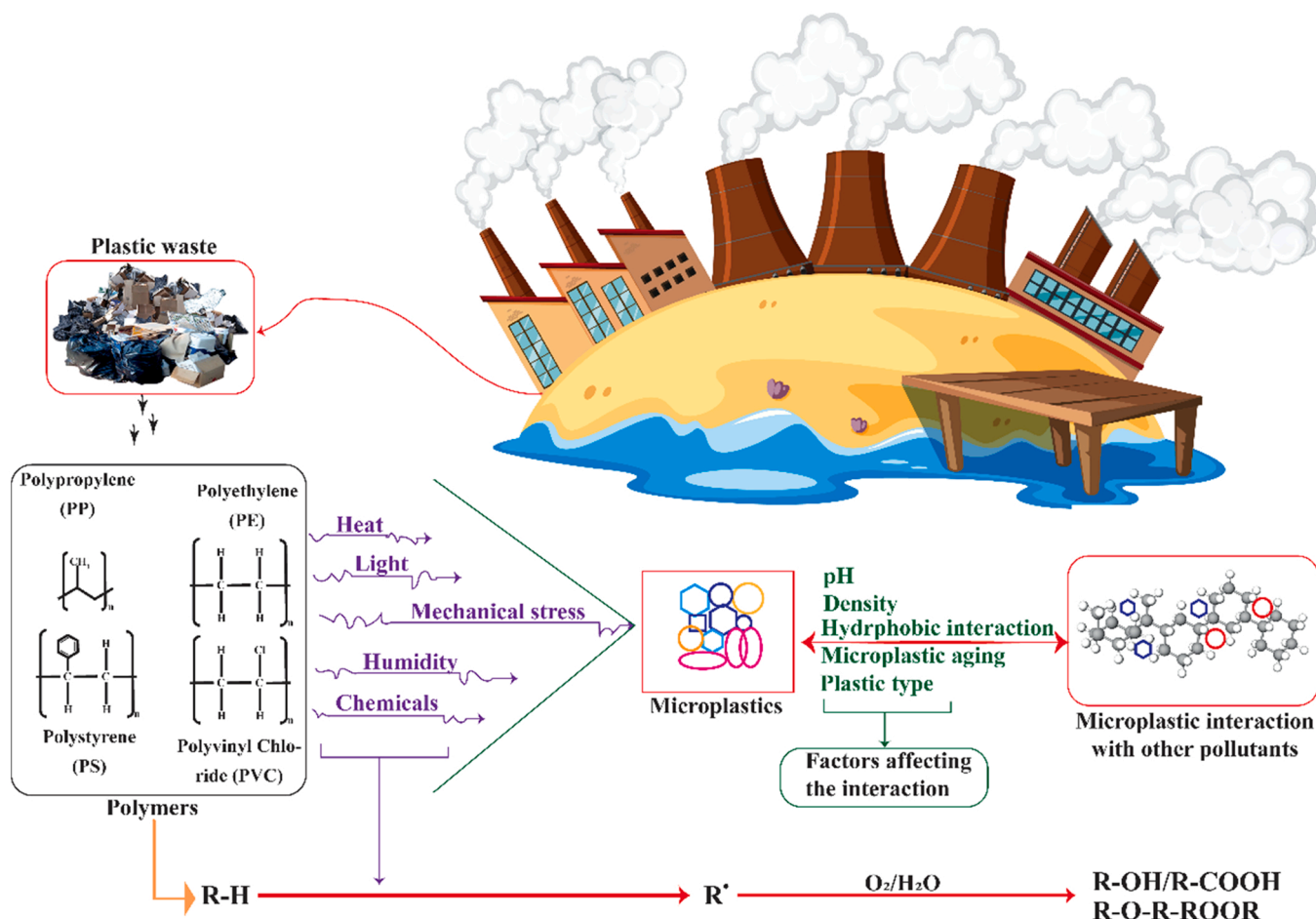


Fig. 1. Structures of some polymers, modifications under environmental conditions and interaction with other pollutants.

knowledge gaps regarding their distribution, behavior in soil-plant systems, and aging processes. Addressing these gaps is essential for comprehending the long-term environmental consequences of MPs and developing effective mitigation policies and regulations. This study aims to fill these knowledge gaps by conducting a comprehensive literature review on the complexities of MPs in soil ecosystems. Specifically, it examines the role of additives in plastics, the distribution patterns of MPs, their interactions with soil, plants, and other contaminants, as well as their aging processes. Furthermore, the study aims to identify sustainable mitigation measures to combat MPs contamination in terrestrial environments. Ultimately, the findings of this study will contribute to the development of sustainable soil management practices, ensuring the long-term health, productivity, and ecological integrity of soils.

2. Distribution of microplastics around the globe

MPs exist in the environment as primary and secondary particles [115]. Primary MPs originate from cosmetic products, synthetic textiles, city dust, tires, road markings etc., while secondary MPs are formed through the degradation or abrasion of bulk plastic waste in soil and can also come from atmospheric deposition, and wastewater irrigation

[258]. Agricultural soils receive MPs from various sources, including agricultural practices, landfills, tire wear, sewage irrigation, and atmospheric deposition (Fig. 2). Soil contamination with MPs in the terrestrial environment remains poorly understood [223,239]. China, being a major producer and consumer of plastic with approximately 30% of global consumption [219], has been the focus of numerous studies on MPs in terrestrial environments (Table 2). In China, MP sampling from soil includes agricultural and non-agricultural soils. Agricultural soil includes crop lands, farmlands, pastures, greenhouses, grasslands, and rangelands. In eastern China's Shanghai, the abundance of MPs was found to be 10.3 ± 2.2 numbers per kilogram (n/kg) in paddy soil (10 cm depth), 78 ± 12.91 n/kg in shallow soils (3 cm depth), and 62.5 ± 12.98 n/kg in deep soil (6 cm depth) of farmland [128,139]. In the Dian Lake region of Yunnan province, China, the abundance of MPs reached 18,760 n/kg at a depth of 5–10 cm in greenhouse soils due to sludge and sewage irrigation [260]. Non-agricultural soils include wetland, industrial, coastal, residential, and campus soils (Table 2). Coastal soils in Hebei province, China, reported an abundance of 634 n/kg at a depth of 2 cm. Wetland soils in Shandong Province, China, showed an abundance of MPs ranging from 136 to 2060 n/kg at a depth of 2 cm [56]. Additionally, a lawn soil sample from Tianjin, China,



Fig. 2. Conceptual illustration of microplastic sources in the environment.

Table 1

Types of additives in plastics and their functions. Data collected from [10,57].

Function	Substance name	Polymer type	CAS number	EC number	Other function in plastic	Typical concentration (%)
Light stabilizers	Octabenzene	Polyolefin-I; PUR; Polyolefin-II; polyvinyl chloride (PVC) (soft); ABS; PVC (rigid); PMMA; PC; (E)PS	1843–05–6	217–421–2	Other stabilizer	0.2–5.0
	2-(2 H-benzotriazol-2-yl)-p-cresol	Polyolefin-I; Polyolefin-II; PVC (soft); ABS; PVC (rigid); PMMA; (E)PS	2440–22–4	219–470–5	Other stabilizer	0.0015–0.5
	2-(2 H-benzotriazol-2-yl)– 4-(1,1,3,3-tetramethylbutyl)phenol	PC	3147–75–9	221–573–5	Other stabilizer	0.3
	Bumetrizole	Polyolefin-I; PUR; Polyolefin-II; PVC (soft); ABS; PVC (rigid); PC; (E)PS	05/11/3896	223–445–4	–	0.3–1.0
	N-(2-ethoxyphenyl)-N'-(2-ethylphenyl) oxamide	PVC (soft); ABS; PVC (rigid); PA; PC; (E)PS	23949–66–8	245–950–9	Other stabilizer	0.7
Heat Stabilizers	2-(2 H-benzotriazol-2-yl)– 4,6-ditertpentylphenol		25973–55–1	247–384–8	–	–
	Dibutyltin dilaurate	Polyolefin-I; PVC (soft); PVC (rigid)	77–58–7	201–039–8	–	3
	2-ethylhexyl 10-ethyl-4,4-dioctyl-7-oxo-8-oxa-3,5-dithia-	PVC (soft); PVC (rigid)	15571–58–1	239–622–4	–	2
	2-ethylhexyl diphenyl phosphite	PVC (soft); PVC (rigid)	15647–08–2	239–716–5	–	2
	Triisodecyl phosphite	PVC (soft); PVC (rigid)	25448–25–3	246–998–3	–	2
	Diisodecyl phenyl phosphite	PVC (soft); PVC (rigid)	25550–98–5	247–098–3	–	3
	Isodecyl diphenyl phosphite	PVC (soft); PVC (rigid)	26544–23–0	247–777–4	–	3
	2,2',2''-nitritoltriethanol	–	102–71–6	203–049–8	Acts as a pigment	–
	N,N'-ethylenedi(stearamide)	Polyolefin-I; Polyolefin-II; ABS; (E).	110–30–5	203–755–6	–	0.3–0.5
	1,1'-iminodiprop-2-ol	–	110–97–4	203–820–9	–	–
Other Stabilizers	1,3-diphenylpropane-1,3-dione	PVC (soft), PVC (rigid), PET	120–46–7	204–398–9	–	–
	Potassium hydrogencarbonate	–	298–14–6	206–059–0	–	–
	Magnesium carbonate	Polyolefin-I, PA	546–93–0	208–915–9	Stabilizer	1
	Isooctadecan-1-ol	–	27458–93–1	248–470–8	–	–
	Hexadecan-1-ol	–	36653–82–4	253–149–0	–	–
	6,6'-di-tert-butyl-4,4'-butyldenedi-m-cresol	PVC (rigid), PA	85–60–9	201–618–5	Other stabilizer	0.5
	2,6-di-tert-butyl- α -dimethylamino-p-cresol	–	88–27–7	201–816–1	–	–
	6,6'-di-tert-butyl-4,4'-thiodi-m-cresol	Polyolefin-I	96–69–5	202–525–2	–	0.001
	2,2',6,6'-tetra-tert-butyl-4,4'-methylenediphenol	–	118–82–1	204–279–1	–	–
	6,6'-di-tert-butyl-2,2'-methylenedi-p-cresol	Polyolefin-I, ABS	119–47–1	204–327–1	–	0.5
Antioxidants	2,6-di-tert-butyl-p-cresol	–	128–37–0	204–881–4	–	–
	Diocetadecyl 3,3'-thiodipropionate	Polyolefin-I, Polyolefin-II, ABS, PET, PA	693–36–7	211–750–5	–	0.25–3.0
	Ethanol, 2,2'-iminobis-, N-(C13–15-branched and linear alkyl) derivs.	PVC (soft)	97925–95–6	308–208–6	Antistatic	–
	1,2-Dihydro-2,2,4-trimethylquinoline, oligomers	–	26780–96–1	500–051–3	Heat stabilizer	–
	Sodium benzoate	Polyolefin-II	532–32–1	208–534–8	–	0.2
	Fumes, silica	–	69012–64–2	273–761–1	Flame retardant	–
	2,2'-methylene bis-(4,6-di-tert-butylphenyl) sodium phosphate	Polyolefin-II	85209–91–2	286–344–4	–	0.2
	Fatty acids, C8–10, zinc salts	PVC (soft), PVC (rigid)	91051–00–2	293–048–9	Other stabilizer	–
	Copper (tetrachloro-29 H,31 H-phthalocyaninato(2-)-N29,N30,N31, N32)	Polyolefin-I, Polyolefin-II	27614–71–7	248–573–8	–	0.05
	2,2'-(octadec-9-enylimino)bisethanol	ABS, (E)PS	25307–17–9	246–807–3	–	–
Antistatic	Tributyl-O-Acetyl citrate	PUR, PVC (soft)	77–90–7	201–067–0	–	10.0–35.0
	Triethyl citrate	PUR, PVC (soft)	77–93–0	201–070–7	–	10.0–35.0
	Dibutyl phthalate	PUR, PVC (soft)	84–74–2	201–557–4	–	10.0–35.0
	Bis(2-ethylhexyl) adipate	PUR, PVC (soft)	103–23–1	203–090–1	–	10.0–35.0
	Dibutyl adipate	PUR, PVC (soft)	105–99–7	203–350–4	–	10.0–35.0
	Di-2-ethylhexyl phthalate	PUR, PVC (soft), ABS, (E)PS	117–81–7	204–211–0	–	2.0–35.0
	Oxydiethylene dibenzoate	PVC (soft)	120–55–8	204–407–6	–	–
	Decanedioic acid, 1,10-bis (2-ethylhexyl) ester	PUR, PVC (soft)	122–62–3	204–558–8	–	10.0–35.0
	Di-allyl phthalate	PUR, PVC (soft)	131–17–9	205–016–3	–	10.0–35.0
	Bis(tridecyl) adipate	PUR, PVC (soft)	16958–92–2	241–029–0	–	10.0–35.0
Plasticizers	Isobutyric acid, monoester with 2,2,4-trimethylpentane-1,3-diol	PVC (soft)	25265–77–4	246–771–9	–	–
	Diisononyladipate	PUR, PVC (soft)	33703–08–1	251–646–7	–	10.0–35.0
	1,2-Benzenedicarboxylic acid, di-C16–18-alkyl esters	PUR, PVC (soft)	90193–76–3	290–580–3	–	10.0–35.0
	Triethyl phosphate	PUR	78–40–0	201–114–5	–	10
	Melamine	PUR	108–78–1	203–615–4	–	25

(continued on next page)

Table 1 (continued)

Function	Substance name	Polymer type	CAS number	EC number	Other function in plastic	Typical concentration (%)
	Bis(pentabromophenyl) ether	–	1163–19–5	214–604–9	–	–
	Aluminium sodium dioxide	–	1302–42–7	215–100–1	–	–
	Calcium dihydroxide	–	1305–62–0	215–137–3	–	–
	Hexaboron dizinc undecaoxide	Polyolefin-I, Polyolefin-II, PA	12767–90–7	235–804–2	–	0.3–0.4

Table 2

Distribution of microplastics around the globe.

Soil Type	Depth	Shape	Size	Intensity (numbers or mass)	Identified by	Location	References
Farmland (mulch & non-mulch)	10 cm	Fragment (domain), Fiber, & film	1–3 mm	Mulch 571 n/kg, non-mulch 263 n/kg	Microscope & μ -FTIR	Hangzhou Bay, China	[277]
Forest buffer zone & greenhouse soils	5–10 cm	Fiber (92%), Film/fragment (8%)	0.05–1 mm	18,760 (7100–42,960) n/kg	Microscope	Yunnan, China	[260]
Woodland, vegetable, & vacant land soils	5 cm	Fiber (14%), Fragments- (52%), film (1.6%), foam (10%), beads (14%)	< 0.1 mm (82%)	2.23×10^5 (2.23×10^4 – 6.93×10^5) n/kg	Microscope, SEM, & Raman spectroscopy	Wuhan, China	[276]
Farmland (vegetable)	5 cm	Microbeads (48%), Fragments (15%), Foams (1%), fibers (37%)	< 0.2 mm	320–12,560 n/kg (dry weight)	Microscope & micro-Raman spectroscopy	Wuhan, China	[33]
Farmland (cotton field)	0–5, 5–20, & 20–40 cm	Film & Fragment	~2 mm	80.3–1075.6 n/kg	Microscope, SEM, & FTIR spectroscopy	Xinjiang, China	[91]
Farmland paddy soils	10 cm	Fibers, Granules, Fragment, Film	0.02–1 mm	10.36 ± 2.2 n/kg	Microscope & μ -FTIR	Shanghai, China	[139]
Coastal soils	2 cm	Foams (28%), Flakes (69%), Fragment (1%), Fibers (1%)	~5 mm	740 (1.3–14712.5) n/kg (dry weight)	Microscope, SEM & FTIR	Shandong, China	[274]
Farmland	5 cm	Film (44%), Fragment (44%), Fiber (12%)	1–5 mm	0.346–0.36 (0–1.25) n/kg (dry weight) or 35,000 mg/ha	Microscope & FTIR	Franconia, Germany	[159]
Rice cultivation, mulching, & greenhouse soils	5 cm	Fragment>fiber>sheet (Inside the greenhouse); Fiber>sheet>fragment (Outside greenhouse)	Inside greenhouse (0.1–0.2 mm), Outside greenhouse (0.2–0.3 mm)	Inside greenhouse: 188,061–563 n/kg, Outside greenhouse: 130,262–389 n/kg	Microscope & FTIR	Yongin suburb, Korea	[100]
Agricultural soils	10–30 cm	Fragments, Films & fibers	0.15–0.25 mm	With sludge: 2.13×10^6 – 3.06×10^8 n/kg, Without sludge: 9.30×10^6 – 1.10×10^7 n/kg	Microscope & μ -FTIR	Valencia, Spain	[210]
Agricultural soils	25 cm	Fiber (>97%), Film, Fragment, & pellets	0.97 mm	600–10,400 n/kg	Microscope	Mellipilla, Chile	[41]
Agricultural soils	0–5, 5–10, & 10–15 cm	Fibers, Fragments	0.1–1 mm	With biosolid: 18–54 n/kg, Without biosolid: 25–298 n/kg	Microscope & FTIR	Ontario, Canada	[45]
Wetland soils	5 cm	Fragment, Fiber	0.075–5 mm	1270 ± 150 n/kg	Microscope & FTIR	Washington DC, United States	[85]
Floodplain soils	5 cm	–	0.125–0.500 mm	< 593 n/kg; 5 (0–55.5) mg/kg	FTIR & Raman spectroscopy	Switzerland	[179]
Soil amendments from compost	0–27 cm	Fragments, Fibers, Films	0.05–5 mm	TEM-EDX, py-GCMS	Feucherolles, France	–	[230]
Soil amendments from sludge	–	PET, PE, PP	Fragment (0.03–0.53 mm), Fiber (0.07–2.22 mm)	302,000 $\pm$ 83,000 n/kg as heat dry pellets	Microscope & ATR-FTIR	Madrid, Spain	[58]

detected 96 n/kg of MPs at a depth of 10 cm [78].

MP contamination in soil has also been reported in other countries, particularly in agricultural soils. Vollertsen and Hansen [212] investigated the role of Danish wastewater treatment plants in emitting MPs to agricultural soils, finding MP abundances of 236,000 n/kg in soils with sludge and 82,000 n/kg in soils without sludge. In the Mellipilla region of Chile, MPs in agricultural soils ranged from 600 to 10,400 n/kg [40, 42]. Studies have also examined other soil types. For example, Fuller and Gautam [70] utilized a pressurized fluid extraction method and discovered an average of 4191 mg/kg MPs in industrial soils in Sydney,

Australia. Furthermore, floodplain soils in Switzerland reported MP concentrations of 593 n/kg at a depth of 5 cm [179]. A survey conducted in Lahore, Pakistan, analyzed soils from eight different land use types, showing MP abundances ranging from 1750 to 12,200 MPs/kg [165]. However, due to the lack of consistent methods for isolation and quantification, there is no uniform expression of MP abundance in soil [110]. Additionally, studies on the characteristics of soil MP contamination, such as concentration and distribution, are scarce, with a majority of studies focusing on Asia. Thus, there is a need to enhance monitoring of soil MP pollution in the future. While some countries may

not have reported data, it is evident that soil contamination with MPs is a prevalent global issue.

3. Functional additives in plastics

Plastics contain additives that enhance their physical and chemical properties, influencing their functions and production costs [141]. The global plastic additives market was valued at USD 48.41 billion in 2020 and is projected to reach \$75.20 billion by 2028, with an average annual growth rate of 5.7% [43]. However, accurately estimating the quantities, levels, and types of additives used in different plastic products is challenging due to limited disclosure by manufacturers, making it difficult to identify and assess their potential environmental consequences.

