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Review

Microplastic Pollution in Terrestrial Ecosystems and Its Interaction with Other Soil Pollutants: A Potential Threat to Soil Ecosystem Sustainability

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Abstract: The production and disposal of plastics have become significant concerns for the sustainability of the planet. During the past 75 years, around 80% of plastic waste has either ended up in landfills or been released into the environment. Plastic debris released into the environment breaks down into smaller particles through fragmentation, weathering, and other disintegration processes, generating microplastics (plastic particles $\leq$ 5 mm in size). Although marine and aquatic ecosystems have been the primary focus of microplastic pollution research, a growing body of evidence suggests that terrestrial ecosystems are equally at risk. Microplastic contamination has been reported in various terrestrial environments from several sources such as plastics mulch, pharmaceuticals and cosmetics, tire abrasions (tire wear particles), textiles industries (microfibers), sewage sludge, and plastic dumping. Recent studies suggest that the soil has become a significant sink for pollutants released into terrestrial ecosystems and is often contaminated with a mixture of organic and inorganic pollutants. This has gradually caused adverse impacts on soil health and fertility by affecting soil pH, porosity, water-holding capacity, and soil microbial enzymatic activities. Microplastics can interact with the co-existing pollutants of the environments by adsorbing the contaminants onto their surfaces through various intermolecular forces, including electrostatic, hydrophobic, non-covalent, partition effects, van der Waals forces, and microporous filling mechanisms. This subsequently delays the degradation process of existing contaminants, thereby affecting the soil and various ecological activities of the ecosystem. Thus, the present article aims to elucidate the deleterious impact of microplastics and their interactions with other pollutants in the terrestrial ecosystem. This review also addresses the impact of microplastics in disrupting the soil sustainability of the planet.

Keywords: microplastics; soil sustainability; terrestrial ecosystems; co-contamination; heavy metals; pesticides

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1. Introduction

Soil is an essential component of the planet Earth, as it provides a plethora of services for the functioning of the ecosystem. However, it has been reported that approximately 25% and 44% of the world's soils are greatly and mildly affected, respectively, mostly due to pesticides, persistent organic pollutants, metals, and metalloids. Additionally, the new emerging pollutants that cause severe environmental threats to the soil system, caused by the mass manufacture of synthetic organic polymers and plastics, have shown prominent growth over the last decade [1,2]. Therefore, there is a need to study the interactions of pollutants with each other to mitigate pollution and maintain soil sustainability [1,2]. The pollutants impact soil homeostasis by altering the soil's properties, such as moisture content, water holding capacity, soil texture, pH, and porosity, thereby affecting everything dependent on them [3]. The predominant conventional types of plastics present in the terrestrial ecosystem include Polypropylene, Polyethylene, Polystyrene, Polyvinylchloride, and Polyethylene terephthalate [4,5]. In recent years, promising alternatives to non-degradable conventional plastics, such as Polyhydroxyalkanoates, Polylactic acid, Polybutylene adipate terephthalate, and Polyhydroxybutyrate termed biodegradable plastics (Bioplastics), have been introduced [6]. Although the recycling rate of plastic products is escalating, a maximum number of plastics are still being liberated into the environment [7,8]. For instance, millions of tons of plastic are generated every year to facilitate many aspects of mankind [9]. According to EPRO, the global manufacturing of plastics in 2016 was 335 million tons, with an average annual increment of 8.6% since the 1950s [8,9]. Consequently, the past trends of plastic overproduction, dumping patterns, low renewal rates, and demographic records all promoted the accumulation of plastic debris in the environment [10]. Over decades, plastics became a potential emerging pollutant and a serious environmental threat [11]. The degradation process of plastic wastes triggers drastic environmental issues as surface brittle plastics are microcracked by microbes or by weathering mechanisms including light and hydrolysis and are progressively broken down into fine fragments known as Microplastics (MPs) [12]. Microplastics are fine particles of plastics ranging from 5 mm–1 mm [11]. Due to their low density, smaller size, and resistance to environmental biodegradation, these MPs easily disintegrate in water, soil, and air currents (Figure 1) [13,14]. Once in the soil, MPs can persist for decades or even centuries, slowly breaking down into smaller particles known as nano-plastics. Microplastic pollution in the soil ecosystem can have a range of adverse impacts on soil health and ecosystem functioning. In addition to their impact on the physical and chemical properties of soil, MPs can also have detrimental impacts on soil-dwelling organisms such as plants, invertebrates, and microorganisms [10,15,16]. For example, MPs can impact the germination and growth of plants, and alter the physiology and metabolism of soil microbes [15,16].