Plastic additives are diverse in nature and chemistry, serving various functions. They can be present in small traces (<1% w/w) or as significant components (>50% w/w) embedded in the polymer structure. Multiple additives may be used in plastics (Table 1) depending on their purpose, with studies indicating that an average plastic product contains around 20 additives [211]. Due to their weak binding to plastics, additives can leach during use or disposal, potentially degrading and forming toxic compounds that persist in the environment and accumulate in organisms [158]. The hazards associated with additives persist throughout the life cycle of plastics. When plastics are recycled, these compounds are likely to be incorporated into new products due to their difficulty in removal [215]. Lack of transparency from industrial manufacturers regarding additives and concentrations hinders understanding of the chemical profiles and associated health risks of final products [43]. For instance, recycled products, including household items and toys, may contain brominated flame retardants, recognized endocrine disruptors, posing significant health risks [8].

Burning plastic waste, especially in low-technology incinerators or uncontrolled conditions, exacerbates health risks. Incomplete combustion leads to the emission of hazardous compounds, including persistent organic pollutants (POPs) such as dioxins, acid gases, and contaminated ashes [13,86]. Consequently, the presence of additives in MPs poses risks to ecosystems and biota due to their inherent hazards and exposure within the environment [23]. Initiatives like the Stockholm Convention regulate additives identified as hazardous to humans, the environment, and organisms. However, the convention only covers a small fraction of the hazardous chemical compounds present in plastics and plastic waste, with exemptions allowing continued use of certain additives [141]. The majority of additives remain unregulated. Despite reviewing the toxicity of additives towards biota, there is limited understanding of their exposure. Further research is needed to comprehend the mechanisms driving the release of additives at the plastic-biota-environment interface and assess biota exposure accurately.

4. Microplastics and co-occurring contaminants

MPs engage in physicochemical interactions with pollutants through sorption, involving adsorption and absorption processes [80]. Adsorption forms chemical bonds between MPs and other substances, while the absorption process involves the uptake of substances into the bulk of the plastic particles through mechanisms such as diffusion or partitioning, where they interact with the plastic surface or penetrate the plastic matrix [174]. This sorption capability transforms MPs into carriers for potentially carcinogenic substances, posing risks to organisms through ingestion and inhalation [87]. Hydrophobic interactions, color, pH, and density are influential factors in the sorption of contaminants onto MPs [144]. Toxicity has been observed in interactions between MPs and pollutants, as seen with polypropylene MPs and polycyclic aromatic hydrocarbons (PAHs) [12,65]. A scheme of the factors that may influence the interaction between MPs and other pollutants is presented in Fig. 1.

The sorption mechanisms of organic contaminants onto MPs are

complex and involve multiple interactions. These mechanisms include hydrophobic, partitioning, electrostatic, and other non-covalent interactions [122,237]. The hydrophobicity, functional groups, and physicochemical properties of MPs contribute to these complex adsorption processes [226]. MPs possess a higher adsorption capacity for hydrophobic pollutants, such as PCBs and PAHs, due to their greater hydrophobicity compared to natural organic matter [113]. Hydrophobic interactions play a significant role in the adsorption of neutral pollutants, while partitioning effects are driven by van der Waals forces [108,123]. The presence of electrostatic interactions depends on pH, resulting in the attraction of positively charged pollutants to negatively charged MP surfaces [264]. Additionally, other non-covalent interactions, including hydrogen bonds and halogen bonds, contribute to the sorption of organic pollutants onto MPs [68]. Hydrogen bonding is particularly crucial for the adsorption of hydrophilic pollutants like antibiotics [32]. Factors such as the presence of hydrophobic regions on MP surfaces, interactions involving π bonds, and the number of hydrogen bonds formed influence the adsorption capacities of MPs [97,170].

The sorption of heavy metals (HMs) by MPs in soil environments has been extensively studied [112,237]. Possible sorption mechanisms include complexation of HMs with organic matter and its interaction with hydrophobic MP surfaces [228,252], and co-precipitation of MPs with soil iron and manganese oxides [249]. MPs' sorption of HMs can lead to changes in soil properties, influencing HM chemical speciation, reducing bioavailability, and potentially affecting soil pH, cation exchange capacity (CEC), and dissolved organic carbon (DOC) content [83,249]. The impact of MPs on HM adsorption in soil depends on various factors, including size, dose, exposure time, and soil pH [268]. The metal content in MPs correlates with soil HM pollution, affecting soil organisms and HM availability in the food web [9232]. These interactions highlight the importance of further research for understanding the ecological implications of MPs and HMs.

MPs fall under the category of contaminants of emerging concern (CEC) due to the absence of legal standards regarding their occurrence and control in the environment [208]. CEC encompass illicit and licit drugs, pesticides, flame retardants, and chemicals from personal care products, which have significant environmental impacts [150,218]. Interactions between MPs and other CEC contribute to the increased accumulation and dispersion of these contaminants in the environment [43]. A study investigated the sorption of phthalate esters onto MPs made from different polymers (PE, PS, and PVC) [123]. Phthalate sorption onto MPs exhibited a linear relationship, primarily governed by partition as the sorption mechanism [123]. Another study explored the sorption of amlodipine and carbamazepine onto colloidal MP models, natural organic matter (NOM), and fullerene nanomaterials. Amlodipine displayed higher accumulation than carbamazepine in colloidal solutions. Surfaces containing carboxylic groups exhibited a preference for amlodipine sorption, while carbamazepine sorption occurred on both modified surfaces [231]. Therefore, the surface chemistry of MPs significantly influences their interactions with other contaminants.

The combination of MPs with pollutants can result in complex toxic effects [26,237]. Studies have shown that polystyrene NPs worsened the negative impacts on wheat when combined with Cd [119]. In a related study, the effects of three MPs (PET, PLA, and PES) on Cd accumulation in rice plants and the diversity and structure of arbuscular mycorrhizal fungi (AMF) communities demonstrated that the presence of both MPs and Cd influenced rice performance and AMF symbiosis, leading to significant shifts in these factors [132]. Similarly, in another study both MPs and arsenic (As (III)) harmed cell membranes and inhibited the biomass accumulation of rice seedlings [54]. The toxicity of As(III) for rice depends on the concentration of MPs present. PET particles were identified as carriers, transporting Zn, Pb, and Cd into the rhizosphere of *Triticum aestivum* [1]. In another investigation, PE MPs and ZnO NPs individually increased weight loss and mortality in earthworms (*Eisenia fetida*). However, their combined exposure resulted in higher weight loss and lower mortality [270]. MPs and ciprofloxacin (CIP) exhibited

antagonistic effects on the toxicity of the cyanobacterium *Synechocystis* sp. due to MP adsorption to CIP [248]. These findings underscore the need for more studies regarding the co-toxicity of microplastics and other environmental pollutants.

5. Influence of MPs on soil and plants

5.1. Effects on soil

The deposition of MPs on soil surfaces can cause changes in soil texture and structure as they become incorporated into the soil matrix through external forces. The physical properties of MPs, such as their type, shape, and form, play a crucial role in influencing soil properties [219,271]. Linear-shaped polymers tend to blend more uniformly with the soil matrix, leading to improved soil agglomeration [52]. MPs have been found to impact various soil properties, including water holding capacity (WHC), bulk density (BD), water-stable aggregation (WSA), porosity, and permeability [29,77]. However, the effects of different polymer types on these properties are inconsistent. For instance, some studies have observed negative correlations between PET-based MPs and soil BD and WSA, while others have found negative effects on soil WHC [50,262]. These discrepancies may be attributed to variations in soil physicochemical properties (Fig. 3) [77].

Furthermore, MPs can have a negative impact on soil biology and

function, particularly in terms of air, water, and nutrient exchange, by reducing overall soil aggregate stability [49]. Soil porosity, influenced by MPs, can affect hydraulic conductivity and water retention, which are crucial for maintaining soil structure [272]. MPs can also influence soil enzyme activity, which serves as an indicator of fertility, nutrient cycling, and microbial activity [77,130]. Certain enzymes, such as catalase, urease, and fluorescein diacetate hydrolase (FDAse), have been shown to be stimulated by MPs, thereby activating carbon, nitrogen, and phosphorus cycles in dissolved organic matter [92,241]. Additionally, MP residues from plastic mulch materials can affect soil nitrate and water dynamics [254].

5.1.1. Effects on soil microbial properties

Soil microbes play a vital role in maintaining soil structure, nutrient cycling, and organic matter decomposition [153,213]. The presence of MPs in soil can disrupt the soil habitat, affecting soil moisture, porosity, and consequently influencing the abundance of aerobic and anaerobic microbes [163,277]. Studies have shown that MPs can increase microbial activity, alter soil pH, and impact soil enzyme activities, leading to changes in soil microbial function and community structure [50,63,92]. MPs can also contribute to the release of dissolved organic matter in the soil, influencing microbial activity and substrate availability. This makes MPs a potential source of organic carbon for soil microbes [49,172].

The presence of MPs has a significant impact on soil microbial

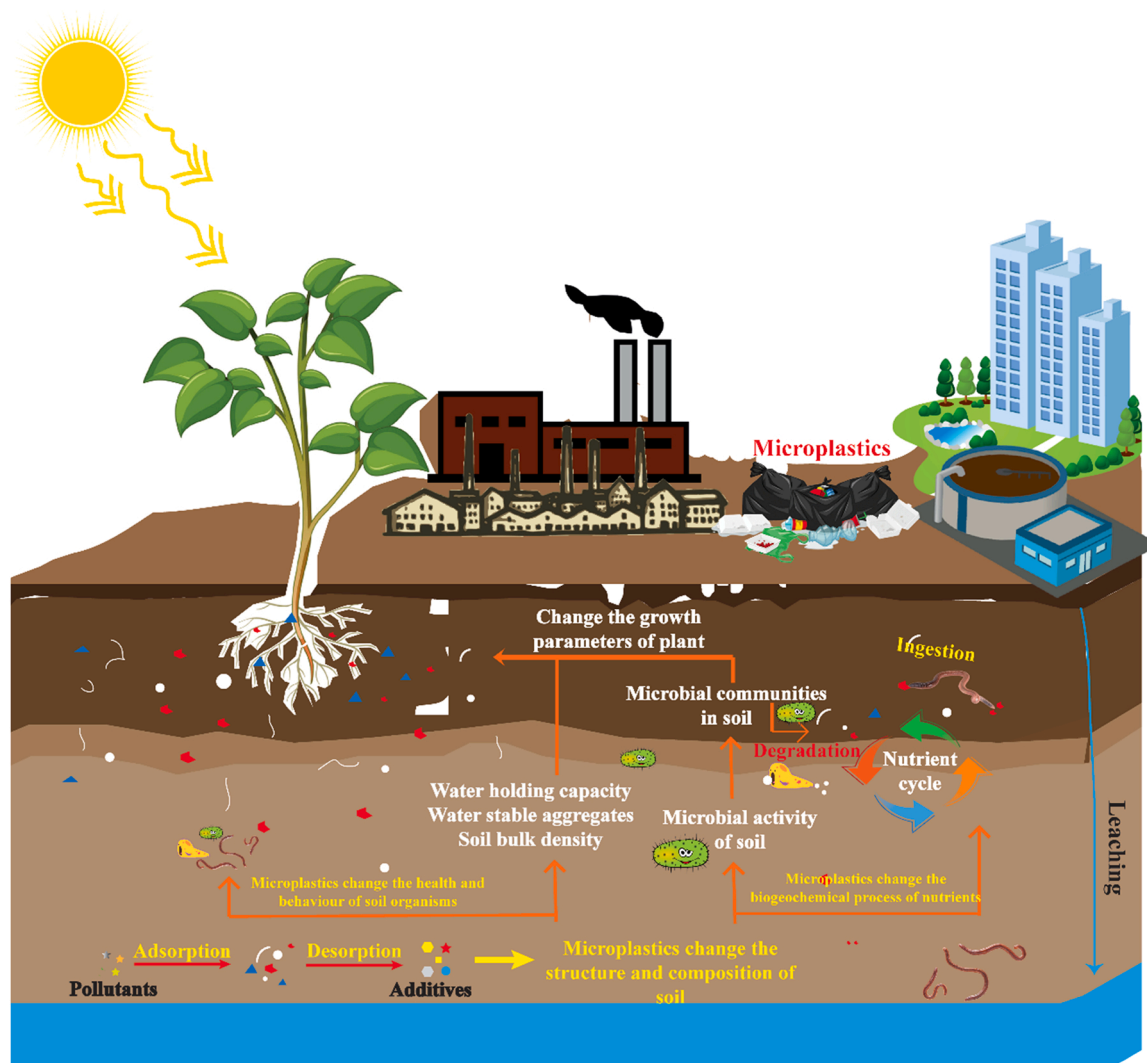


Fig. 3. Graphical illustration of complexities of microplastics in soil ecosystem.

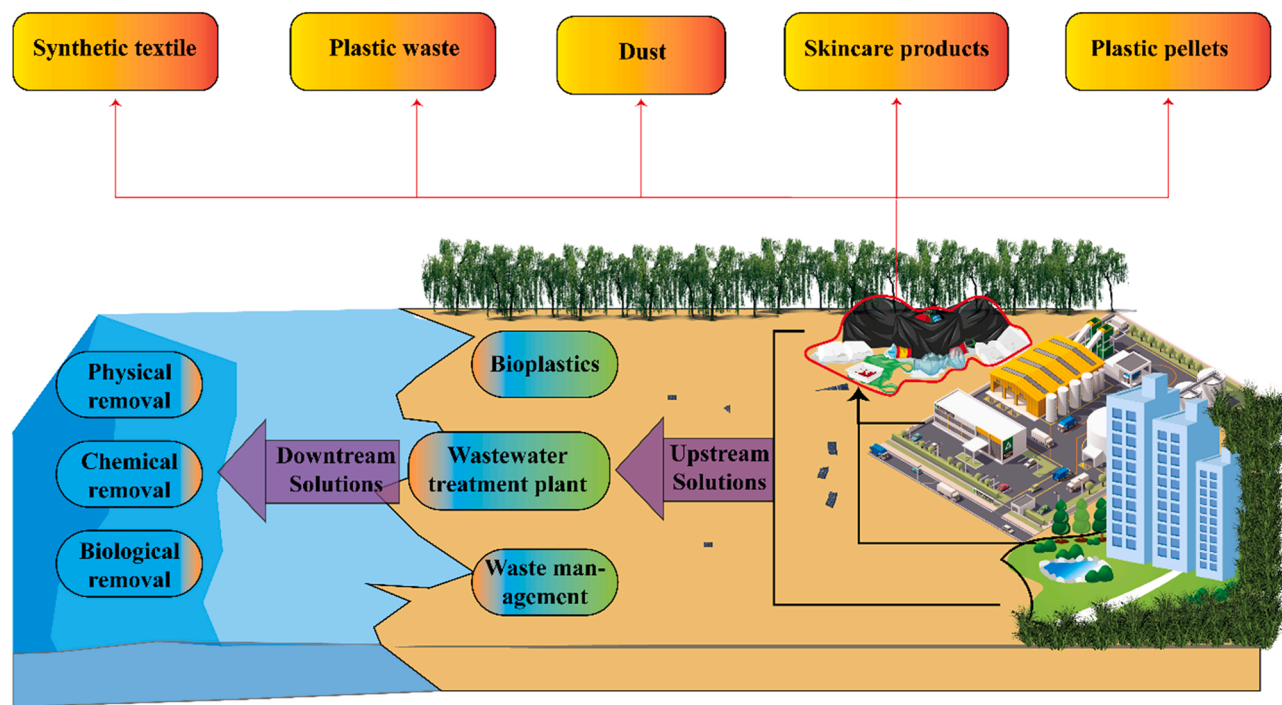


Fig. 4. The potential solutions to microplastics pollution in the environment.

communities, causing changes in their composition, diversity, and metabolic functions [92,111]. MPs act as surfaces where specific microorganisms, including plastic-degrading bacteria and potential

pathogens, can thrive [266]. The fragmentation of mulch film further enhances microbial growth by providing favorable conditions for microbes (Yongguan et al., 2019). MPs harbor distinct microbial

Table 3

The impact of microplastics on microbial activity, nutrient types and cycling in soils.

Microplastics	Size (μm)	Concentrations (% w/w)	Countries	Soil Type	Effects	References
Polyester microfibers	1.70	0.4	Germany	Sandy loam	Increased colonization with arbuscular mycorrhizal fungi	[107]
LDPE and Biodegradable	50	1	the Netherlands	Sandy	Imposed selective pressure on distinct microbial taxa	[164]
Polyvinyl chloride and PE	125	0, 1, 5, 10 and 20	UK	silty clay loam	Increased microbial biomass but altered microbial community structure and metabolism	[255]
PE	150–180	0.2	China	-	Increased the abundance and diversity of microorganisms	[69]
Polyester microfibers	10.5	0.1, 0.2	China	Sandy loam	Altered the rhizospheric bacterial communities in lettuce cultivated soil, affecting beneficial bacteria	[257]
LDPE and PBAT	59, 56	2	China	-	Altered the bacterial community structures	[126]
PE and PLA	20–50 and 20–60	0.1, 1	China	Sandy loam	Simpson and Shannon indices changed significantly only with 0.1% PLA MPs, affecting key nitrogen-fixing bacteria	[121]
PP	< 180	7, 28	China	Loess	Increased dissolved organic matter (DOM), total dissolved nitrogen (TDN), dissolved organic nitrogen (DON), total dissolved phosphorus (TDP), DOP	[14]
LDPE	200–630	1	Germany	Sandy clay loam	No significant effect on DOC, DON, inorganic nitrogen	[18]
Polyvinylchloride	Length: 500; Width: 500; Thickness: 8	-	China	Laterite soil	Decreased the soil organic carbon (SOC), total organic carbon (TOC), SOM	[133]
PE	< 13 μm , < 150 μm	5, 3	China	Clay, Artificial soil	No significant effect on dissolved organic carbon (DOC), Increased the daily flux of CO_2	[166], [152]
HDPE	102.6	0.1	Ireland	Sandy clay loam	No significant effect on soil organic matter (SOM)	[19]
PLA	20–50	2	China	Sandy clay loam	No significant effect on DOC, TDN, NH_4^+ , NO_3^- , NO_2^- , IP (=)	[30]
PE	150–180	1	China	Loess soil	Minor effect on soil mineral N	[184]
PLA	150–180	1	China	Loess soil	Decreased soil mineral N by 91–141%	[184]
PP and rubber crumb	68 and 100	1	China	-	Reduced the available N (including NH_4^+ and NO_3^-) in the soil	[134]
PET	56.3 $\pm$ 12.8	0.2, 0.4	-	Artificial soil	No significant effect on CH_4 , N_2O	[14]
PE and biodegradable MPs	-	0.1–5	China	Mollisol soil	Stimulated the processes of N fixation, N degradation and assimilatory nitrate reduction	[88]

communities, including plastic-degrading bacteria such as Actinobacteria, Bacteroidetes, and Proteobacteria, which differ from those found in the surrounding soil [266].

MPs also influence microbial metabolism, leading to increased activity in processes such as amino acid metabolism, biodegradation, and metabolism of exogenous substances [92]. The biofilms formed on MP surfaces can act as carriers for potential pathogens, affecting the transfer of resistance genes between bacteria and phages [196,202]. Pathogenic bacteria like *Pseudomonas* and *Bacillus* are found to be more abundant on the surfaces of MPs compared to the surrounding environment [233]. The composition and concentration of MPs have been found to have an impact on soil microbes, as highlighted by Fei et al. [63]. Both PE and PVC were found to reduce the diversity and abundance of bacterial communities in the soil. However, the influence of PE was more pronounced compared to PVC. Furthermore, the relative abundance of *Burkholderiaceae*, associated with nitrogen fixation, was significantly increased in the presence of MPs. Consequently, MPs have the potential to impact the microbes involved in nitrogen cycling and the breakdown of organic compounds in the soil [224].

5.1.2. Effects on the biogeochemical processes of nutrients in soils

MPs have been found to significantly impact the biogeochemical processes of nutrients in soil (Fig. 3). They can modify the physico-chemical properties of soil, leading to alterations in the soil microbiome and nutrient cycles, particularly nitrogen and carbon [198,269]. These modifications in microbial activities and functionalities can result in substantial shifts in functional processes within terrestrial environments, affecting soil nutrients and various nutrient cycles [173,178] (Table 3). For instance, polypropylene MPs were shown to increase the accumulation of organic matter in soil and stimulate the release of dissolved organic nitrogen, dissolved organic carbon, and dissolved organic phosphorus [124]. Additionally, polyester microfibers were found to influence the concentration of total organic carbon in certain aggregate fractions [261].

MPs, primarily composed of carbon, differ from more labile organic carbon sources of natural origin [171,173]. The excess nutrients, such as carbon and nitrogen, derived from MPs can enhance microbial growth and community, consequently influencing nutrient cycles in terrestrial soils [49,175]. Moreover, MPs can affect specific microbial families responsible for organic matter degradation and nitrogen cycling [278], and can also disrupt nematode communities, impacting biogeochemical cycles in the soil [227]. Alterations in nutrient ratios, such as the carbon-to-nitrogen ratio (C/N), have been observed in soil due to the presence of MPs, potentially affecting the entire plant community [164]. These changes in nutrient cycles caused by MPs can have unpredictable effects on greenhouse gas emissions, including terrestrial CO₂, CH₄, and N₂O emissions [199,201,253].

The influence of MPs on the soil nitrogen cycle depends on the type of MPs. For example, polyurethane foam (PUF) and PLA promote nitrification and denitrification in soil, while PVC inhibits these processes [244]. The concentration of MPs also plays a role; high MP concentrations can impact soil porosity, aggregation, inhibiting denitrification, and boosting the total nitrogen content [244]. The interactions between MPs and other soil factors should not be underestimated, as they can affect the emission flux of carbon dioxide and nitrous oxide, exacerbating global warming [167].

MPs can affect the soil carbon cycle by changing the functional genes of microbes. Primary MPs reduce the abundance of functional genes responsible for hemicellulose breakdown, while secondary MPs reduce the abundance of functional genes responsible for cellulose, hemicellulose, and starch breakdown [238]. Furthermore, MPs, with their carbon content, can slowly decompose and integrate into the soil matrix, increasing the concentration of soil organic carbon (SOC) [180]. Changes in the microbial community composition and structure caused by MPs can influence the abundance of functional genes involved in carbon, nitrogen, and phosphorus recycling, potentially impacting the

decomposition of soil organic matter and SOC [113]. However, the effects of MPs on soil parameters such as SOC can vary depending on soil type and measurement methods [101].

The impact of MPs on phosphorus, an essential nutrient for plant growth, should not be overlooked. MPs in the soil can release bio-unstable dissolved organic carbon, stimulating the activities of soil microorganisms and enzymes, and facilitating the accumulation of dissolved organic carbon, nitrogen, and phosphorus [124]. However, studies have also shown that MPs can reduce soil phosphorus content due to physical or chemical reactions, changes in soil aggregates, and reduced soil bulk density [35,96]. MPs can influence nutrient cycling directly through metabolism or the release of carbon-containing compounds and indirectly by altering soil properties and microbial communities [267].

5.2. Effects on terrestrial plants

MPs have the potential to impact plants by causing alterations in plant growth indicators and physio-biochemical processes, such as the photosynthetic rate, root elongation, and modulation of antioxidant enzymes and metabolites (Table 4).

5.2.1. Effects on plant growth

The growth of plants can be disturbed by MPs, and assessing their effects often involves evaluating biological indicators in different parts of the plant to determine phytotoxicity [217]. Shape and polymer composition are key factors influencing the impact of MPs on plant growth. Shape-related differences are primarily seen as physical, where fragmented MPs with sharp edges can have more adverse effects on plants compared to smooth-edged MPs [151,176]. For example, duckweed exposed to MPs with sharp edges showed significantly shorter root lengths compared to smooth-edged MPs and controls [99]. The polymer composition of MPs also plays a crucial role, with plastics of different compositions having varying effects on plant growth. PVC MPs were found to significantly inhibit the growth of garden cress compared to PE and PP [160]. Additionally, the effects of MPs on plants vary among different plant species. *Lemna minor* and *Spirodela polyrrhiza* showed no significant growth effects when exposed to PE MPs, while lettuce exhibited marked growth changes [81,145]. Moreover, the concentration of MPs can have different effects on plants, with both low and high doses causing notable impacts depending on the study [280,72,89].

In the natural environment, aged plastics often bear a range of charge groups on their surface [127]. In light of this, researchers conducted investigations into the accumulation patterns of differentially charged MPs in plants and examined their associated toxic effects. The exposure to MPs was found to have detrimental effects on plant growth; however, the extent of damage varied depending on the specific surface functional groups present on the MPs [242]. Understanding these factors and their interactions is crucial for comprehending the diverse responses of plant species to MP exposure [263].

5.2.2. Effect on chlorophyll and photosynthesis

The impact of MPs on plant growth is reflected in photosynthesis, particularly in leaves [37]. Measurement of photosynthetic pigments like chlorophyll-a, chlorophyll-b, and carotenoids is commonly used to assess the effects of MPs on plant photosynthesis [209]. The findings regarding the impact of MPs on plant photosynthesis are mixed, with some studies showing noticeable changes while others do not. For instance, exposure to PE MPs led to a decrease in chlorophyll-a content in lettuce, while chlorophyll-b remained relatively unchanged [72]. Changes in chlorophyll-a content correlated with altered photosynthetic parameters, such as reduced photosynthetic and transpiration rates, increased stomatal conductivity, and elevated intercellular CO₂ concentration. Wheat leaves exposed to PS MPs exhibited significant changes in chlorophyll-a, chlorophyll-b, and carotenoid levels, with different trends observed at different MP concentrations [280]. Low MP

Table 4
Effects of microplastics on different parameters of terrestrial plants.

MPs	Plant species	Medium	Size	Dose	Effects	References
PS spheres	Lettuce (<i>Lactuca sativa</i> L.)	Soil	Average 93.6 nm	0.1, 1 mg/L	Inhibited the plant growth and nutrient accumulation	[118]
Polyvinyl chloride	Lettuce (<i>Lactuca sativa</i> L.)	Soil	100 nm–18 μ m	0.5%, 1%, 2% (w/w)	Smaller MPs had negative effects on the antioxidant system and photosynthesis while positive effects on root morphology	[116]
PS spheres	Maize (<i>Zea mays</i> L.)	Sterile soil	21–26 nm	100 mg/L	Impaired leaf photosynthesis and showed more significant activation of oxidative defense mechanisms	[195]
PE and PLA	Soybean (<i>Glycine max</i>)	Soil	20 and 50 μ m	0.1%, 1%	The POD activity was reduced and CAT activity was increased by MPs in plant leaves	[121]
PS	Fava beans (<i>Vicia faba</i>)	Emulsion solutions	5 μ m	10, 50 and 100 mg/L	Biomass and CAT activity of roots decreased whereas SOD and POD enzymes activity significantly increased	[95]
Fibers	Spring onion (<i>Allium fistulosum</i>)	Soil	222–258 μ m	2%	The total biomass is increased while the water content of onion bulbs decreased 2-fold	[49]
PS	Cucumber (<i>Cucumis sativus</i>)	Hoagland nutrient solution	100, 300, and 700 nm	50 mg/L	Accumulated in roots, and increased the MDA, and proline content	[117]
Negatively (PS–SO ₃ H) and positively charged MPs (PS–NH ₂)	<i>Arabidopsis thaliana</i>	Sterile soil	55 $\pm$ 7 nm and 71 $\pm$ 6 nm	0.3 g/kg and 1 g/kg	The length of shoots has increased, but the growth of primary roots and aboveground fresh weights have decreased.	[197]
PE terephthalate and polyvinyl chloride	Tomato (<i>Solanum lycopersicum</i> L.)	Soil	40 and 50 μ m	0.5% w/w	PVC caused a significant reduction in shoot fresh weight. Whereas both microplastics decreased the number of fruits. Lycopene, soluble solids and phenols were also decreased in fruits from PET/PVC-treated plants.	[48]
PP	Tomato (<i>Solanum lycopersicum</i> L.)	Hoagland solution	< 500 μ m	0.1 g/L	Significantly increased the root elongation by 34%. While the nitrogen uptake was decreased	[187]
PS, HDPE, and PLA	Peanut (<i>Arachis hypogaea</i> L.)	Soil	67, 39, and 67 μ m	1% and 10% (w/w)	Negatively affected plant N content, and high-dose PLA had the most pronounced effects. PS and PLA increased plant height	[224]
LDPE and Biodegradable	Wheat (<i>Triticum aestivum</i>)	Soil	4000–10,000, 50–1000 μ m	1% (w/w)	Significantly reduced the total plant biomass, thereby affecting the development of the rhizosphere	[164]
PE, PS	Maize (<i>Zea mays</i> L. var.)	Soil	100–154 μ m	0%, 0.1%, 1%, and 10% (w/w)	The dry weight of rhizomes was reduced, leading to an overall decrease in the total dry weight.	[220]
PS	Barley (<i>Hordeum vulgare</i> L.) and wheat, carrot (<i>Daucus carota</i> L.) and lettuce	Hoagland solution	500 nm	10 ⁷ particles/mL	Significantly impacted germination and growth in lettuce and carrot. Biochemical stress indicators were up-regulated in both lettuce and wheat	[256]
LDPE fragments, polyvinyl chloride fragments, and LDPE fiber	Lettuce (<i>Lactuca sativa</i> L.)	Soil	$\leq$ 125 μ m	0–3% (w/w)	As the concentration of MPs increased, there was a corresponding increase in negative impacts on lettuce growth. Of the three types of MPs investigated, LDPE fragments exhibited the strongest detrimental effects on lettuce growth.	(Hasan and Jho, 2023)

concentrations enhanced plant photosynthetic pigments, while higher concentrations resulted in a reduction. Similarly, *Utricularia vulgaris* showed significant differences in chlorophyll-a and chlorophyll-b content when exposed to MPs of different sizes [251].

The exact mechanisms through which MPs affect photosynthesis and chlorophyll content in plants are still not fully understood, but several hypotheses have been proposed. Physical blockage of stomata and the generation of reactive oxygen species (ROS) by MPs are potential mechanisms. MPs can physically block stomata, hindering gas exchange [79]. Additionally, MPs can induce oxidative stress in plants, reducing chlorophyll content through ROS generation [214,245]. Interference with nutrient uptake and transport, particularly nitrogen and phosphorus essential for chlorophyll synthesis, is another suggested mechanism [95]. This interference can lead to decreased chlorophyll content and subsequently impair photosynthesis. Despite these hypotheses, further research is needed to fully understand the mechanisms by which MPs affect photosynthesis and chlorophyll content in plants.

5.2.3. Effects on the oxidative stress

The impact of MPs on oxidative stress in plants has received significant attention. Oxidative stress occurs when the balance between reactive oxygen species (ROS) and the antioxidant defense system is

disrupted, and MPs have been found to increase ROS levels in plants [217]. The accumulation of ROS can lead to oxidative damage, as observed in onion seedlings [74]. However, our understanding of the phytotoxicity of MPs and NPs in relation to oxidative stress is still limited. Several biochemical indicators, such as metabolites, lignin, genotoxicity, and phytohormones, have been investigated in various studies and hold potential for future research directions [114,246].

MPs can influence the ROS content and antioxidant system in plants, leading to changes in antioxidant enzyme activity. Studies often assess oxidative damage by measuring antioxidant enzyme activity and malondialdehyde (MDA) content [120,183]. Low concentrations of MPs can enhance the expression of genes encoding ROS-scavenging enzymes, thereby increasing antioxidant enzyme activity [131]. Minor changes in MDA content indicate the effectiveness of the plant's antioxidant system [72]. However, high levels of MPs can weaken the antioxidant defense systems and disrupt the balance. With increasing concentrations of MPs, the activities of antioxidant enzymes in wheat and lettuce first increase and then decrease, while MDA levels increase, indicating cell damage [72].

The impact of varying concentrations of MPs and NPs on oxidative stress in plants can exhibit variability. In *Vicia faba*, the activities of superoxide dismutase (SOD) and peroxidase (POD) significantly

increased under different concentrations of 5 μm PS MPs. The changes in SOD and POD activities were relatively small after exposure to 100 nm MPs, and the activity of high-concentration MPs (100 mg/L) was lower than that of the controls. Catalase (CAT) activity decreased with increasing concentration of 5 μm MPs, while it increased significantly when exposed to 100 nm MPs [95]. In rice seedlings exposed to different concentrations of 20 nm PS NPs, the activities of POD, SOD, and CAT significantly increased at 50 mg/L and 100 mg/L concentrations. However, this phenomenon was not observed at a concentration of 10 mg/L, indicating the importance of considering MPs concentration when studying their effects on oxidative stress in plants [273].

5.2.4. Effects on plants metabolome

Metabolites are small molecules that play a crucial role in various biological processes in plants, including energy production, carbon fixation, nitrogen fixation, and the synthesis of plant hormones and secondary metabolites [118,121]. However, emerging studies have highlighted that MPs and NPs can significantly impact the metabolome of plants, which may lead to alterations in various metabolite levels, potentially affecting plant growth and development.

For example, in one study, rice leaves exposed to different concentrations of polystyrene MPs (PS-MPs) showed significant changes in their metabolites. A total of 249 metabolites were identified and pseudo-quantified using GC-MS-based metabolomics, with over 70% of the metabolites changing significantly in the exposed rice leaves. The levels of most amino acids, organic acids, and saccharides decreased with increasing concentrations of PS-MPs, and the rice leaves exposed to 500 mg L⁻¹ of PS-MPs showed significantly lowered biomass and poorer growth conditions than those exposed to lower concentrations [236]. In another study, lettuce plants were exposed to various concentrations of PS-MPs, and the metabolites related to lipids, peptides, steroids, carbohydrates, vitamins and cofactors, nucleic acids, hormones, and transmitters were the main metabolites differing from the control. Similarly, a widely targeted metabolomics analysis revealed that polyvinyl chloride (PVC) MPs could affect the biosynthesis and metabolism of primary and secondary metabolites in floating plant *Spirodela polyrrhiza*. A total of 942 metabolites were detected, and the number of altered metabolites increased with increasing concentrations of PVC MPs, indicating a dosage-dependent effect of MP stress on metabolite expression [229]. Furthermore, our previous studies have shown that various polymers of micro/nanoplastics (e.g., PE, PLA, PS, PP, and microfibers) can alter the metabolic profiles of several terrestrial and submerged plants [109,121,186,225,257].

The changed metabolites due to MPs stress mainly involve amino acids, saccharides, and organic acids. Amino acids play a crucial role in modulating plant biological functioning by acting as osmolytes, regulating ion transport, modulating stomatal opening, serving as precursors for the synthesis of defense-related metabolites, and signaling metabolites [31,236]. Similarly, organic acids are intermediates of carbon metabolism (photosynthesis and respiration) in plant cells and their alteration due to MPs exposure can interfere with photosynthesis and respiration in plants. Additionally, saccharides play an important role in protecting and stabilizing cell membranes and function as ROS scavengers and signals in stress-induced pathways [169]. Further research is required to understand the underlying mechanisms and the potential long-term impacts of these changes on plant growth, and development.

6. Microplastic aging

Microplastic aging refers to the process by which plastic materials undergo changes in their physical, chemical, and mechanical properties over time due to various environmental factors [168,206]. Plastic aging occurs naturally or artificially. Natural aging of MPs occurs when these materials are exposed to outdoor conditions such as sunlight, temperature variations, and water. This process can result in color fading, embrittlement, and loss of mechanical strength in the plastic [222].

Similarly, artificial aging of plastics can occur when these materials are subjected to accelerated laboratory testing, simulating environmental conditions such as high temperatures and intense UV radiation [222].

6.1. Mechanisms involved in microplastic aging

6.1.1. Fragmentation

Fragmentation of MPs occurs when external forces cause them to break into smaller particles. Examples include farming processes and tire wear during driving [51,82]. In aquatic environments, factors like sediments, pebbles, waves, and tides contribute to the physical effects on MPs [200]. Defects in MPs themselves can enhance fragmentation, as longer cracks require less stress to propagate, facilitating decomposition [60]. Mechanical fragmentation and other aging processes of MPs reinforce each other [11,193]. Studies have shown that UV irradiation and mechanical forces, such as sand, accelerate the fragmentation of MPs on beaches [193]. This increased surface area from fragmentation allows for more light and oxygen exposure, promoting other aging processes [76]. Additional aging processes can affect the polymer's crystallinity, mechanical properties, and fragmentation behavior of MPs [265].

6.1.2. Photo and thermal aging mechanisms

MPs in soil undergo chemical aging through UV radiation and thermal oxidation. UV irradiation is commonly used for aging studies [279]. Aging involves the following free radical reactions [28,168]:

1. Chain initiation ($\text{RH} \rightarrow \text{R}^\cdot + \text{H}^\cdot$, $\text{RH} + \text{O}_2 \rightarrow \text{R}^\cdot + \text{HO}_2^\cdot$, $\text{R}^\cdot + \text{O}_2 \rightarrow \text{RO}_2^\cdot$)
2. Chain propagation and transfer ($\text{RO}_2^\cdot + \text{RH} \rightarrow \text{ROOH} + \text{R}^\cdot$, $\text{ROOH} \rightarrow \text{RO}^\cdot + \text{OH}^\cdot$, $\text{ROOH} + \text{RH} \rightarrow \text{RO}^\cdot + \text{R}^\cdot + \text{H}_2\text{O}$, $\text{RO}^\cdot + \text{RH} \rightarrow \text{ROH} + \text{R}^\cdot$)
3. Chain termination ($\text{R}^\cdot + \text{R}^\cdot \rightarrow \text{R}-\text{R}$, $\text{R}^\cdot + \text{RO}_2^\cdot \rightarrow \text{ROOR}$, $\text{RO}_2^\cdot + \text{RO}_2^\cdot \rightarrow \text{ROOR} + \text{O}_2$).

This leads to changes in surface topography, polymer structure, charge, hydrophilicity, and polarity of MPs [143]. UV exposure in air increases functional groups ($-\text{OH}$, $\text{C}=\text{O}$, and $=\text{CH}$) and the carbonyl index of polyethylene MPs [228]. Reactive oxygen species induce the formation of oxidative functional groups, decreasing particle size and enhancing negative surface charge and roughness of polystyrene MPs [279]. The extent of aging depends on environmental conditions, such as temperature, intensity, time, soil microbial species, and microplastic characteristics [138,148]. MPs exhibit different properties when exposed to UV radiation in air compared to pure water or seawater [143]. Aging increases the specific surface area, decreases particle size, and introduces O-containing functional groups, making aged MPs attractive for pollutants like heavy metals and organic contaminants [140,250]. Conventional chemical oxidation methods, such as persulfate oxidation or UV light, are used to simulate aging but lack standardization. The complexity of natural aging processes involving multiple exposure agents poses challenges in quantifying and comparing the extent of microplastic aging.