Microplastics can also act as a carrier for existing contaminants in the environment, such as heavy metals, agrochemicals, organic pollutants, and atmospheric deposition. The contaminants that accumulate in organisms ingest the MPs, potentially harming both wildlife and human health (Figure 1) [3,17,18]. The existing contaminants adsorb onto the surface of the MPs and interrupt the degradation process [15,16]. Despite this, plastic fragments are ubiquitous and have a variety of applications in everyday life, including the textiles industry [19], cosmetic products, pharmaceutical preparations, car manufacturing, etc. [18]. The burgeoning production and overutilization of these plastics and their disintegration generates MPs which are reluctant to degrade and difficult to eradicate, thus disrupting the ecosystem [18]. Microplastics are the complex mixture of various micropollutants, such as conventional microplastics, biodegradable microplastics, microfibers (clothing fabric), and tire wear particles (tire abrasions), consequently making microplastics eccentric among the other pollutants present in the environment [5,6,18,19]. Therefore, there is an extensive need to develop strategies to mitigate these risks and maintain healthy soil ecosystems by disposing of plastic products, reducing their use, and preventing microplastic pollution. The present review discusses the prevailing literature and is thoroughly synthesized to understand the interactions of microplastics with existing contaminants and their effects on soil sustainability.

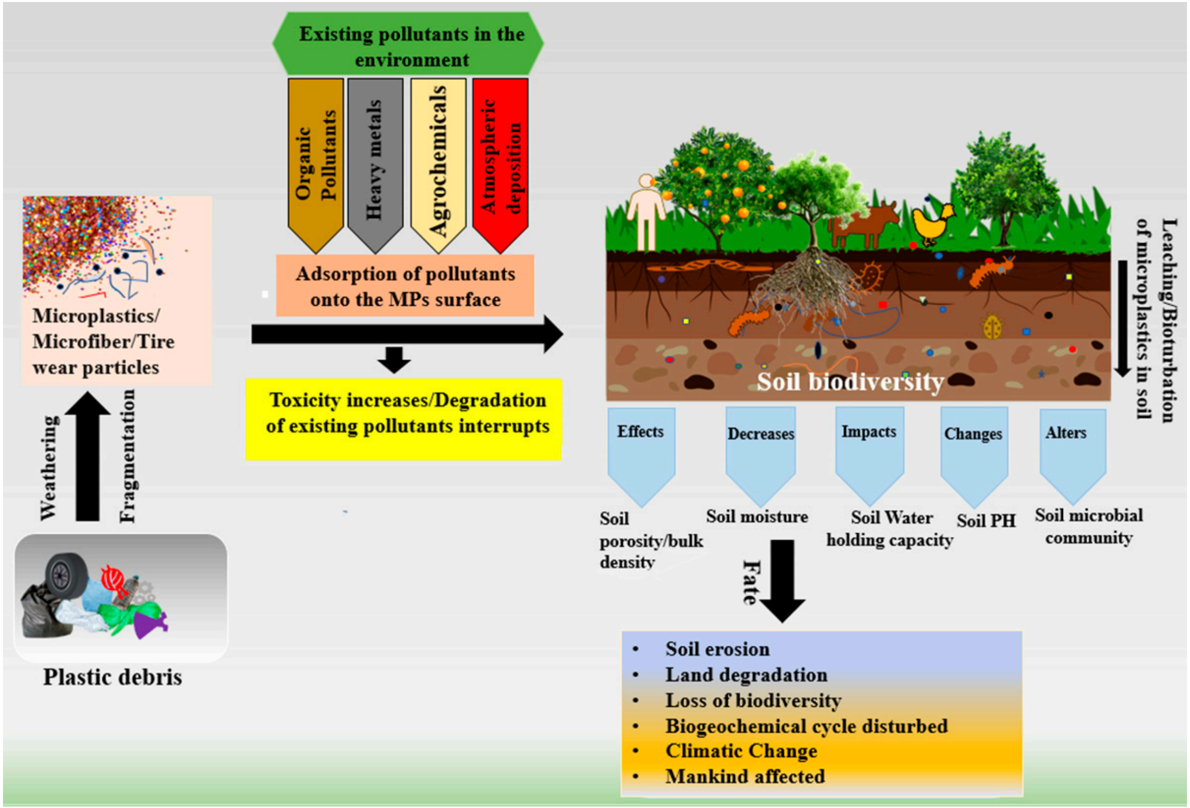

Figure 1. The fate and interactions of microplastics with existing co-contaminants in the soil and impacts on other ecological activities.

2. Potential Sources of Microplastic Pollution in Soil