Thermal aging and photoaging differ in initiators and aging products. Thermal aging occurs throughout the polymer bulk, initiated by heat, while photoaging is limited to the exposed surface [55]. Thermal aging involves random and chain degradation initiated by heat [265]. In thermal aging of MPs, the polymer chain breaks through absorbing heat, generating free radicals and undergoing subsequent free radical reactions [142]. PET's radical aging pathway involves ester bond breakage, forming carboxyl and vinyl groups [190]. Concerted reactions dominate the initial aging process, producing CH_3CHO , CO_2 through decarboxylation, and CO through free radical decarboxylation [90]. Thermal aging operates at high temperatures ($>100^\circ\text{C}$), less prevalent in the environment, where photoaging becomes dominant, and its rate increases with temperature [142]. Under normal conditions, thermal aging's contribution is minimal, primarily observed in laboratory simulations [5].

6.1.3. Microbial biodegradation

MPs can be categorized as non-biodegradable (e.g., PE, PP, PS, PET, PVC, polyurethane) and biodegradable MPs, further classified into biodegradable polymers (e.g., PHA, PLA), fossil-based biodegradable MPs (e.g., PCL, Polyethylene succinate), and biodegradable polymer blends (e.g., starch/polyester blends, starch/PVA blends) [4103]. MPs can undergo biodegradation by microorganisms, including bacteria, fungi, and microalgae [17].

The biodegradation process involves biofilm formation, biodegradation, biofragmentation, and mineralization [192]. Microorganisms form biofilms on MPs by adsorbing organic and inorganic materials [136]. Extracellular polymers secreted by microorganisms create a protective biofilm, aiding colonization and growth [102,177]. Microbial enzymes, such as lipase, esterase, and keratinase, degrade the MP surface through chain cleavage [147]. Biofragmentation occurs when enzymes destabilize and break down the polymer, yielding oligomers or monomers. Microorganisms assimilate released monomers as carbon or energy sources [191]. Complete degradation results in mineralization, releasing CO₂, CH₄, and H₂O into the environment [235].

6.2. Factors affecting the aging process

The physicochemical properties of MPs play an important role in their aging process. The physical properties of MPs include particle size and crystallinity. Smaller sized MPs with high specific surface areas tend to have higher aging rates. For example, smaller PVC fragments released higher concentrations of chloride ions in response to photoaging, indicating a higher rate of aging [216]. However, there are cases where smaller MP fragments have lower aging rates. This can be seen in PE NPs, where the polymer chains are more compact and crystalline, making them more resistant to heat aging [155].

The crystallinity of MPs refers to the proportion of crystalline regions present within the molecular chain of the microplastics. MPs can have crystalline, semi-crystalline or amorphous phases [66]. Proper crystallinity can make MPs stronger, but excessive crystallinity can make it brittle and easily broken into smaller particles [182]. In addition, the amorphous regions of MPs have higher oxygen permeability, which is beneficial to their aging process [11]. For example, under UV radiation, oxygen and UV preferentially act on the amorphous regions of polypropylene (PP) MPs, causing more severe degradation in these regions. MPs with less crystallinity tends to be more biodegradable because the amorphous regions are more accessible to microorganisms [46].

The chemical properties of MPs, especially its chemical structure, also influence the aging process [84]. Carbon-based MPs, such as polyolefins, are highly resistant to aging processes due to their stable C-C bonds and lack of brittle functional groups [205]. On the other hand, MPs with ester bonds in their chemical structure, such as polyester and polyurethane, are more susceptible to aging because these bonds are hydrolyzed and attacked by microorganisms [125]. The presence of additives in MPs, such as antioxidants, plasticizers, stabilizers, lubricants, and pigments, also affects its aging process [53]. For example, antioxidants can scavenge free radicals and inhibit the photoaging process of MP [234].

Environmental factors play an important role in the aging process of MPs. Factors such as light exposure (wavelength and energy of light), oxygen, temperature, and pH affect the aging process [193]. Light, especially UV, accelerates MP aging [47,154]. Oxygen is a precursor to the generation of reactive oxygen species (ROS), which play an important role in photoaging and biodegradation [47,216]. Temperature affects the activity of enzymes involved in biodegradation, but very high temperatures lead to enzyme inactivation [34]. The pH affects the microbial activity during biodegradation, with different pH levels favoring or inhibiting the degradation process [21].

The presence of biofilm on the surface of MP affects its aging process. Biofilms provide habitats for microorganisms to reproduce and facilitate biodegradation through metabolic means [194]. They also protect MPs

from UV exposure, which inhibits the photoaging process [221]. In general, the aging process of MPs is jointly influenced by physicochemical properties and environmental factors. Understanding these factors can help researchers and policymakers develop strategies to mitigate the environmental impact of MPS.

7. Global legislation on plastic waste

7.1. Legislations on plastic litter

Over the past three decades, global legislation has aimed to manage the risks and impacts of MPs and larger plastic debris. Strategies like levies and bans have effectively controlled plastic pollution at regional levels, particularly reducing the use of low-density polyethylene (LDPE) bags [105]. Bangladesh and Kenya implemented bans on LDPE bags, with numerous countries following suit [105,149]. Wales introduced charges on single-use plastic bags [162], while supermarkets in several European countries, such as Switzerland, Germany, and Portugal, charged customers for plastic bags, resulting in significant consumption reductions [137]. Ireland's levy implementation led to a more than 90% decrease in plastic bag usage [39]. Voluntary campaigns also played a role, with supermarkets in Portugal voluntarily ceasing the distribution of free plastic bags [137]. Recycling and energy recovery have been employed as means to manage plastic waste, with European countries achieving successful plastic recycling rates and utilizing energy recovery methods [93]. In addition, China has issued the "Economic Structure Adjustment Guidance Catalogue," which prohibits the use of light plastic bags (<0.025 mm thickness), disposable-foamed plastic tableware, disposable plastic swabs, daily chemical products etc. Xu et al., [240]. These measures demonstrate global efforts to reduce plastic consumption and address plastic pollution.

7.2. Legislations on microplastics

MPs pose a threat to the terrestrial and marine environments, as well as to human health [20,185]. While legislative data on terrestrial MPs are limited, early adoption of bans on microspheres in personal care products was observed in several European countries and in the US state of Illinois [44,146]. Amendments to the Canadian Environmental Protection Act they have also imposed restrictions on the use of microspheres [25]. Concerns raised by European countries have given rise to the European Recommendation on Cosmetics on Solid Plastic Particles, which has played a role in shaping legislation around the world [62]. In addition, countries such as the United Kingdom, France, South Korea, Italy, New Zealand, India and South Africa have also joined the "no microbeads" movement [16]. It is important to note that microspheres represent only a small fraction of total microplastic contamination. Therefore, in January 2019, the European Chemicals Agency (ECHA) proposed a general restriction of MPs in products placed on the EU/EEA market to minimize their release into the environment [57]. China has also implemented regulations against imports of foreign waste, including post-consumer plastics, and has banned the use of non-biodegradable plastic bags in major cities to mitigate microplastic pollution levels [75].

8. Sustainable mitigation strategies for MPs pollution

This review also aims to propose sustainable solutions for MPs pollution in terrestrial ecosystems. While the solutions discussed below are not exhaustive, they would significantly contribute to reducing MP abundance in the environment. These solutions can be categorized into upstream and downstream approaches.

8.1. Upstream approaches

Upstream solutions focus on intervention and prevention of plastic

release into the environment throughout the plastic life cycle. Bioplastics, derived from renewable sources, have the potential to replace conventional plastics [94]. They can biodegrade in a matter of months or years, with the terrestrial environment being more suitable for their degradation. Bioplastics can be used in the packaging industry, particularly for single-use plastics, such as food packaging [207]. Advances in cheaper crop production and microalgae-based bioplastics grown on non-arable land offer promising alternatives [36]. Adhering to standards like the European standard for compostable packaging (EN 13432) can streamline bioplastic waste management, emphasizing composting as part of an integrated waste management strategy. Disposal of bioplastics in landfills or incineration should be avoided due to associated environmental and health risks [59,61].

Addressing key anthropogenic factors, such as population density and waste management quality, is crucial [161,275]. While controlling population density is impractical, improving waste management quality should be prioritized through better legislation and law enforcement [240]. Enforcing penalties for indiscriminate disposal of plastic wastes and restricting the use of primary MPs in products (e.g., microbeads in cosmetics) aligns with the polluter pays principle. Landfilling and incineration are unsustainable waste disposal methods, emphasizing the need for plastic recycling [24]. However, lack of infrastructure and high costs hinder recycling efforts. To improve waste management, a shift towards prioritizing plastic recycling is necessary [27].

Supplementing existing wastewater treatment plants with additional treatment technologies can enhance MPs removal efficiency. Membrane bioreactors (MBRs) have shown the highest removal efficiency at 99.9%, while rapid sand filters and dissolved air flotation can remove 97% and 95% of MPs, respectively [98,203]. Despite the high investment costs and issues like membrane clogging, MBRs have gained attention due to their potential for energy efficiency, fouling resistance, and cost-effectiveness after initial implementation [71,181].

8.2. Downstream approaches

To achieve sustainable solutions for microplastic pollution, addressing both upstream and downstream approaches is crucial. While physical methods like mesh nets and capturing devices can technically remove MPs from the environment, their large-scale implementation is logistically challenging due to the significant existing MPs presence and potential harm to local ecosystems. These methods are primarily used for scientific research.

Chemical and biological approaches offer alternatives for MPs removal. Studies have shown progress in using plastic-degrading bacteria, like *Ideonella sakaiensis* 201-F6, to break down PET in controlled lab-scale conditions [204,247]. However, applying this biological method in open environments is limited and requires further research to assess effectiveness. Challenges include the bacteria's inability to distinguish desired plastics from unwanted ones and the impact of plastic additives on degradation efficiency. Developing plastics that can be targeted by engineered bacteria would require significant changes in manufacturing processes and high costs for replacing current materials [104]. Biological removal of MPs is currently not feasible on a large scale and should be primarily used for targeted recycling at specific facilities with a thorough understanding of plastic properties [7]. Similar considerations apply to the chemical degradation of MPs in the open environment [64].

Implementing sustainable upstream solutions is essential, as cleaning up MPs in freshwater and terrestrial ecosystems alone is economically and logistically challenging. By combining sustainable practices at the source of plastic generation with targeted downstream interventions, a gradual reduction in MPs can be achieved. Dynamic freshwater systems transport MPs to sinks like lakes and the marine environment, while in the terrestrial environment, vertical transport through biota or agricultural activities can lead MPs to enter groundwater systems and eventually reach lakes, streams, or wetlands [168]. However, in areas

lacking transport mechanisms, MPs tend to accumulate in subsurface locations shielded from degradation [152]. For static regions with high MPs concentrations, downstream solutions like physical removal using filters or pumps can be implemented, followed by intensive chemical or biological degradation in controlled reactors [3]. Allowing plastic materials to naturally biodegrade in situ is another option but requires understanding long-term environmental impacts and constant monitoring in sensitive areas [34]. Responsibility for existing MPs beyond national jurisdictions raises important questions. Effective legislation and international agreements on plastic manufacturing, usage, and management are vital to control MPs pollution [38]. Collaboration and consensus among policymakers are imperative to address this emerging pollutant and work towards its removal from the environment.

9. Conclusion and future prospects

The continued production and degradation of plastics lead to the presence of MPs that have a negative impact on soil-plant systems. These MPs disturb the physicochemical properties of soils, resulting in unstable soil aggregates through both abiotic and biotic interactions. In addition, they alter the dominant flora and associated genes and enzymes involved in the C/N/P cycle, leading to the disruption of soil nutrient cycling. MPs can also modify the chl-a/chl-b ratio in plants, potentially reducing photosynthetic efficiency and influencing their stress responses through the alteration of antioxidant enzymes. Furthermore, plastic materials undergo natural and artificial aging processes that involve several mechanisms and influencing factors critical in predicting their long-term fate. To mitigate the environmental impact of MPs, it is imperative to enact effective global legislation on plastic waste. This should encompass regulations on plastic and MPs waste, and highlight the necessity for sustainable upstream solutions such as reducing plastic usage and enhancing waste management. Efficient downstream strategies, such as physical removal of MPs using filters or pumps, should also be employed. To enhance our understanding of MPs in the environment, several research gaps need to be addressed:

1. Non-targeted screening analyses are essential to identify substances leached from plastics, inclusive of potentially endocrine-disrupting additives. A comprehensive understanding of plastic leachates' chemical composition is vital for assessing their environmental and human health impacts.
2. Experiments involving different plastic polymers and soil types are required to explore dominant factors influencing MPs transport. Studies on aged MPs with unique surface characteristics can offer critical insights into their behavior.
3. Long-term experiments with various soil organisms, to include plants and soil fauna, are essential to ascertain how MPs impact these organisms under realistic conditions, taking into account biophysical interactions.
4. It's crucial to understand the biogeochemical behavior of MPs in the soil-plant system. This involves developing detection methods for MPs accumulation in plant tissues, studying sorption mechanisms, investigating plant uptake, translocation, and distribution of MPs, and assessing the toxic effects of MPs co-exposure with other pollutants.
5. Research should be directed towards understanding the changes in physical, chemical, and toxicological properties of MPs during aging under different environmental stressors. This involves developing accurate detection and identification technologies, simulating aging processes, exploring photoaging mechanisms, investigating the interactions between aging and environmental factors, and assessing the release of additives from MPs and their potential toxicity to organisms.
6. Comprehending the mechanisms of MPs formation, fragmentation, agglomeration, and degradation is crucial. The various

physicochemical and biological pathways involved, as well as the combined effects of these processes, warrant further investigation given the current research deficit in this area.

7. The extent of MPs contamination in agricultural land, especially in soils previously exposed to plastic mulch, necessitates investigation. Surveys across different soils worldwide in actual agricultural areas are recommended to gather data on MPs presence. Additionally, the adsorption behavior of MPs on agricultural soils needs to be studied more extensively, given the predominant focus on aquatic environments in current research.

Environmental implication

This review reveals the pervasive issue of microplastics (MPs) pollution in terrestrial ecosystems, covering their global distribution, impacts on soil, plants, their synergistic interactions with other contaminants and aging mechanisms. It evaluates legislative measures and sustainable solutions while proposing potential mitigation strategies for plastic waste management. Furthermore, it identifies research gaps and suggests future studies. This study emphasizes the urgency of international cooperation and robust legislation to address this escalating environmental challenge and safeguard terrestrial ecosystems and agricultural productivity.

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.

Data Availability

Data will be made available on request.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (32171614).

Author contributions

A.Z. and W.L. were responsible for managing the entire manuscript, writing the outlines, and drafting the manuscript. The third author (N. A.) proofread the manuscript, while the fourth author (R. S.) evaluated and revised it. Q.W., J.W., and J.L. contributed to the figures, while C.Y., J.L., M.Y. and J.N contributed to the data collection, and revision of the manuscript.

References

- [1] Abbasi, S., Moore, F., Keshavarzi, B., Hopke, P.K., Naidu, R., Rahman, M.M., et al., 2020. PET-microplastics as a vector for heavy metals in a simulated plant rhizosphere zone. *Sci Total Environ* 744, 140984. <https://doi.org/10.1016/j.scitotenv.2020.140984>.
- [2] Aghilinasrollahabadi, K., Salehi, M., Fujiwara, T., 2021. Investigate the influence of microplastics weathering on their heavy metals uptake in stormwater. *J Hazard Mater* 408, 124439. <https://doi.org/10.1016/j.jhazmat.2020.124439>.
- [3] Ahmed, R., Hamid, A.K., Krebsbach, S.A., He, J., Wang, D., 2022. Critical review of microplastics removal from the environment. *Chemosphere* 293, 133557. <https://doi.org/10.1016/j.chemosphere.2022.133557>.
- [4] Ahmed, T., Shahid, M., Azeem, F., Rasul, I., Shah, A.A., Noman, M., et al., 2018. Biodegradation of plastics: current scenario and future prospects for environmental safety. *Environ Sci Pollut Res* 25, 7287–7298. <https://doi.org/10.1007/s11356-018-1234-9>.
- [5] Ali, S.S., Elsamahy, T., Koutra, E., Kornaros, M., El-Sheekh, M., Abdelkarim, E.A., et al., 2021. Degradation of conventional plastic wastes in the environment: A review on current status of knowledge and future perspectives of disposal. *Sci Total Environ* 771, 144719. <https://doi.org/10.1016/j.scitotenv.2020.144719>.
- [6] Alimi, O.S., Claveau-Mallet, D., Kurusu, R.S., Lapointe, M., Bayen, S., Tufenkji, N., 2022. Weathering pathways and protocols for environmentally relevant microplastics and nanoplastics: What are we missing? *J Hazard Mater* 423, 126955. <https://doi.org/10.1016/j.jhazmat.2021.126955>.
- [7] Amjad, M., Intisar, A., Afzal, A., Hussain, N., 2023. Chapter Four - Biological methods for the removal of microplastics from water. In: Ferreira, L.F.R., Kumar, A., Bilal, M. (Eds.), *Advances in Chemical Pollution, Environmental Management and Protection*, 9. Elsevier, pp. 65–78. <https://doi.org/10.1016/b.sapmp.2022.10.003>.
- [8] An, Q., Yang, L., Yang, S., Wang, Y., Shi, L., Aamir, M., et al., 2023. Legacy and novel brominated flame retardants in agricultural soils of eastern China (2011–2021): Concentration level, temporal trend, and health risk assessment. *J Hazard Mater* 446, 130631. <https://doi.org/10.1016/j.jhazmat.2022.130631>.
- [9] An, Q., Zhou, T., Wen, C., Yan, C., 2023. The effects of microplastics on heavy metals bioavailability in soils: a meta-analysis. *J Hazard Mater* 460, 132369. <https://doi.org/10.1016/j.jhazmat.2023.132369>.
- [10] Andrade, H., Glüge, J., Herzke, D., Ashta, N.M., Nayagar, S.M., Scheringer, M., 2021. Oceanic long-range transport of organic additives present in plastic products: an overview. *Environ Sci Eur* 33, 85. <https://doi.org/10.1186/s12302-021-00522-x>.
- [11] Andradóttir, A.L., 2017. The plastic in microplastics: A review. *Mar Pollut Bull* 119, 12–22. <https://doi.org/10.1016/j.marpolbul.2017.01.082>.
- [12] Antunes, J.C., Frias, J.G.L., Micaelo, A.C., Sobral, P., 2013. Resin pellets from beaches of the Portuguese coast and adsorbed persistent organic pollutants. *Estuar Coast Shelf Sci* 130, 62–69. <https://doi.org/10.1016/j.ecss.2013.06.016>.
- [13] Arias, A.H., Alvarez, G., Pozo, K., Pribylova, P., Klanova, J., Rodríguez Pirani, et al., 2023. Beached microplastics at the Bahía Blanca Estuary (Argentina): Plastic pellets as potential vectors of environmental pollution by POPs. *Mar Pollut Bull* 187, 114520. <https://doi.org/10.1016/j.marpolbul.2022.114520>.
- [14] Awet, T.T., Kohl, Y., Meier, F., Straskraba, S., Grün, A.L., Ruf, T., et al., 2018. Effects of polystyrene nanoparticles on the microbiota and functional diversity of enzymes in soil. *Environ Sci Eur* 30, 11. <https://doi.org/10.1186/s12302-018-0140-6>.
- [15] Barriá, C., Brandts, I., Tort, L., Oliveira, M., Teles, M., 2020. Effect of nanoplastics on fish health and performance: A review. *Mar Pollut Bull* 151, 110791. <https://doi.org/10.1016/j.marpolbul.2019.110791>.
- [16] BeatTheMicrobead, 2020. Glob Impact Beat Microbe. (<https://www.beattthemicrobead.org/impact/global-impact/>) (accessed May 24, 2023).
- [17] Behera, S., Das, S., 2023. Environmental impacts of microplastic and role of plastisphere microbes in the biodegradation and upcycling of microplastic. *Chemosphere* 334, 138928. <https://doi.org/10.1016/j.chemosphere.2023.138928>.
- [18] Blöcker, L., Watson, C., Wichern, F., 2020. Living in the plastic age - Different short-term microbial response to microplastics addition to arable soils with contrasting soil organic matter content and farm management legacy. *Environ Pollut* 267, 115468. <https://doi.org/10.1016/j.envpol.2020.115468>.
- [19] 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. <https://doi.org/10.1021/acs.est.9b03304>.
- [20] Bostan, N., Ilyas, N., Akhtar, N., Mehmood, S., Saman, R.U., Sayyed, R.Z., et al., 2023. Toxicity assessment of microplastic (MPs): a threat to the ecosystem. *Environ Res* 234, 116523. <https://doi.org/10.1016/j.envres.2023.116523>.
- [21] Boyandin, A.N., Prudnikova, S.V., Karpov, V.A., Ivonin, V.N., Đỗ NL, Nguyễn, T. H., et al., 2013. Microbial degradation of polyhydroxyalkanoates in tropical soils. *Int Biodeterior Biodegrad* 83, 77–84. <https://doi.org/10.1016/j.ibiod.2013.04.014>.
- [22] Bridson, J.H., Abbel, R., Smith, D.A., Northcott, G.L., Gaw, S., 2023. Impact of accelerated weathering on the leaching kinetics of stabiliser additives from microplastics. *J Hazard Mater* 459, 132303. <https://doi.org/10.1016/j.jhazmat.2023.132303>.
- [23] Bridson, J.H., Abbel, R., Smith, D.A., Northcott, G.L., Gaw, S., 2023. Release of additives and non-intentionally added substances from microplastics under environmentally relevant conditions. *Environ Adv* 12, 100359. <https://doi.org/10.1016/j.envadv.2023.100359>.
- [24] Brown, E., MacDonald, A., Allen, S., Allen, D., 2023. The potential for a plastic recycling facility to release microplastic pollution and possible filtration remediation effectiveness. *J Hazard Mater Adv* 10, 100309. <https://doi.org/10.1016/j.hazadv.2023.100309>.
- [25] Canada., 2015. Chemical substances glossary. Canada.ca. (<https://www.canada.ca/en/health-canada/services/chemical-substances/chemical-substances-glossary.html#s>). (accessed May 24, 2023).
- [26] Cao, Y., Zhao, M., Ma, X., Song, Y., Zuo, S., Li, H., et al., 2021. A critical review on the interactions of microplastics with heavy metals: Mechanism and their combined effect on organisms and humans. *Sci Total Environ* 788, 147620. <https://doi.org/10.1016/j.scitotenv.2021.147620>.
- [27] Cascone, S., Gagliano, A., 2022. Recycled agricultural plastic waste as green roof drainage layer within the perspective of ecological transition for the built environment. *J Clean Prod* 380, 135032. <https://doi.org/10.1016/j.jclepro.2022.135032>.
- [28] Celina, M., Linde, E., Brunson, D., Quintana, A., Giron, N., 2019. Overview of accelerated aging and polymer degradation kinetics for combined radiation-thermal environments. *Polym Degrad Stab* 166, 353–378. <https://doi.org/10.1016/j.polymdegradstab.2019.06.007>.
- [29] Chen, G., Li, Y., Liu, S., Junaid, M., Wang, J., 2022. Effects of micro(nano)plastics on higher plants and the rhizosphere environment. *Sci Total Environ* 807, 150841. <https://doi.org/10.1016/j.scitotenv.2021.150841>.
- [30] 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, 125271. <https://doi.org/10.1016/j.chemosphere.2019.125271>.
- [31] Chen, J., Li, K., Le, X.C., Zhu, L., 2018. Metabolomic analysis of two rice (*Oryza sativa*) varieties exposed to 2, 2', 4, 4'-tetrabromodiphenyl ether. *Environ Pollut* 237, 308–317. <https://doi.org/10.1016/j.envpol.2018.02.027>.
- [32] Chen, X., Gu, X., Bao, L., Ma, S., Mu, Y., 2021. Comparison of adsorption and desorption of triclosan between microplastics and soil particles. *Chemosphere* 263, 127947. <https://doi.org/10.1016/j.chemosphere.2020.127947>.
- [33] Chen, Y., Leng, Y., Liu, X., Wang, J., 2020. Microplastic pollution in vegetable farmlands of suburb Wuhan, central China. *Environ Pollut* 257, 113449. <https://doi.org/10.1016/j.envpol.2019.113449>.
- [34] Chen, Z., Zhao, W., Xing, R., Xie, S., Yang, X., Cui, P., et al., 2020. Enhanced in situ biodegradation of microplastics in sewage sludge using hyperthermophilic composting technology. *J Hazard Mater* 384, 121271. <https://doi.org/10.1016/j.jhazmat.2019.121271>.
- [35] Chia, R.W., Lee, J.-Y., Jang, J., Kim, H., Kwon, K.D., 2022. Soil health and microplastics: a review of the impacts of microplastic contamination on soil properties. *J Soils Sediment* 22, 2690–2705. <https://doi.org/10.1007/s11368-022-03254-4>.
- [36] Chong, J.W.R., Khoo, K.S., Yew, G.Y., Leong, W.H., Lim, J.W., Lam, M.K., et al., 2021. Advances in production of bioplastics by microalgae using food waste hydrolysate and wastewater: A review. *Bioresour Technol* 342, 125947. <https://doi.org/10.1016/j.biortech.2021.125947>.
- [37] Colzi, I., Renna, L., Bianchi, E., Castellani, M.B., Coppi, A., Pignattelli, S., et al., 2022. Impact of microplastics on growth, photosynthesis and essential elements in *Cucurbita pepo* L. *J Hazard Mater* 423, 127238. <https://doi.org/10.1016/j.jhazmat.2021.127238>.
- [38] Conti, I., Simioni, C., Varano, G., Brenna, C., Costanzi, E., Neri, L.M., 2021. Legislation to limit the environmental plastic and microplastic pollution and their influence on human exposure. *Environ Pollut* 288, 117708. <https://doi.org/10.1016/j.envpol.2021.117708>.
- [39] Convery, F., McDonnell, S., Ferreira, S., 2007. The most popular tax in Europe? Lessons from the Irish plastic bags levy. *Environ Resour Econ* 38, 1–11. <https://doi.org/10.1007/s10640-006-9059-2>.
- [40] Corradini, F., Bartholomeus, H., Huerta Lwanga, E., Gertsens, H., Geissen, V., 2019. Predicting soil microplastic concentration using vis-NIR spectroscopy. *Sci Total Environ* 650, 922–932. <https://doi.org/10.1016/j.scitotenv.2018.09.101>.
- [41] Corradini, F., Casado, F., Leiva, V., Huerta-Lwanga, E., Geissen, V., 2021. Microplastics occurrence and frequency in soils under different land uses on a regional scale. *Sci Total Environ* 752, 14917. <https://doi.org/10.1016/j.scitotenv.2020.14917>.
- [42] Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., Geissen, V., 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Sci Total Environ* 671, 411–420. <https://doi.org/10.1016/j.scitotenv.2019.03.368>.
- [43] Costa, J.P.D., Avellan, A., Mouneyrac, C., Duarte, A., Rocha-Santos, T., 2023. Plastic additives and microplastics as emerging contaminants: Mechanisms and analytical assessment. *TrAC, Trends Anal Chem* 158, 116898. <https://doi.org/10.1016/j.trac.2022.116898>.
- [44] Crawford, C.B., Quinn, B., 2017. Plastic production, waste and legislation. In: Crawford, C.B., Quinn, B. (Eds.), *Microplastic Pollutants*, 3. Elsevier, pp. 39–56. <https://doi.org/10.1016/B978-0-12-809406-8.00003-7>.
- [45] Crossman, J., Hurley, R.R., Futter, M., Nizzetto, L., 2020. Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment. *Sci Total Environ* 724, 138334. <https://doi.org/10.1016/j.scitotenv.2020.138334>.
- [46] Cui, Q., Yang, X., Li, J., Miao, Y., Zhang, X., 2022. Microplastics generation behavior of polypropylene films with different crystalline structures under UV irradiation. *Polym Degrad Stab* 199, 109916. <https://doi.org/10.1016/j.polymdegradstab.2022.109916>.
- [47] Dai, J., Liu, P., Wang, C., Li, H., Qiang, H., Yang, Z., et al., 2023. Which factors mainly drive the photoaging of microplastics in freshwater? *Sci Total Environ* 858, 159845. <https://doi.org/10.1016/j.scitotenv.2022.159845>.
- [48] Dainelli, M., Pignattelli, S., Bazihizina, N., Falsini, S., Papini, A., Baccelli, I., et al., 2023. Can microplastics threaten plant productivity and fruit quality? Insights from Micro-Tom and Micro-PET/PVC. *Sci Total Environ* 895, 165119. <https://doi.org/10.1016/j.scitotenv.2023.165119>.
- [49] de Souza Machado, A.A., Lau, C.W., Kloas, W., Bergmann, J., Bachelier, J.B., Faltin, E., et al., 2019. Microplastics can change soil properties and affect plant performance. *Environ Sci Technol* 53, 6044–6052. <https://doi.org/10.1021/acs.est.9b01339>.
- [50] de Souza Machado, A.A., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R., et al., 2018. Impacts of microplastics on the soil biophysical environment. *Environ Sci Technol* 52, 9656–9665. <https://doi.org/10.1021/acs.est.8b02212>.
- [51] Ding, J., Zhu, D., Wang, H.-T., Lassen, S.B., Chen, Q.-L., Li, G., et al., 2020. Dysbiosis in the gut microbiota of soil fauna explains the toxicity of tire tread particles. *Environ Sci Technol* 54, 7450–7460. <https://doi.org/10.1021/acs.est.0c00917>.
- [52] Dissanayake, P.D., Kim, S., Sarkar, B., Oleszczuk, P., Sang, M.K., Haque, M.N., et al., 2022. Effects of microplastics on the terrestrial environment: A critical review. *Environ Res* 209, 112734. <https://doi.org/10.1016/j.envres.2022.112734>.
- [53] Do, A.T.N., Ha, Y., Kwon, J.-H., 2022. Leaching of microplastic-associated additives in aquatic environments: A critical review. *Environ Pollut* 305, 119258. <https://doi.org/10.1016/j.envpol.2022.119258>.
- [54] Dong, Y., Gao, M., Song, Z., Qiu, W., 2020. Microplastic particles increase arsenic toxicity to rice seedlings. *Environ Pollut* 259, 113892. <https://doi.org/10.1016/j.envpol.2019.113892>.
- [55] Duan, J., Bolan, N., Li, Y., Ding, S., Atugoda, T., Vithanage, M., et al., 2021. Weathering of microplastics and interaction with other coexisting constituents in terrestrial and aquatic environments. *Water Res* 196, 117011. <https://doi.org/10.1016/j.watres.2021.117011>.
- [56] Duan, Z., Zhao, S., Zhao, L., Duan, X., Xie, S., Zhang, H., et al., 2020. Microplastics in Yellow River Delta wetland: Occurrence, characteristics, human influences, and marker. *Environ Pollut* 258, 113232. <https://doi.org/10.1016/j.envpol.2019.113232>.
- [57] ECHA., 2023. European Chemicals Agency. (<https://echa.europa.eu/hot-topics/microplastics>) (accessed May 24, 2023).
- [58] Edo, C., González-Pleiter, M., Leganés, F., Fernández-Piñas, F., Rosal, R., 2020. Fate of microplastics in wastewater treatment plants and their environmental dispersion with effluent and sludge. *Environ Pollut* 259, 113837. <https://doi.org/10.1016/j.envpol.2019.113837>.
- [59] Emadian, S.M., Onay, T.T., Demirel, B., 2017. Biodegradation of bioplastics in natural environments. *Waste Manag* 59, 526–536. <https://doi.org/10.1016/j.wasman.2016.10.006>.
- [60] Enfrin, M., Lee, J., Gibert, Y., Basheer, F., Kong, L., Dumée, L.F., 2020. Release of hazardous nanoplastic contaminants due to microplastics fragmentation under shear stress forces. *J Hazard Mater* 384, 121393. <https://doi.org/10.1016/j.jhazmat.2019.121393>.
- [61] Eriksen, M., Thiel, M., Prindiville, M., Kiessling, T., 2018. Microplastic: What Are the Solutions? In: Wagner, M., Lambert, S. (Eds.), *Freshwater Microplastics: Emerging Environmental Contaminants?* Springer International Publishing, Cham, pp. 273–298. https://doi.org/10.1007/978-3-319-61615-5_13.
- [62] Europe C., 2015. Cosmetics Europe recommendation on solid plastic particles (Plastic micro particles). Cosmetics Europe. (https://www.cosmeticeurope.eu/files/3714/7636/5652/Recommendation_on_Solid_Plastic_Particles.pdf) (accessed May 24, 2023).
- [63] Fei, Y., Huang, S., Zhang, H., Tong, Y., Wen, D., Xia, X., et al., 2020. Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil. *Sci Total Environ* 707, 135634. <https://doi.org/10.1016/j.scitotenv.2019.135634>.
- [64] Feilizadeh, M., Karimi Estahbanati, M.R., Nayernia, Z., Avazpour, S., Drogui, P., Tyagi, R.D., 2023. Chapter 13 - Chemical degradation of microplastics and nanoplastics in water and wastewater. In: Tyagi, R.D., Pandey, A., Drogui, P., Yadav, B., Pilli, S. (Eds.), *Current Developments in Biotechnology and Bioengineering*. Elsevier, pp. 315–332. <https://doi.org/10.1016/B978-0-323-99908-3.00014-2>.
- [65] Fisner, M., Majer, A., Taniguchi, S., Bicego, M., Turra, A., Gorman, D., 2017. Colour spectrum and resin-type determine the concentration and composition of Polycyclic Aromatic Hydrocarbons (PAHs) in plastic pellets. *Mar Pollut Bull* 122, 323–330. <https://doi.org/10.1016/j.marpolbul.2017.06.072>.
- [66] Fred-Ahmadu, O.H., Bhagwat, G., Oluoye, I., Benson, N.U., Ayejuyo, O.O., Palanisami, T., 2020. Interaction of chemical contaminants with microplastics: Principles and perspectives. *Sci Total Environ* 706, 135978. <https://doi.org/10.1016/j.scitotenv.2019.135978>.
- [67] Frias, J.P.G.L., Nash, R., 2019. Microplastics: Finding a consensus on the definition. *Mar Pollut Bull* 138, 145–147. <https://doi.org/10.1016/j.marpolbul.2018.11.022>.
- [68] Fu, L., Li, J., Wang, G., Luan, Y., Dai, W., 2021. Adsorption behavior of organic pollutants on microplastics. *Ecotoxicol Environ Saf* 217, 112207. <https://doi.org/10.1016/j.ecoenv.2021.112207>.
- [69] Fu, Q., Lai, J.-I., Ji, X.-h., Luo, Z.-x., Wu, G., Luo, X.-g., 2022. Alterations of the rhizosphere soil microbial community composition and metabolite profiles of *Zea mays* by polyethylene-particles of different molecular weights. *J Hazard Mater* 423, 127062. <https://doi.org/10.1016/j.jhazmat.2021.127062>.
- [70] Fuller, S., Gautam, A., 2016. A procedure for measuring microplastics using pressurized fluid extraction. *Environ Sci Technol* 50, 5774–5780. <https://doi.org/10.1021/acs.est.6b00816>.
- [71] Gabarrón, S., Ferrero, G., Dalmau, M., Comas, J., Rodríguez-Roda, I., 2014. Assessment of energy-saving strategies and operational costs in full-scale membrane bioreactors. *J Environ Manag* 134, 8–14. <https://doi.org/10.1016/j.jenvman.2013.12.023>.
- [72] Gao, M., Liu, Y., Song, Z., 2019. Effects of polyethylene microplastic on the phytotoxicity of di-n-butyl phthalate in lettuce (*Lactuca sativa* L. var. ramosa Hort). *Chemosphere* 237, 124482. <https://doi.org/10.1016/j.chemosphere.2019.124482>.
- [73] Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. *Sci Adv* 3, e1700782. <https://doi.org/10.1126/sciadv.1700782>.
- [74] Giorgetti, L., Spanò, C., Muccifora, S., Bottega, S., Barbieri, F., Bellani, L., et al., 2020. Exploring the interaction between polystyrene nanoplastics and *Allium cepa* during germination: Internalization in root cells, induction of toxicity and oxidative stress. *Plant Physiol Biochem* 149, 170–177. <https://doi.org/10.1016/j.plaphy.2020.02.014>.
- [75] GOCSC., 2017. Notice of the General Office of the State Council on issuing the implementation plan for prohibiting the entry of foreign waste and advancing the reform of the solid waste import administration system. (http://www.gov.cn/zhengce/content/2017-07/27/content_5213738.htm) (accessed 24 May, 2023).
- [76] Golmohammadi, M., Fatemeh Musavi, S., Habibi, M., Maleki, R., Golgoli, M., Zargar, M., et al., 2023. Molecular mechanisms of microplastics degradation: A review. *Sep Purif Technol* 309, 122906. <https://doi.org/10.1016/j.seppur.2022.122906>.