Microplastics are the most versatile, inexpensive, and non-biodegradable materials widely used in daily life. Regardless of their enormous applications, MPs have developed into a critical ecological issue. According to a study, MPs are broadly categorized into primary and secondary MPs [10]. The primary MPs are deliberately produced for certain utilization such as plastic mulch, drug vectors, cosmetics, industrial (textiles, wastewater treatment), and engineering products manufacturing (Figure 2) [12]. These types of MPs are generally challenging to mitigate through sewage disposal technologies, and after invading sewage water they ultimately bioaccumulate in the environment [10]. Furthermore, secondary MPs are generated from the fragmentation of larger plastic debris in complex environmental conditions, such as temperature, wind, waves, and exposure to UV light [20]. The plastic debris in soils can also be fragmentized into MPs by biological processes through soil fauna, including feeding habits as well as digestion and excretion processes (Figure 1) [16]. Its sources are relatively associated with anthropoid utilization, such as mulching, cosmetics, washing and care, textile industries (microfiber) [19], car manufacturing (tire abrasions/tire wear particles) [21], and plastic commodities, containing all attributes of agriculture, industry, and manufacturing (Figure 2) [22]. Therefore, the inevitable occurrence of MPs in the biome and everyday products make the exposure of mankind to MPs certain [14]. It has been reported that major sources of MPs in soil ecosystems are sewage sludge, mulching plastic films, inappropriate dumping of plastic waste, agricultural amendments, etc. which pose a severe environmental threat to the different ecosystems of the earth [10,22]. Soil has become the reservoir of various micropollutants released from several potential sources (Figure 2) over decades of applications, harming the soil and the environment [20].