- [77] Guo, J.-J., Huang, X.-P., Xiang, L., Wang, Y.-Z., Li, Y.-W., Li, H., et al., 2020. Source, migration and toxicology of microplastics in soil. *Environ Int* 137, 105263. <https://doi.org/10.1016/j.envint.2019.105263>.
- [78] Han, X., Lu, X., Vogt, R.D., 2019. An optimized density-based approach for extracting microplastics from soil and sediment samples. *Environ Pollut* 254, 113009. <https://doi.org/10.1016/j.envpol.2019.113009>.
- [79] Hartmann, G.F., Ricachenevsky, F.K., Silveira, N.M., Pita-Barbosa, A., 2022. Phytotoxic effects of plastic pollution in crops: what is the size of the problem? *Environ Pollut* 292, 118420. <https://doi.org/10.1016/j.envpol.2021.118420>.
- [80] Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H.S., Schmidt, S.N., Mayer, P., et al., 2017. Microplastics as vectors for environmental contaminants: Exploring sorption, desorption, and transfer to biota. *Integr Environ Assess Manag* 13, 488–493. <https://doi.org/10.1002/ieam.1904>.
- [81] Hasan, M.M., Jho, E.H., 2023. Effect of different types and shapes of microplastics on the growth of lettuce. *Chemosphere* 339, 139660. <https://doi.org/10.1016/j.chemosphere.2023.139660>.
- [82] He, D., Luo, Y., Lu, S., Liu, M., Song, Y., Lei, L., 2018. Microplastics in soils: Analytical methods, pollution characteristics and ecological risks. *TrAC, Trends Anal Chem* 109, 163–172. <https://doi.org/10.1016/j.trac.2018.10.006>.
- [83] He, S., Wei, Y., Yang, C., He, Z., 2022. Interactions of microplastics and soil pollutants in soil-plant systems. *Environ Pollut* 315, 120357. <https://doi.org/10.1016/j.envpol.2022.120357>.
- [84] He, W., Liu, S., Zhang, W., Yi, K., Zhang, C., Pang, H., et al., 2023. Recent advances on microplastic aging: Identification, mechanism, influence factors, and additives release. *Sci Total Environ* 889, 164035. <https://doi.org/10.1016/j.scitotenv.2023.164035>.
- [85] Helcoski, R., Yonkos, L.T., Sanchez, A., Baldwin, A.H., 2020. Wetland soil microplastics are negatively related to vegetation cover and stem density. *Environ Pollut* 256, 113391. <https://doi.org/10.1016/j.envpol.2019.113391>.
- [86] Heskett, M., Takada, H., Yamashita, R., Yuyama, M., Ito, M., Geok, Y.B., et al., 2012. Measurement of persistent organic pollutants (POPs) in plastic resin pellets from remote islands: Toward establishment of background concentrations for International Pellet Watch. *Mar Pollut Bull* 64, 445–448. <https://doi.org/10.1016/j.marpolbul.2011.11.004>.
- [87] Ho, W.-K., Law, J.C.-F., Zhang, T., Leung, K.S.-Y., 2020. Effects of Weathering on the Sorption Behavior and Toxicity of Polystyrene Microplastics in Multi-solute Systems. *Water Res* 187, 116419. <https://doi.org/10.1016/j.watres.2020.116419>.
- [88] Hu, X., Gu, H., Sun, X., Wang, Y., Liu, J., Yu, Z., et al., 2023. Distinct influence of conventional and biodegradable microplastics on microbe-driving nitrogen cycling processes in soils and plastispheres as evaluated by metagenomic analysis. *J Hazard Mater* 451, 131097. <https://doi.org/10.1016/j.jhazmat.2023.131097>.
- [89] Huang, D., Wang, X., Yin, L., Chen, S., Tao, J., Zhou, W., et al., 2022. Research progress of microplastics in soil-plant system: Ecological effects and potential risks. *Sci Total Environ* 812, 151487. <https://doi.org/10.1016/j.scitotenv.2021.151487>.
- [90] Huang, J., Meng, H., Luo, X., Mu, X., Xu, W., Jin, L., et al., 2022. Insights into the thermal degradation mechanisms of polyethylene terephthalate dimer using DFT method. *Chemosphere* 291, 133112. <https://doi.org/10.1016/j.chemosphere.2021.133112>.
- [91] 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. <https://doi.org/10.1016/j.envpol.2020.114096>.
- [92] Huang, Y., Zhao, Y., Wang, J., Zhang, M., Jia, W., Qin, X., 2019. LDPE microplastic films alter microbial community composition and enzymatic activities in soil. *Environ Pollut* 254, 112983. <https://doi.org/10.1016/j.envpol.2019.112983>.
- [93] Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., et al., 2015. Plastic waste inputs from land into the ocean. *Science* 347, 768–771. <https://doi.org/10.1126/science.1260352>.
- [94] Jayakumar, A., Radoor, S., Siengchin, S., Shin, G.H., Kim, J.T., 2023. Recent progress of bioplastics in their properties, standards, certifications and regulations: A review. *Sci Total Environ* 878, 163156. <https://doi.org/10.1016/j.scitotenv.2023.163156>.
- [95] Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M., Klobučar, G., 2019. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant *Vicia faba*. *Environ Pollut* 250, 831–838. <https://doi.org/10.1016/j.envpol.2019.04.055>.
- [96] 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. <https://doi.org/10.1016/j.still.2016.10.011>.
- [97] Jiang, Z., Huang, L., Fan, Y., Zhou, S., Zou, X., 2022. Contrasting effects of microplastic aging upon the adsorption of sulfonamides and its mechanism. *Chem Eng J* 430, 132939. <https://doi.org/10.1016/j.cej.2021.132939>.
- [98] Judd, S.J., 2016. The status of industrial and municipal effluent treatment with membrane bioreactor technology. *Chem Eng J* 305, 37–45. <https://doi.org/10.1016/j.cej.2015.08.141>.
- [99] Kalčíková, G., Zgajnar Gotvajn, A., Kladnik, A., Jemec, A., 2017. Impact of polyethylene microbeads on the floating freshwater plant duckweed *Lemna minor*. *Environ Pollut* 230, 1108–1115. <https://doi.org/10.1016/j.envpol.2017.07.050>.
- [100] Kim, S.-K., Kim, J.-S., Lee, H., Lee, H.-J., 2021. Abundance and characteristics of microplastics in soils with different agricultural practices: Importance of sources with internal origin and environmental fate. *J Hazard Mater* 403, 123997. <https://doi.org/10.1016/j.jhazmat.2020.123997>.
- [101] Kim, S.W., Jeong, S.-W., An, Y.-J., 2021. Microplastics disrupt accurate soil organic carbon measurement based on chemical oxidation method. *Chemosphere* 276, 130178. <https://doi.org/10.1016/j.chemosphere.2021.130178>.
- [102] Koerd, A., Gödeke, J., Berger, J., Thormann, K.M., Albers, S.-V., 2010. Crenarchaeal biofilm formation under extreme conditions. *PloS One* 5, e14104. <https://doi.org/10.1371/journal.pone.0014104>.
- [103] Krueger, M.C., Harms, H., Schlosser, D., 2015. Prospects for microbiological solutions to environmental pollution with plastics. *Appl Microbiol Biotechnol* 99, 8857–8874. <https://doi.org/10.1007/s00253-015-6879-4>.
- [104] Kushwaha, A., Goswami, L., Singhvi, M., Kim, B.S., 2023. Biodegradation of poly (ethylene terephthalate): Mechanistic insights, advances, and future innovative strategies. *Chem Eng J* 457, 141230. <https://doi.org/10.1016/j.cej.2022.141230>.
- [105] Lam, C.-S., Ramanathan, S., Carbery, M., Gray, K., Vanka, K.S., Maurin, C., et al., 2018. A Comprehensive Analysis of Plastics and Microplastic Legislation Worldwide. *Water Air Soil Pollut* 229, 345. <https://doi.org/10.1007/s11270-018-4002-z>.
- [106] Lang, M., Yu, X., Liu, J., Xia, T., Wang, T., Jia, H., et al., 2020. Fenton aging significantly affects the heavy metal adsorption capacity of polystyrene microplastics. *Sci Total Environ* 722, 137762. <https://doi.org/10.1016/j.scitotenv.2020.137762>.
- [107] Lehmann, A., Leifheit, E.F., Feng, L., Bergmann, J., Wulf, A., Rillig, M.C., 2022. Microplastic fiber and drought effects on plants and soil are only slightly modified by arbuscular mycorrhizal fungi. *Soil Ecol Lett* 4, 32–44. <https://doi.org/10.1007/s42832-020-0060-4>.
- [108] Li, J., Huang, X., Hou, Z., Ding, T., 2022. Sorption of diclofenac by polystyrene microplastics: Kinetics, isotherms and particle size effects. *Chemosphere* 290, 133311. <https://doi.org/10.1016/j.chemosphere.2021.133311>.
- [109] Li, J., Liu, W., Lian, Y., Shi, R., Wang, Q., Zeb, A., 2023. Single and combined toxicity of polystyrene nanoplastics and arsenic on submerged plant *Myriophyllum verticillatum* L. *Plant Physiol Biochem* 194, 513–523. <https://doi.org/10.1016/j.plaphy.2022.12.008>.
- [110] Li, J., Song, Y., Cai, Y., 2020. Focus topics on microplastics in soil: Analytical methods, occurrence, transport, and ecological risks. *Environ Pollut* 257, 113570. <https://doi.org/10.1016/j.envpol.2019.113570>.
- [111] Li, K., Jia, W., Xu, L., Zhang, M., Huang, Y., 2023. The plastisphere of biodegradable and conventional microplastics from residues exhibit distinct microbial structure, network and function in plastic-mulching farmland. *J Hazard Mater* 442, 130011. <https://doi.org/10.1016/j.jhazmat.2022.130011>.
- [112] Li, K., Wang, F., 2023. Global hotspots and trends in interactions of microplastics and heavy metals: a bibliometric analysis and literature review. *Environ Sci Pollut Res* 30, 93309–93322. <https://doi.org/10.1007/s11356-023-29091-7>.
- [113] Li, M., Liu, Y., Xu, G., Wang, Y., Yu, Y., 2021. Impacts of polyethylene microplastics on bioavailability and toxicity of metals in soil. *Sci Total Environ* 760, 144037. <https://doi.org/10.1016/j.scitotenv.2020.144037>.
- [114] Li, S., Wang, T., Guo, J., Dong, Y., Wang, Z., Gong, L., et al., 2021. Polystyrene microplastics disturb the redox homeostasis, carbohydrate metabolism and phytohormone regulatory network in barley. *J Hazard Mater* 415, 125614. <https://doi.org/10.1016/j.jhazmat.2021.125614>.
- [115] Li, Y., Liu, Q., Junaid, M., Chen, G., Wang, J., 2023. Distribution, sources, transportation and biodegradation of microplastics in the soil environment. *TrAC, Trends Anal Chem* 164, 117106. <https://doi.org/10.1016/j.trac.2023.117106>.
- [116] Li, Z., Li, Q., Li, R., Zhao, Y., Geng, J., Wang, G., 2020. Physiological responses of lettuce (*Lactuca sativa* L.) to microplastic pollution. *Environ Sci Pollut Res* 27, 30306–30314. <https://doi.org/10.1007/s11356-020-09349-0>.
- [117] Li, Z., Li, Q., Li, R., Zhou, J., Wang, G., 2021. The distribution and impact of polystyrene nanoplastics on cucumber plants. *Environ Sci Pollut Res* 28, 16042–16053. <https://doi.org/10.1007/s11356-020-11702-2>.
- [118] Lian, J., Liu, W., Meng, L., Wu, J., Chao, L., Zeb, A., et al., 2021. Foliar-applied polystyrene nanoplastics (PSNPs) reduce the growth and nutritional quality of lettuce (*Lactuca sativa* L.). *Environ Pollut* 280, 116978. <https://doi.org/10.1016/j.envpol.2021.116978>.
- [119] Lian, J., Wu, J., Zeb, A., Zheng, S., Ma, T., Peng, F., et al., 2020. Do polystyrene nanoplastics affect the toxicity of cadmium to wheat (*Triticum aestivum* L.)? *Environ Pollut* 263, 114498. <https://doi.org/10.1016/j.envpol.2020.114498>.
- [120] Lian, J., Zhao, L., Wu, J., Xiong, H., Bao, Y., Zeb, A., et al., 2019. Foliar spray of TiO₂ nanoparticles prevails over root application in reducing Cd accumulation and mitigating Cd-induced phytotoxicity in maize (*Zea mays* L.). *Chemosphere*, 124794. <https://doi.org/10.1016/j.chemosphere.2019.124794>.
- [121] Lian, Y., Liu, W., Shi, R., Zeb, A., Wang, Q., Li, J., et al., 2022. Effects of polyethylene and polylactic acid microplastics on plant growth and bacterial community in the soil. *J Hazard Mater* 435, 129057. <https://doi.org/10.1016/j.jhazmat.2022.129057>.
- [122] Lin, L., Tang, S., Wang, X., Sun, X., Liu, Y., 2021. Sorption of tetracycline onto hexabromocyclododecane/polystyrene composite and polystyrene microplastics: Statistical physics models, influencing factors, and interaction mechanisms. *Environ Pollut* 284, 117164. <https://doi.org/10.1016/j.envpol.2021.117164>.
- [123] Liu, F.-f., Liu, G.-z., Zhu, Z.-l., Wang, S.-c., Zhao, F.-f., 2019. Interactions between microplastics and phthalate esters as affected by microplastics characteristics and solution chemistry. *Chemosphere* 214, 688–694. <https://doi.org/10.1016/j.chemosphere.2018.09.174>.
- [124] Liu, H., Yang, X., Liu, G., Liang, C., Xue, S., Chen, H., et al., 2017. Response of soil dissolved organic matter to microplastic addition in Chinese loess soil. *Chemosphere* 185, 907–917. <https://doi.org/10.1016/j.chemosphere.2017.07.064>.

- [125] Liu, J., He, J., Xue, R., Xu, B., Qian, X., Xin, F., et al., 2021. Biodegradation and up-cycling of polyurethanes: Progress, challenges, and prospects. *Biotechnol Adv* 48, 107730. <https://doi.org/10.1016/j.biotechadv.2021.107730>.
- [126] Liu, J., Wang, P., Wang, Y., Zhang, Y., Xu, T., Zhang, Y., et al., 2022. Negative effects of poly(butylene adipate-co-terephthalate) microplastics on *Arabidopsis* and its root-associated microbiome. *J Hazard Mater* 437, 129294. <https://doi.org/10.1016/j.jhazmat.2022.129294>.
- [127] Liu, J., Zhang, T., Tian, L., Liu, X., Qi, Z., Ma, Y., et al., 2019. Aging significantly affects mobility and contaminant-mobilizing ability of nanoplastics in saturated loamy sand. *Environ Sci Technol* 53, 5805–5815. <https://doi.org/10.1021/acs.est.9b00787>.
- [128] Liu, M., Lu, S., Song, Y., Lei, L., Hu, J., Lv, W., et al., 2018. Microplastic and mesoplastic pollution in farmland soils in suburbs of Shanghai, China. *Environ Pollut* 242, 855–862. <https://doi.org/10.1016/j.envpol.2018.07.051>.
- [129] Liu, S., Huang, J., He, W., Zhang, W., Yi, K., Zhang, C., et al., 2023. Impact of microplastics on lead-contaminated riverine sediments: Based on the enzyme activities, DOM fractions, and bacterial community structure. *J Hazard Mater* 447, 130763. <https://doi.org/10.1016/j.jhazmat.2023.130763>.
- [130] Liu, X., Li, Y., Yu, Y., Yao, H., 2023. Effect of nonbiodegradable microplastics on soil respiration and enzyme activity: A meta-analysis. *Appl Soil Ecol* 184, 104770. <https://doi.org/10.1016/j.apsoil.2022.104770>.
- [131] Liu, Y.-Q., Chen, Y., Ren, X.-M., Li, Y.-Y., Zhang, Y.-J., Zhang, H., et al., 2023. Plant growth-promoting bacteria modulate gene expression and induce antioxidant tolerance to alleviate synergistic toxicity from combined microplastic and Cd pollution in sorghum. *Ecotoxicol Environ Saf* 264, 115439. <https://doi.org/10.1016/j.ecoenv.2023.115439>.
- [132] Liu, Y., Cui, W., Li, W., Xu, S., Sun, Y., Xu, G., et al., 2023. Effects of microplastics on cadmium accumulation by rice and arbuscular mycorrhizal fungal communities in cadmium-contaminated soil. *J Hazard Mater* 442, 130102. <https://doi.org/10.1016/j.jhazmat.2022.130102>.
- [133] Liu, Y., Huang, Q., Hu, W., Qin, J., Zheng, Y., Wang, J., et al., 2021. Effects of plastic mulch film residues on soil-microbe-plant systems under different soil pH conditions. *Chemosphere* 267, 128901. <https://doi.org/10.1016/j.chemosphere.2020.128901>.
- [134] Liu, Y., Xu, F., Ding, L., Zhang, G., Bai, B., Han, Y., et al., 2023. Microplastics reduce nitrogen uptake in peanut plants by damaging root cells and impairing soil nitrogen cycling. *J Hazard Mater* 443, 130384. <https://doi.org/10.1016/j.jhazmat.2022.130384>.
- [135] Liwarska-Bizukojc, E., 2021. Effect of (bio)plastics on soil environment: A review. *Sci Total Environ* 795, 148889. <https://doi.org/10.1016/j.scitotenv.2021.148889>.
- [136] Lorite, G.S., Rodrigues, C.M., de Souza, A.A., Kranz, C., Mizakoff, B., Cotta, M.A., 2011. The role of conditioning film formation and surface chemical changes on *Xylella fastidiosa* adhesion and biofilm evolution. *J Colloid Interface Sci* 359, 289–295. <https://doi.org/10.1016/j.jcis.2011.03.066>.
- [137] Luís, I.P., Spínola, H., 2010. The influence of a voluntary fee in the consumption of plastic bags on supermarkets from Madeira Island (Portugal). *J Environ Plan Manag* 53, 883–889. <https://doi.org/10.1080/09640568.2010.490054>.
- [138] Luo, H., Zhao, Y., Li, Y., Xiang, Y., He, D., Pan, X., 2020. Aging of microplastics affects their surface properties, thermal decomposition, additives leaching and interactions in simulated fluids. *Sci Total Environ* 714, 136862. <https://doi.org/10.1016/j.scitotenv.2020.136862>.
- [139] Lv, W., Zhou, W., Lu, S., Huang, W., Yuan, Q., Tian, M., et al., 2019. Microplastic pollution in rice-fish co-culture system: A report of three farmland stations in Shanghai, China. *Sci Total Environ* 652, 1209–1218. <https://doi.org/10.1016/j.scitotenv.2018.10.321>.
- [140] Ma, J., Zhao, J., Zhu, Z., Li, L., Yu, F., 2019. Effect of microplastic size on the adsorption behavior and mechanism of triclosan on polyvinyl chloride. *Environ Pollut* 254, 113104. <https://doi.org/10.1016/j.envpol.2019.113104>.
- [141] Mafuta, C., et al., 2021. Drowning in Plastics: Marine Litter and Plastic Waste Vital Graphics, UNEP, Secretariats of the Basel, Rotterdam and Stockholm Secretariats and GRID-Arendal. Naroribi and Arendal. (<https://policycommons.net/artifacts/2390247/drowning-in-plastics/3411476/>) (accessed 12 Sep 2023).
- [142] Manzoor, S., Naqash, N., Rashid, G., Singh, R., 2022. Plastic Material Degradation and Formation of Microplastic in the Environment: A Review. *Mater Today: Proc* 56, 3254–3260. <https://doi.org/10.1016/j.matpr.2021.09.379>.
- [143] Mao, R., Lang, M., Yu, X., Wu, R., Yang, X., Guo, X., 2020. Aging mechanism of microplastics with UV irradiation and its effects on the adsorption of heavy metals. *J Hazard Mater* 393, 122515. <https://doi.org/10.1016/j.jhazmat.2020.122515>.
- [144] Martín, J., Santos, J.L., Aparicio, I., Alonso, E., 2022. Microplastics and associated emerging contaminants in the environment: Analysis, sorption mechanisms and effects of co-exposure. *Trends Environ Anal Chem* 35, e00170. <https://doi.org/10.1016/j.teac.2022.e00170>.
- [145] Mateos-Cárdenas, A., Scott, D.T., Seitmaganbetova, G., Frank, N.A.M. vP., John, O.H., Marcel, A.K.J., 2019. Polyethylene microplastics adhere to *Lemna minor* (L.), yet have no effects on plant growth or feeding by *Gammarus duebeni* (Lillj.). *Sci Total Environ* 689, 413–421. <https://doi.org/10.1016/j.scitotenv.2019.06.359>.
- [146] 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. <https://doi.org/10.1021/es503610r>.
- [147] Miri, S., Saini, R., Davoodi, S.M., Pulicharla, R., Brar, S.K., Magdoui, S., 2022. Biodegradation of microplastics: Better late than never. *Chemosphere* 286, 131670. <https://doi.org/10.1016/j.chemosphere.2021.131670>.
- [148] Montazer, Z., Habibi-Najafi, M.B., Mohebbi, M., Oromiehei, A., 2018. Microbial Degradation of UV-Pretreated Low-Density Polyethylene Films by Novel Polyethylene-Degrading Bacteria Isolated from Plastic-Dump Soil. *J Polym Environ* 26, 3613–3625. <https://doi.org/10.1007/s10924-018-1245-0>.
- [149] Mourshed, M., Masud, M.H., Rashid, F., Joardder, M.U.H., 2017. Towards the effective plastic waste management in Bangladesh: a review. *Environ Sci Pollut Res* 24, 27021–27046. <https://doi.org/10.1007/s11356-017-0429-9>.
- [150] Naidu, R., Arias Espana, V.A., Liu, Y., Jit, J., 2016. Emerging contaminants in the environment: Risk-based analysis for better management. *Chemosphere* 154, 350–357. <https://doi.org/10.1016/j.chemosphere.2016.03.068>.
- [151] Nematollahi, M.J., Keshavarzi, B., Mohit, F., Moore, F., Busquets, R., 2022. Microplastic occurrence in urban and industrial soils of Ahvaz metropolis: A city with a sustained record of air pollution. *Sci Total Environ* 819, 152051. <https://doi.org/10.1016/j.scitotenv.2021.152051>.
- [152] Ng, E.-L., Huerta Lwanga, E., Eldridge, S.M., Johnston, P., Hu, H.-W., Geissen, V., et al., 2018. An overview of microplastic and nanoplastic pollution in agroecosystems. *Sci Total Environ* 627, 1377–1388. <https://doi.org/10.1016/j.scitotenv.2018.01.341>.
- [153] Oliveira, M.F., Barreto-Garcia, P.A.B., da Conceição Júnior, V., Monroe, P.H.M., Gomes, V.D.S., Sousa, J.P., 2022. Changes in microbial biomass and activity of tropical soil submitted to successive Eucalyptus rotations in the semi-arid region of Brazil. *Geoderma Reg* 29, e00492. <https://doi.org/10.1016/j.geodrs.2022.e00492>.
- [154] Ouyang, Z., Zhang, Z., Jing, Y., Bai, L., Zhao, M., Hao, X., et al., 2022. The photodegradation of polyvinyl chloride microplastics under different UV irradiations. *Gondwana Res* 108, 72–80. <https://doi.org/10.1016/j.gr.2021.07.010>.
- [155] Paik, P., Kar, K.K., 2009. Thermal degradation kinetics and estimation of lifetime of polyethylene particles: Effects of particle size. *Mater Chem Phys* 113, 953–961. <https://doi.org/10.1016/j.matchemphys.2008.08.075>.
- [156] Pathak, G., Nichter, M., Hardon, A., Moyer, E., Latkar, A., Simbaya, J., et al., 2023. Plastic pollution and the open burning of plastic wastes. *Glob Environ Change* 80, 102648. <https://doi.org/10.1016/j.gloenvcha.2023.102648>.
- [157] Peixoto, D., Pinheiro, C., Amorim, J., Oliva-Teles, L., Guilhermino, L., Vieira, M. N., 2019. Microplastic pollution in commercial salt for human consumption: A review. *Estuar Coast Shelf Sci* 219, 161–168. <https://doi.org/10.1016/j.ecss.2019.02.018>.
- [158] Peng, X., Chen, G., Fan, Y., Zhu, Z., Guo, S., Zhou, J., et al., 2021. Lifetime bioaccumulation, gender difference, tissue distribution, and parental transfer of organophosphorus plastic additives in freshwater fish. *Environ Pollut* 280, 116948. <https://doi.org/10.1016/j.envpol.2021.116948>.
- [159] Piehl, S., Leibner, A., Löder, M.G.J., Dris, R., Bogner, C., Laforsch, C., 2018. Identification and quantification of macro- and microplastics on an agricultural farmland. *Sci Rep* 8, 17950. <https://doi.org/10.1038/s41598-018-36172-y>.
- [160] Pignatelli, S., Broccoli, A., Renzi, M., 2020. Physiological responses of garden cress (*L. sativum*) to different types of microplastics. *Sci Total Environ* 727, 138609. <https://doi.org/10.1016/j.scitotenv.2020.138609>.
- [161] Ponti, M.G., Allen, D., White, C.J., Bertram, D., Switzer, C., 2022. A framework to assess the impact of flooding on the release of microplastics from waste management facilities. *J Hazard Mater Adv* 7, 100105. <https://doi.org/10.1016/j.jhazadv.2022.100105>.
- [162] Poortinga, W., Whitmarsh, L., Suffolk, C., 2013. The introduction of a single-use carrier bag charge in Wales: Attitude change and behavioural spillover effects. *J Environ Psychol* 36, 240–247. <https://doi.org/10.1016/j.jenvp.2013.09.001>.
- [163] Priya, A.K., Jalil, A.A., Dutta, K., Rajendran, S., Vasseghian, Y., Qin, J., et al., 2022. Microplastics in the environment: Recent developments in characteristic, occurrence, identification and ecological risk. *Chemosphere* 298, 134161. <https://doi.org/10.1016/j.chemosphere.2022.134161>.
- [164] Qi, Y., Ossowski, A., Yang, X., Huerta Lwanga, E., Dini-Andreote, F., Geissen, V., et al., 2020. Effects of plastic mulch film residues on wheat rhizosphere and soil properties. *J Hazard Mater* 387, 121711. <https://doi.org/10.1016/j.jhazmat.2019.121711>.
- [165] Rafique, A., Irfan, M., Mumtaz, M., Qadir, A., 2020. Spatial distribution of microplastics in soil with context to human activities: a case study from the urban center. *Environ Monit Assess* 192. <https://doi.org/10.1007/s10661-020-08641-3>.
- [166] 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, 113347. <https://doi.org/10.1016/j.envpol.2019.113347>.
- [167] Ren, X., Yin, S., Wang, L., Tang, J., 2022. Microplastics in plant-microbes-soil system: A review on recent studies. *Sci Total Environ* 816, 151523. <https://doi.org/10.1016/j.scitotenv.2021.151523>.
- [168] Ren, Z., Gui, X., Xu, X., Zhao, L., Qiu, H., Cao, X., 2021. Microplastics in the soil-groundwater environment: Aging, migration, and co-transport of contaminants – A critical review. *J Hazard Mater* 419, 126455. <https://doi.org/10.1016/j.jhazmat.2021.126455>.
- [169] Ribeiro, D.M., Silva Júnior, D.D., Cardoso, F.B., Martins, A.O., Silva, W.A., Nascimento, V.L., et al., 2016. Growth inhibition by selenium is associated with changes in primary metabolism and nutrient levels in *Arabidopsis thaliana*. *Plant Cell Environ* 39, 2235–2246. <https://doi.org/10.1111/pce.12783>.
- [170] Ricardo, I.A., Alberto, E.A., Silva Júnior, A.H., Macuvel, D.L.P., Padoin, N., Soares, C., et al., 2021. A critical review on microplastics, interaction with organic and inorganic pollutants, impacts and effectiveness of advanced oxidation processes applied for their removal from aqueous matrices. *Chem Eng J* 424, 130282. <https://doi.org/10.1016/j.cej.2021.130282>.
- [171] Rillig, M.C., 2012. Microplastic in terrestrial ecosystems and the soil? *Environ Sci Technol* 46, 6453–6454. <https://doi.org/10.1021/es302011r>.

- [172] Rillig, M.C., 2018. Microplastic disguising as soil carbon storage. *Environ Sci Technol* 52, 6079–6080. <https://doi.org/10.1021/acs.est.8b02338>.
- [173] Rillig, M.C., Leifheit, E., Lehmann, J., 2021. Microplastic effects on carbon cycling processes in soils. *PLoS Biol* 19, e3001130. <https://doi.org/10.1371/journal.pbio.3001130>.
- [174] Rodrigues, J.P., Duarte, A.C., Santos-Echeandía, J., Rocha-Santos, T., 2019. Significance of interactions between microplastics and POPs in the marine environment: A critical overview. *TrAC, Trends Anal Chem* 111, 252–260. <https://doi.org/10.1016/j.trac.2018.11.038>.
- [175] Rong, L., Zhao, L., Zhao, L., Cheng, Z., Yao, Y., Yuan, C., et al., 2021. LDPE microplastics affect soil microbial communities and nitrogen cycling. *Sci Total Environ* 773, 145640. <https://doi.org/10.1016/j.scitotenv.2021.145640>.
- [176] Rozman, U., Turk, T., Skalar, T., Zupančič, M., Čelan Korosin, N., Marinšek, M., et al., 2021. An extensive characterization of various environmentally relevant microplastics – Material properties, leaching and ecotoxicity testing. *Sci Total Environ* 773, 145576. <https://doi.org/10.1016/j.scitotenv.2021.145576>.
- [177] Rummel, C.D., Jahnke, A., Gorokhova, E., Kühnel, D., Schmitt-Jansen, M., 2017. Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. *Environ Sci Technol Lett* 4, 258–267. <https://doi.org/10.1021/acs.estlett.7b00164>.
- [178] Salam, M., Zheng, H., Liu, Y., Zaib, A., Rehman, S.A.U., Riaz, N., et al., 2023. Effects of micro(nano)plastics on soil nutrient cycling: State of the knowledge. *J Environ Manag* 344, 118437. <https://doi.org/10.1016/j.jenvman.2023.118437>.
- [179] Scheurer, M., Bigalke, M., 2018. Microplastics in Swiss Floodplain Soils. *Environ Sci Technol* 52, 3591–3598. <https://doi.org/10.1021/acs.est.7b06003>.
- [180] Seeley, M.E., Song, B., Passie, R., Hale, R.C., 2020. Microplastics affect sedimentary microbial communities and nitrogen cycling. *Nat Commun* 11, 2372. <https://doi.org/10.1038/s41467-020-16235-3>.
- [181] Sepelhi, A., Sarrafzadeh, M.-H., 2018. Effect of nitrifiers community on fouling mitigation and nitrification efficiency in a membrane bioreactor. *Chem Eng Process: Process* 128, 10–18. <https://doi.org/10.1016/j.ccep.2018.04.006>.
- [182] Sharma, S., Sharma, V., Chatterjee, S., 2023. Contribution of plastic and microplastic to global climate change and their conjoining impacts on the environment - A review. *Sci Total Environ* 875, 162627. <https://doi.org/10.1016/j.scitotenv.2023.162627>.
- [183] Shen, M., Liu, W., Zeb, A., Lian, J., Wu, J., Lin, M., 2022. Bioaccumulation and phytotoxicity of ZnO nanoparticles in soil-grown *Brassica chinensis* L. and potential risks. *J Environ Manag* 306, 114454. <https://doi.org/10.1016/j.jenvman.2022.114454>.
- [184] Shi, J., Wang, Z., Peng, Y., Zhang, Z., Fan, Z., Wang, J., et al., 2023. Microbes drive metabolism, community diversity, and interactions in response to microplastic-induced nutrient imbalance. *Sci Total Environ* 877, 162885. <https://doi.org/10.1016/j.scitotenv.2023.162885>.
- [185] Shi, R., Liu, W., Lian, Y., Wang, Q., Zeb, A., Tang, J., 2022. Phytotoxicity of polystyrene, polyethylene and polypropylene microplastics on tomato (*Lycopersicon esculentum* L.). *J Environ Manag* 317, 115441. <https://doi.org/10.1016/j.jenvman.2022.115441>.
- [186] Shi, R., Liu, W., Lian, Y., Zeb, A., Wang, Q., 2023. Type-dependent effects of microplastics on tomato (*Lycopersicon esculentum* L.): Focus on root exudates and metabolic reprogramming. *Sci Total Environ* 859, 160025. <https://doi.org/10.1016/j.scitotenv.2022.160025>.
- [187] Shorobi, F.M., Vyavahare, G.D., Seok, Y.J., Park, J.H., 2023. Effect of polypropylene microplastics on seed germination and nutrient uptake of tomato and cherry tomato plants. *Chemosphere* 329, 138679. <https://doi.org/10.1016/j.chemosphere.2023.138679>.
- [188] Shruti, V.C., Pérez-Guevara, F., Kutralam-Muniasamy, G., 2021. The current state of microplastic pollution in the world's largest gulf and its future directions. *Environ Pollut* 291, 118142. <https://doi.org/10.1016/j.envpol.2021.118142>.
- [189] Sills, J., Bank, M.S., Ok, Y.S., Swarzenski, P.W., 2020. Microplastic's role in antibiotic resistance. *Science* 1315–1315. <https://doi.org/10.1126/science.abd9937>.
- [190] Singh, B., Sharma, N., 2008. Mechanistic implications of plastic degradation. *Polym Degrad Stab* 93, 561–584. <https://doi.org/10.1016/j.polymdegradstab.2007.11.008>.
- [191] Singh Jadaun, J., Bansal, S., Sonthalia, A., Rai, A.K., Singh, S.P., 2022. Biodegradation of plastics for sustainable environment. *Bioresour Technol* 347, 126697. <https://doi.org/10.1016/j.biortech.2022.126697>.
- [192] Skariyachan, S., Taskeen, N., Kishore, A.P., Krishna, B.V., 2022. Recent advances in plastic degradation – From microbial consortia-based methods to data sciences and computational biology driven approaches. *J Hazard Mater* 426, 128086. <https://doi.org/10.1016/j.jhazmat.2021.128086>.
- [193] Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Jung, S.W., Shim, W.J., 2017. Combined effects of uv exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. *Environ Sci Technol* 51, 4368–4376. <https://doi.org/10.1021/acs.est.6b06155>.
- [194] Sooriyakumar, P., Bolan, N., Kumar, M., Singh, L., Yu, Y., Li, Y., et al., 2022. Biofilm formation and its implications on the properties and fate of microplastics in aquatic environments: A review. *J Hazard Mater Adv* 6, 100077. <https://doi.org/10.1016/j.hazadv.2022.100077>.
- [195] Sun, H., Lei, C., Xu, J., Li, R., 2021. Foliar uptake and leaf-to-root translocation of nanoparticles with different coating charge in maize plants. *J Hazard Mater* 416, 125854. <https://doi.org/10.1016/j.jhazmat.2021.125854>.
- [196] Sun, M., Ye, M., Jiao, W., Feng, Y., Yu, P., Liu, M., et al., 2018. Changes in tetracycline partitioning and bacteria/phage-mediated ARGs in microplastic-contaminated greenhouse soil facilitated by sophorolipid. *J Hazard Mater* 345, 131–139. <https://doi.org/10.1016/j.jhazmat.2017.11.036>.
- [197] Sun, X.-D., Yuan, X.-Z., Jia, Y., Feng, L.-J., Zhu, F.-P., Dong, S.-S., et al., 2020. Differentially charged nanoplastics demonstrate distinct accumulation in *Arabidopsis thaliana*. *Nat Nanotechnol* 15, 755–760. <https://doi.org/10.1038/s41565-020-0707-4>.
- [198] Sun, X., Tao, R., Xu, D., Qu, M., Zheng, M., Zhang, M., et al., 2023. Role of polyamide microplastic in altering microbial consortium and carbon and nitrogen cycles in a simulated agricultural soil microcosm. *Chemosphere* 312, 137155. <https://doi.org/10.1016/j.chemosphere.2022.137155>.
- [199] Sun, X., Zhang, X., Xia, Y., Tao, R., Zhang, M., Mei, Y., et al., 2022. Simulation of the effects of microplastics on the microbial community structure and nitrogen cycle of paddy soil. *Sci Total Environ* 818, 151768. <https://doi.org/10.1016/j.scitotenv.2021.151768>.
- [200] Sun, Y., Ji, J., Tao, J., Yang, Y., Wu, D., Han, L., et al., Current advances in interactions between microplastics and dissolved organic matters in aquatic and terrestrial ecosystems. *TrAC, Trends Anal Chem* 158, 116882. <https://doi.org/10.1016/j.trac.2022.116882>.
- [201] Sun, Y., Ren, X., Pan, J., Zhang, Z., Tsui, T.-H., Luo, L., et al., 2020. Effect of microplastics on greenhouse gas and ammonia emissions during aerobic composting. *Sci Total Environ* 737, 139856. <https://doi.org/10.1016/j.scitotenv.2020.139856>.
- [202] Syberg, K., Khan, F.R., Selck, H., Palmqvist, A., Banta, G.T., Daley, J., et al., 2015. Microplastics: addressing ecological risk through lessons learned. *Environ Toxicol Chem* 34, 945–953. <https://doi.org/10.1002/etc.2914>.
- [203] Talvitie, J., Mikola, A., Koistinen, A., Setälä, O., 2017. Solutions to microplastic pollution – Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. *Water Res* 123, 401–407. <https://doi.org/10.1016/j.watres.2017.07.005>.
- [204] Tan, H.T., Chek, M.F., Neoh, S.Z., Ang, S.L., Yoshida, S., Hakoshima, T., et al., 2022. Characterization of the polyhydroxyalkanoate (PHA) synthase from *Ideonella sakaiensis*, a bacterium that is capable of degrading and assimilating poly(ethylene terephthalate). *Polym Degrad Stab* 206, 110160. <https://doi.org/10.1016/j.polymdegradstab.2022.110160>.
- [205] Taniguchi, I., Yoshida, S., Hiraga, K., Miyamoto, K., Kimura, Y., Oda, K., 2019. Biodegradation of PET: Current status and application aspects. *ACS Catal* 9, 4089–4105. <https://doi.org/10.1021/acscatal.8b05171>.
- [206] ter Halle, A., Ladirat, L., Martignac, M., Mingotau, A.F., Boyron, O., Perez, E., 2017. To what extent are microplastics from the open ocean weathered? *Environ Pollut* 227, 167–174. <https://doi.org/10.1016/j.envpol.2017.04.051>.
- [207] Thakur, S., Chaudhary, J., Sharma, B., Verma, A., Tamulevicius, S., Thakur, V.K., 2018. Sustainability of bioplastics: Opportunities and challenges. *Curr Opin Green Sustain Chem* 13, 68–75. <https://doi.org/10.1016/j.cogsc.2018.04.013>.
- [208] Tumwesigye, E., Felicitas Nnadozie, C., C Akamagwuna, F., Siwe Noundou, X., William Nyakairu, G., Odume, O.N., 2023. Microplastics as vectors of chemical contaminants and biological agents in freshwater ecosystems: Current knowledge status and future perspectives. *Environ Pollut* 330, 121829. <https://doi.org/10.1016/j.envpol.2023.121829>.
- [209] Tunali, M., Uzoefuna, E.N., Tunali, M.M., Yenigun, O., 2020. Effect of microplastics and microplastic-metal combinations on growth and chlorophyll a concentration of *Chlorella vulgaris*. *Sci Total Environ* 743, 140479. <https://doi.org/10.1016/j.scitotenv.2020.140479>.
- [210] van den Berg, P., Huerta-Lwanga, E., Corradini, F., Geissen, V., 2020. Sewage sludge application as a vehicle for microplastics in eastern Spanish agricultural soils. *Environ Pollut* 261, 114198. <https://doi.org/10.1016/j.envpol.2020.114198>.
- [211] van Oers, L., van der Voet, E., Grundmann, V., 2012. Additives in the Plastics Industry. In: Bilitewski, B., Darbra, R.M., Barceló, D. (Eds.), *Global Risk-Based Management of Chemical Additives I: Production, Usage and Environmental Occurrence*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 133–149. <https://doi.org/10.1007/978-2011-112>.
- [212] Vollertsen, J., Hansen, A.-A., 2017. Microplastic in Danish Wastewater: Sources, Occurrences and Fate, Vol. 1906. The Danish Environmental Protection Agency. Environmental Project, p. 55. (<https://vbn.aau.dk/en/publications/microplastic-in-danish-wastewater-sources-occurrences-and-fate>) (accessed on September 13, 2023).
- [213] Wagg, C., Bender, S.F., Widmer, F., van der Heijden, M.G.A., 2014. Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proc Natl Acad Sci USA* 111, 5266–5270. <https://doi.org/10.1073/pnas.1320054111>.
- [214] Waggoner, D.C., Wozniak, A.S., Cory, R.M., Hatcher, P.G., 2017. The role of reactive oxygen species in the degradation of lignin derived dissolved organic matter. *Geochim Cosmochim Acta* 208, 171–184. <https://doi.org/10.1016/j.gca.2017.03.036>.
- [215] Wagner, S., Schlummer, M., 2020. Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures. *Resour Conserv Recycl* 158, 104800. <https://doi.org/10.1016/j.resconrec.2020.104800>.
- [216] Wang, C., Xian, Z., Jin, X., Liang, S., Chen, Z., Pan, B., et al., 2020. Photo-aging of polyvinyl chloride microplastic in the presence of natural organic acids. *Water Res* 183, 116082. <https://doi.org/10.1016/j.watres.2020.116082>.
- [217] Wang, F., Feng, X., Liu, Y., Adams, C.A., Sun, Y., Zhang, S., 2022. Micro(nano) plastics and terrestrial plants: Up-to-date knowledge on uptake, translocation, and phytotoxicity. *Resour Conserv Recycl* 185, 106503. <https://doi.org/10.1016/j.resconrec.2022.106503>.
- [218] Wang, F., Liu, W., 2023. Plant responses to emerging contaminants. *Plant Physiol Biochem* 201, 107873. <https://doi.org/10.1016/j.plaphy.2023.107873>.