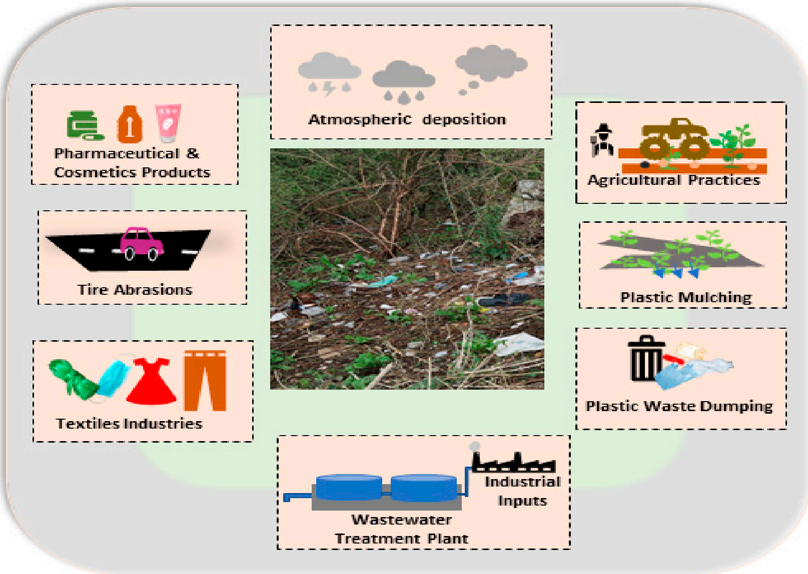

Figure 2. Potential sources of microplastics in soil: agricultural practices, plastic dumping, mulching plastic films, sludge waste, pharmaceuticals, cosmetic products, textile industries (microfiber), tire abrasions (tire wear particles), etc.

2.1. Microplastics as a Driver of Land Pollution

Unauthorized dumping of plastic waste and inefficient waste management are critical reasons for land pollution [18]. The existing literature shows that soil is a bigger reservoir of MPs (plastics) than oceanic basins since most plastic debris is generated and dumped on land [7]. Thus, it is estimated that MP contamination could be 4–23 times more on land than in the oceans [23]. Austen et al. [13] reported that the concentration of MPs reached the maximum in soil near agricultural environments and roads. The estimated concentration of MPs may vary; up to 7% of plastic particles by mass are reported to be present in the topsoil of industries, though levels are often much lower in non-industrialized areas [13]. Microplastics act as a vector for land pollution due to their inevitable and ubiquitous occurrence in the environment. There, sources are reported to be sludge application, plastic mulch, tire abrasions [21], litter run-off from roads and textiles industries [19], and atmospheric depositions [13]. The dispersion of MPs in the environment might influence their interaction with several plant, animal, and microbial species, as depicted in Figure 1, and alter the behavior of MPs in soil [24]. Microplastics integrate into the soil aggregates through soil cracking, agronomic practices, plant root elongations, and soil burrowing animals, providing transportation of MPs vertically in the soil [7,16]. For instance, a study reported that some soil fauna, such as *Lumbricus terrestis* L. (earthworm), are likely to produce biopores through which MPs can easily leach deep into the soil and serve as the medium for passage of various organic contaminants that are adsorbed on the MPs surface [16]. The intrusion of MPs onto soil intended for deposition, translocation, erosion, deterioration, and percolation to groundwater subsequently threatens micro-organisms and eventually affects all living organisms through indirect utilization [25]. Recent studies have also suggested that tire wear particles (tire abrasions) and microfiber (textiles) are the major emerging microplastic pollution on land, and these MPs gradually runoff from land into the oceans [19,21]. Overall, a thorough study is required to understand the impacts of various MPs on land degradation, though they have the potential to contribute to soil deterioration and impact flora and fauna diversity [10,26]. Therefore, the over-utilization of MPs is considered a prolonged anthropogenic strain and a driver of the global shift in the terrestrial ecosystem [27].

2.2. Impacts of Microplastics on Physiochemical Properties of Soil

There is a wide occurrence of MP pollution in global soil resources [28]. The abundance, composition, shape, and size of MPs may vary significantly in soil, and their different potential sources are one plausible explanation for this [28]. For example, Qi et al. [29] reported that 5 mm low-density polyethylene (plastic mulch film) noticeably affected the physiochemical and hydrological parameters of tested soil. Further, Machado et al. [30] investigated the impact of polyester fibers (5000 µm, 8 µm) on soil parameters such as water holding capacity and showed that MPs decreased bulk density and affected the soil structure. Microplastics adversely impact the soil's biophysical environment through changes in soil pH, bulk density, water holding capacity, porosity, soil aggregations, and hydraulic conductivity [29,30]. Additionally, the change in soil porosity due to MPs can impact the dissipation of volatile soil pollutants and the agglomeration property of MPs can also impact the vertical distribution of pollutants in the soil column [10]. Consequently, soil fertility and health are gradually affected, disturbing the ecological activities associated with them. Eventually, all these changes impact soil sustainability and the environment [29]. The data from previous literature reported that MPs can alter the chemical and physical properties of soil in most cases, but their impacts vary from positive to negative, and depend on the type, shape, dose, and size of the MPs [29].