- [219] Wang, F., Wang, Q., Adams, C.A., Sun, Y., Zhang, S., 2022. Effects of microplastics on soil properties: Current knowledge and future perspectives. *J Hazard Mater* 424, 127531. <https://doi.org/10.1016/j.jhazmat.2021.127531>.
- [220] Wang, F., Zhang, X., Zhang, S., Zhang, S., Sun, Y., 2020. Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. *Chemosphere* 254, 126791. <https://doi.org/10.1016/j.chemosphere.2020.126791>.
- [221] Wang, J., Guo, X., Xue, J., 2021. Biofilm-developed microplastics as vectors of pollutants in aquatic environments. *Environ Sci Technol* 55, 12780–12790. <https://doi.org/10.1021/acs.est.1c04466>.
- [222] Wang, L., Zhang, J., Huang, W., He, Y., 2023. Laboratory simulated aging methods, mechanisms and characteristic changes of microplastics: A review. *Chemosphere* 315, 137744. <https://doi.org/10.1016/j.chemosphere.2023.137744>.
- [223] Wang, Q., Adams, C.A., Wang, F., Sun, Y., Zhang, S., 2022. Interactions between microplastics and soil fauna: A critical review. *Crit Rev Environ Sci Technol* 52, 3211–3243. <https://doi.org/10.1080/10643389.2021.1915035>.
- [224] Wang, Q., Feng, X., Liu, Y., Li, W., Cui, W., Sun, Y., et al., 2023. Response of peanut plant and soil N-fixing bacterial communities to conventional and biodegradable microplastics. *J Hazard Mater* 459, 132142. <https://doi.org/10.1016/j.jhazmat.2023.132142>.
- [225] Wang, Q., Meng, L., Liu, W., Zeb, A., Shi, R., Lian, Y., et al., 2023. Single and combined effects of polystyrene nanoplastics and Cd on submerged plants *Ceratophyllum demersum* L. *Sci Total Environ* 872, 162291. <https://doi.org/10.1016/j.scitotenv.2023.162291>.
- [226] Wang, T., Wang, L., Chen, Q., Kalogerakis, N., Ji, R., Ma, Y., 2020. Interactions between microplastics and organic pollutants: Effects on toxicity, bioaccumulation, degradation, and transport. *Sci Total Environ* 748, 142427. <https://doi.org/10.1016/j.scitotenv.2020.142427>.
- [227] Wang, W.-M., Chen, C.-Y., Lu, T.-H., Liao, C.-M., 2022. Soil-dwelling species-based biomarker as a sensitivity-risk measure of terrestrial ecosystems response to microplastics: A dose–response modeling approach. *Sci Total Environ* 833, 155178. <https://doi.org/10.1016/j.scitotenv.2022.155178>.
- [228] Wang, Y., Wang, X., Li, Y., Li, J., Liu, Y., Xia, S., et al., 2021. Effects of exposure of polyethylene microplastics to air, water and soil on their adsorption behaviors for copper and tetracycline. *Chem Eng J* 404, 126412. <https://doi.org/10.1016/j.cej.2020.126412>.
- [229] Wang, Y., Xiang, L., Wang, F., Redmile-Gordon, M., Bian, Y., Wang, Z., et al., 2023. Transcriptomic and metabolomic changes in lettuce triggered by microplastics-stress. *Environ Pollut* 320, 121081. <https://doi.org/10.1016/j.envpol.2023.121081>.
- [230] Watteau, F., Dignac, M.-F., Bouchard, A., Revallier, A., Houot, S., 2018. Microplastic Detection in Soil Amended With Municipal Solid Waste Composts as Revealed by Transmission Electronic Microscopy and Pyrolysis/GC/MS. *Front Sustain Food Syst* 2. <https://doi.org/10.3389/fsufs.2018.00081>.
- [231] Williams, T., Walsh, C., Murray, K., Subir, M., 2020. Interactions of emerging contaminants with model colloidal microplastics, C60 fullerene, and natural organic matter – effect of surface functional group and adsorbate properties. *Environ Sci: Process Impacts* 22, 1190–1200. <https://doi.org/10.1039/DOEM00026D>.
- [232] Wu, C., Song, X., Wang, D., Ma, Y., Ren, X., Hu, H., et al., 2023. Effects of long-term microplastic pollution on soil heavy metals and metal resistance genes: Distribution patterns and synergistic effects. *Ecotoxicol Environ Saf* 262, 115180. <https://doi.org/10.1016/j.ecoenv.2023.115180>.
- [233] Wu, N., Zhang, Y., Zhao, Z., He, J., Li, W., Li, J., et al., 2020. Colonization characteristics of bacterial communities on microplastics compared with ambient environments (water and sediment) in Haihe Estuary. *Sci Total Environ* 708, 134876. <https://doi.org/10.1016/j.scitotenv.2019.134876>.
- [234] Wu, X., Liu, P., Shi, H., Wang, H., Huang, H., Shi, Y., et al., 2021. Photo aging and fragmentation of polypropylene food packaging materials in artificial seawater. *Water Res* 188, 116456. <https://doi.org/10.1016/j.watres.2020.116456>.
- [235] Wu, X., Liu, P., Zhao, X., Wang, J., Teng, M., Gao, S., 2022. Critical effect of biodegradation on long-term microplastic weathering in sediment environments: A systematic review. *J Hazard Mater* 437, 129287. <https://doi.org/10.1016/j.jhazmat.2022.129287>.
- [236] Wu, X., Liu, Y., Yin, S., Xiao, K., Xiong, Q., Bian, S., et al., 2020. Metabolomics revealing the response of rice (*Oryza sativa* L.) exposed to polystyrene microplastics. *Environ Pollut* 266, 115159. <https://doi.org/10.1016/j.envpol.2020.115159>.
- [237] Xiang, Y., Jiang, L., Zhou, Y., Luo, Z., Zhi, D., Yang, J., et al., 2022. Microplastics and environmental pollutants: Key interaction and toxicology in aquatic and soil environments. *J Hazard Mater* 422, 126843. <https://doi.org/10.1016/j.jhazmat.2021.126843>.
- [238] Xiao, M., Ding, J.N., Luo, Y., Zhang, H., Yu, Y., Yao, H., et al., 2022. Microplastics shape microbial communities affecting soil organic matter decomposition in paddy soil. *J Hazard Mater* 431, 128589. <https://doi.org/10.1016/j.jhazmat.2022.128589>.
- [239] Xu, B., Liu, F., Cryder, Z., Huang, D., Lu, Z., He, Y., et al., 2020. Microplastics in the soil environment: Occurrence, risks, interactions and fate – A review. *Crit Rev Environ Sci Technol* 50, 2175–2222. <https://doi.org/10.1080/10643389.2019.1694822>.
- [240] Xu, Y., Chan, F.K.S., He, J., Johnson, M., Gibbins, C., Kay, P., et al., 2021. A critical review of microplastic pollution in urban freshwater environments and legislative progress in China: Recommendations and insights. *Crit Rev Environ Sci Technol* 51, 2637–2680. <https://doi.org/10.1080/10643389.2020.1801308>.
- [241] Xu, Z., Qian, X., Wang, C., Zhang, C., Tang, T., Zhao, X., et al., 2020. Environmentally relevant concentrations of microplastic exhibits negligible impacts on thiacloprid dissipation and enzyme activity in soil. *Environ Res* 189, 109892. <https://doi.org/10.1016/j.envres.2020.109892>.
- [242] Xu, Z., Zhang, Y., Lin, L., Wang, L., Sun, W., Liu, C., et al., 2022. Toxic effects of microplastics in plants depend more by their surface functional groups than just accumulation contents. *Sci Total Environ* 833, 155097. <https://doi.org/10.1016/j.scitotenv.2022.155097>.
- [243] Ya, H., Jiang, B., Xing, Y., Zhang, T., Lv, M., Wang, X., 2021. Recent advances on ecological effects of microplastics on soil environment. *Sci Total Environ* 798, 149338. <https://doi.org/10.1016/j.scitotenv.2021.149338>.
- [244] Ya, H., Xing, Y., Zhang, T., Lv, M., Jiang, B., 2022. LDPE microplastics affect soil microbial community and form a unique plastisphere on microplastics. *Appl Soil Ecol* 180, 104623. <https://doi.org/10.1016/j.apsoil.2022.104623>.
- [245] Yan, F., Zhang, J., Li, W., Ding, Y., Zhong, Q., Xu, X., et al., 2021. Exogenous melatonin alleviates salt stress by improving leaf photosynthesis in rice seedlings. *Plant Physiol Biochem* 163, 367–375. <https://doi.org/10.1016/j.plaphy.2021.03.058>.
- [246] Yang, C., Gao, X., 2022. Impact of microplastics from polyethylene and biodegradable mulch films on rice (*Oryza sativa* L.). *Sci Total Environ* 828, 154579. <https://doi.org/10.1016/j.scitotenv.2022.154579>.
- [247] Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., et al., 2016. A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science* 351, 1196–1199. <https://doi.org/10.1126/science.1246359>.
- [248] You, X., Cao, X., Zhang, X., Guo, J., Sun, W., 2021. Unraveling individual and combined toxicity of nano/microplastics and ciprofloxacin to *Synechocystis* sp. at the cellular and molecular levels. *Environ Int* 157, 106842. <https://doi.org/10.1016/j.envint.2021.106842>.
- [249] Yu, F., Yang, C., Huang, G., Zhou, T., Zhao, Y., Ma, J., 2020. Interfacial interaction between diverse microplastics and tetracycline by adsorption in an aqueous solution. *Sci Total Environ* 721, 137729. <https://doi.org/10.1016/j.scitotenv.2020.137729>.
- [250] Yu, F., Yang, C., Zhu, Z., Bai, X., Ma, J., 2019. Adsorption behavior of organic pollutants and metals on micro/nanoplastics in the aquatic environment. *Sci Total Environ* 694, 133643. <https://doi.org/10.1016/j.scitotenv.2019.133643>.
- [251] Yu, H., Zhang, X., Hu, J., Peng, J., Qu, J., 2020. Ecotoxicity of polystyrene microplastics to submerged carnivorous *Utricularia vulgaris* plants in freshwater ecosystems. *Environ Pollut* 265, 114830. <https://doi.org/10.1016/j.envpol.2020.114830>.
- [252] Yu, H., Zhang, Z., Zhang, Y., Fan, P., Xi, B., Tan, W., 2021. Metal type and aggregate microenvironment govern the response sequence of speciation transformation of different heavy metals to microplastics in soil. *Sci Total Environ* 752, 141956. <https://doi.org/10.1016/j.scitotenv.2020.141956>.
- [253] Yu, H., Zhang, Z., Zhang, Y., Song, Q., Fan, P., Xi, B., et al., 2021. Effects of microplastics on soil organic carbon and greenhouse gas emissions in the context of straw incorporation: A comparison with different types of soil. *Environ Pollut* 288, 117733. <https://doi.org/10.1016/j.envpol.2021.117733>.
- [254] Yuanqiao, L., Caixia, Z., Changrong, Y., Lili, M., Qi, L., Zhen, L., et al., 2020. Effects of agricultural plastic film residues on transportation and distribution of water and nitrate in soil. *Chemosphere* 242, 125131. <https://doi.org/10.1016/j.chemosphere.2019.125131>.
- [255] Zang, H., Zhou, J., Marshall, M.R., Chadwick, D.R., Wen, Y., Jones, D.L., 2020. Microplastics in the agroecosystem: Are they an emerging threat to the plant-soil system? *Soil Biol Biochem* 148, 107926. <https://doi.org/10.1016/j.soilbio.2020.107926>.
- [256] Zantis, L.J., Rombach, A., Adamczyk, S., Velmalá, S.M., Adamczyk, B., Vijver, M. G., et al., 2023. Species-dependent responses of crop plants to polystyrene microplastics. *Environ Pollut* 122243. <https://doi.org/10.1016/j.envpol.2023.122243>.
- [257] Zeb, A., Liu, W., Meng, L., Lian, J., Wang, Q., Lian, Y., et al., 2022. Effects of polyester microfibers (PMFs) and cadmium on lettuce (*Lactuca sativa*) and the rhizospheric microbial communities: A study involving physio-biochemical properties and metabolomic profiles. *J Hazard Mater* 424, 127405. <https://doi.org/10.1016/j.jhazmat.2021.127405>.
- [258] Zeb, A., Liu, W., Shi, R., Lian, Y., Wang, Q., Tang, J., et al., 2022. Evaluating the knowledge structure of micro- and nanoplastics in terrestrial environment through scientometric assessment. *Appl Soil Ecol* 177, 104507. <https://doi.org/10.1016/j.apsoil.2022.104507>.
- [259] 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. <https://doi.org/10.1021/es401288x>.
- [260] Zhang, G.S., Liu, Y.F., 2018. The distribution of microplastics in soil aggregate fractions in southwestern China. *Sci Total Environ* 642, 12–20. <https://doi.org/10.1016/j.scitotenv.2018.06.004>.
- [261] Zhang, G.S., Zhang, F.X., 2020. Variations in aggregate-associated organic carbon and polyester microfibers resulting from polyester microfibers addition in a clayey soil. *Environ Pollut* 258, 113716. <https://doi.org/10.1016/j.envpol.2019.113716>.
- [262] Zhang, G.S., Zhang, F.X., Li, X.T., 2019. Effects of polyester microfibers on soil physical properties: Perception from a field and a pot experiment. *Sci Total Environ* 670, 1–7. <https://doi.org/10.1016/j.scitotenv.2019.03.149>.
- [263] Zhang, H., Liang, J., Luo, Y., Tang, N., Li, X., Zhu, Z., et al., 2022. Comparative effects of polystyrene nanoplastics with different surface charge on seedling establishment of Chinese cabbage (*Brassica rapa* L.). *Chemosphere* 292, 133403. <https://doi.org/10.1016/j.chemosphere.2021.133403>.

- [264] Zhang, J., Chen, H., He, H., Cheng, X., Ma, T., Hu, J., et al., 2020. Adsorption behavior and mechanism of 9-Nitroanthracene on typical microplastics in aqueous solutions. *Chemosphere* 245, 125628. <https://doi.org/10.1016/j.chemosphere.2019.125628>.
- [265] Zhang, K., Hamidian, A.H., Tubić, A., Zhang, Y., Fang, J.K.H., Wu, C., et al., 2021. Understanding plastic degradation and microplastic formation in the environment: A review. *Environ Pollut* 274, 116554. <https://doi.org/10.1016/j.envpol.2021.116554>.
- [266] Zhang, M., Zhao, Y., Qin, X., Jia, W., Chai, L., Huang, M., et al., 2019. Microplastics from mulching film is a distinct habitat for bacteria in farmland soil. *Sci Total Environ* 688, 470–478. <https://doi.org/10.1016/j.scitotenv.2019.06.108>.
- [267] Zhang, P., Yuan, Y., Zhang, J., Wen, T., Wang, H., Qu, C., et al., 2023. Specific response of soil properties to microplastics pollution: A review. *Environ Res* 232, 116427. <https://doi.org/10.1016/j.envres.2023.116427>.
- [268] Zhang, S., Han, B., Sun, Y., Wang, F., 2020. Microplastics influence the adsorption and desorption characteristics of Cd in an agricultural soil. *J Hazard Mater* 388, 121775. <https://doi.org/10.1016/j.jhazmat.2019.121775>.
- [269] Zhang, S., Pei, L., Zhao, Y., Shan, J., Zheng, X., Xu, G., et al., 2023. Effects of microplastics and nitrogen deposition on soil multifunctionality, particularly C and N cycling. *J Hazard Mater* 451, 131152. <https://doi.org/10.1016/j.jhazmat.2023.131152>.
- [270] Zhang, S., Ren, S., Pei, L., Sun, Y., Wang, F., 2022. Ecotoxicological effects of polyethylene microplastics and ZnO nanoparticles on earthworm *Eisenia fetida*. *Appl Soil Ecol* 176, 104469. <https://doi.org/10.1016/j.apsoil.2022.104469>.
- [271] Zhao, S., Zhang, Z., Chen, L., Cui, Q., Cui, Y., Song, D., et al., 2022. Review on migration, transformation and ecological impacts of microplastics in soil. *Appl Soil Ecol* 176, 104486. <https://doi.org/10.1016/j.apsoil.2022.104486>.
- [272] Zheng, W., Morris, E.K., Lehmann, A., Rillig, M.C., 2016. Interplay of soil water repellency, soil aggregation and organic carbon. A meta-analysis. *Geoderma* 283, 39–47. <https://doi.org/10.1016/j.geoderma.2016.07.025>.
- [273] Zhou, C.-Q., Lu, C.-H., Mai, L., Bao, L.-J., Liu, L.-Y., Zeng, E.Y., 2021. Response of rice (*Oryza sativa* L.) roots to nanoplastic treatment at seedling stage. *J Hazard Mater* 401, 123412. <https://doi.org/10.1016/j.jhazmat.2020.123412>.
- [274] Zhou, Q., Zhang, H., Fu, C., Zhou, Y., Dai, Z., Li, Y., et al., 2018. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. *Geoderma* 322, 201–208. <https://doi.org/10.1016/j.geoderma.2018.02.015>.
- [275] Zhou, Y., He, G., Jiang, X., Yao, L., Ouyang, L., Liu, X., et al., 2021. Microplastic contamination is ubiquitous in riparian soils and strongly related to elevation, precipitation and population density. *J Hazard Mater* 411, 125178. <https://doi.org/10.1016/j.jhazmat.2021.125178>.
- [276] Zhou, Y., Liu, X., Wang, J., 2019. Characterization of microplastics and the association of heavy metals with microplastics in suburban soil of central China. *Sci Total Environ* 694, 133798. <https://doi.org/10.1016/j.scitotenv.2019.133798>.
- [277] Zhou, Y., Wang, J., Zou, M., Jia, Z., Zhou, S., Li, Y., 2020. Microplastics in soils: A review of methods, occurrence, fate, transport, ecological and environmental risks. *Sci Total Environ* 748, 141368. <https://doi.org/10.1016/j.scitotenv.2020.141368>.
- [278] Zhu, B.-K., Fang, Y.-M., Zhu, D., Christie, P., Ke, X., Zhu, Y.-G., 2018. Exposure to nanoplastics disturbs the gut microbiome in the soil oligochaete *Enchytraeus crypticus*. *Environ Pollut* 239, 408–415. <https://doi.org/10.1016/j.envpol.2018.04.017>.
- [279] Zhu, K., Jia, H., Sun, Y., Dai, Y., Zhang, C., Guo, X., et al., 2020. Long-term phototransformation of microplastics under simulated sunlight irradiation in aquatic environments: Roles of reactive oxygen species. *Water Res* 173, 115564. <https://doi.org/10.1016/j.watres.2020.115564>.
- [280] Zong, X., Zhang, J., Zhu, J., Zhang, L., Jiang, L., Yin, Y., et al., 2021. Effects of polystyrene microplastic on uptake and toxicity of copper and cadmium in hydroponic wheat seedlings (*Triticum aestivum* L.). *Ecotoxicol Environ Saf* 217, 112217. <https://doi.org/10.1016/j.ecoenv.2021.112217>.
- [281] Zurier, H.S., Goddard, J.M., 2021. Biodegradation of microplastics in food and agriculture. *Curr Opin Food* 37, 37–44. <https://doi.org/10.1016/j.cofs.2020.09.001>.