2.3. Microplastic Effects on Soil Microbial Community

Soil microbes comprise a significant reservoir of living biomass in soil, where they modulate biogeochemical cycles and organic matter decomposition and sustain the earth's ecological balance [31,32]. Preliminary studies have revealed that the presence of MPs in the soil affects bacterial and fungal diversity, besides the reduction of soil enzymatic activities involved in nutrient cycling [10,26,27]. Changes in nutrient cycling-associated microbial enzymes, including β-glucosidase, phosphatase, and urease, can subsequently distress the uptake of substances by plant roots [33,34]. For example, the significant impacts of MPs have been reported on studied soil flora and fauna, including *Eisenia fetida*, *Folsomia candida*, *Lumbricus terrestris*, *Triticum aestivum*, and *Allium fistulosum*, thereby altering the soil diversity (Table 1). Microplastics can also directly impact the physiology and metabolism of soil microorganisms by causing oxidative stress and DNA damage in bacteria, which results in cell death and influences microbial activity [27,33]. These alterations also deliver feedback to the microbial environment and affect rhizospheres such as rhizobia and mycorrhiza fungi [26,27,35,36]. For example, Machado et al. [27] reported that the presence of polyamide microplastic beads affected the length and biomass of the plant root, plausibly due to the nitrogen addition and alterations in morpho-physiological traits of roots, and these changes could affect the soil microbial activity related to rhizodeposition. Consequently, soil microbes may directly retort to shifts in soil compositions and structures through inconsistent utilization of nitrogen or organic substrates as an ultimate e- acceptor (organic substrates) [27]. Eventually, changes in microbial activity probably result in a shifting of microorganism composition, which may influence the subset of soil microbes that precisely interact with plant roots [27].

Additionally, Machado et al. [27] reported that the alteration in soil aggregates by MPs can impact pore size and connectivity, thus simultaneously affecting the water holding capacity and permeability of the soil, which can cause a cascade of occurrences that change the biophysical and chemical environment of the soil. In the aging process MPs could absorb, transfer, and desorb other contaminants (ex. pesticides, herbicides, polychlorinated biphenyl, and heavy metals), and all indirectly impact the chemical environment of the soil [10,37]. The exchange of ions in the aging process causes a potential impact on variations in soil pH, water, and nutrient retention [26,27,37,38]. Consequently, the soil microbial community is threatened by changes in soil nutrients, toxins release, and soil pH alteration after interruption by MPs [38]. Rillig et al. [16] reported that soil fauna (earthworms) gulp MPs and co-pollutants sorbed onto the MPs surface and change the microbial gut and associated soil microbial communities in the soil biota [16,34]. In general, MPs have been shown to impact the biophysical and chemical properties of soil, microbial and enzymatic activities, and plant growth, and also cause unfavorable ecotoxicological impacts on soil plant species [15,19]. For instance, a study conducted on wheat (*Triticum aestivum*) (Table 1) reported that MPs enter via roots and can move into the trophic food chain, eventually affecting the growth efficacy of wheat in the reproductive as well as in the vegetative stage [39]. On the contrary, pervasive research on *Allium fistulosum* (spring onion) by Machado et al. [27] reported that the types and size of MPs can also positively affect the plants' performance by increasing roots biomass. The impact of different types of MPs on several organisms and flora present in soil ecosystems that have already been tested in earlier studies showed potential impacts (Table 1). However, a further detailed investigation is required to perceive the fluctuating contamination of MPs on soil microbes and several plant species, which can increase our understanding of the ecotoxicity of this emerging threat.

Table 1. Microplastic effect on the soil ecosystem.

Microplastic Type	Size	Species	Effects	Country of Study	References
LDPE	<150 µm, <50 µm,	*Lumbricus terrestris*	*L. terrestris* propagates microplastics from the soil surface into their burrows.	Netherlands	[40]
LDPE	<5 mm, 5–150 mm	Earthworm, chicken (Manure)	Conc. of plastic increases from soil to *L. terrestris* casts and then Chicken feces.	Netherlands	[41]
PE	<50–100 µm, >100 µm	*Lumbricus terrestris*	Higher conc. of MPs may influence the rate of growth in *L. terrestris*.	Netherlands	[41]
PVC	250–80 µm	*Hypoaspis aculeifer*, *Folsomia candida*,	Trophic predator-prey relationships promote the passage of MPs by 40%.	China	[42]
PE, PS	<250 µm–<300 µm,	*Eisenia fetida*	Conc. of HOC (hydrophobic organic compound) in *E. fetida* was minimized in the presence of MPs by above 1%.	China	[37]
PE	2800–710 µm	*Lumbricus terrestris*	The presence of earthworms greatly maximizes the existence of microplastic particles at the bottom of the soil.	Berlin	[16]
PE	<500 µm	*Folsomia candida*	Inhibited breeding and lower bacterial diversity in the springtail gut.	China	[43]
PE	250–1000 µm	*Lumbricus terrestris*	No substantial conclusions were documented on the survival, number, and *L. terrestris* weight.	Spain	[44]
LDPE	0.25 µm, 1–5 mm	*Lumbricus terrestris*	Microplastics cannot be the carriers of organic pollutants to earthworms.	Spain	[44]
Urea-formaldehyde	200–400 µm	*Folsomia candida*, *Proisotoma minuta*	Movement and distribution of MPs by microarthropods.	Berlin	[45]
Polystyrene	0.1–0.05 µm	*Enchytraeus crypticus*	Reduction of biomass in the animals fed 10% PS and an increase in the breeding of those fed 0.025%.	China	[42]
PVC	80–250 µm	*Folsomia candida*	Alteration and inhibition of the microbiota in the gut of the collembolan.	China	[42]
LDPE	<150 µm	*Lumbricus terrestris*	Earthworm weight was adversely affected by the amalgamation of glyphosate and MPs	China	[46]
PA, PET, PEHD, PES, PS, PP	20–15 µm	Spring onions (*Allium istulosum*)	MPs can affect leaf attributes, roots of plants, and entire biomass.	Berlin	[27]
LDPE	1 mm–50 µm	*Wheat* (*Triticum aestivum*)	Remains of plastics affected the upper/lower parts of the wheat plant.	Netherlands	[39]

PEHD: Polyethylene High Density, PES: Polyether sulfone, PS: Polystyrene, PA: Polyamide, PET: Polyethylene terephthalate, LDPE: Low-density polyethylene, PVC: Polyvinylchloride, PP: Polypropylene.

2.4. Impact of Microplastics on Existing Soil Pollutants

MPs are a ubiquitous micropollutant and are difficult to eradicate from the environment. They intervene in the environment either directly or by fragmentation of plastic substances in the ecosystem [17,47]. Microplastics might have potential health consequences due to their larger surface area, which helps them to adsorb various metals such as Zinc (Zn), Aluminum (Al), Silver (Ag), Lead (Pb), and Copper (Cu), and hazardous pollutants such as Polychlorinated biphenyls (PCBs), Dichlorodiphenyltrichloroethane (DDT), Polycyclic aromatic hydrocarbons (PAHs), other organochlorines and insecticides etc. onto their surfaces [47]. Fu et al. [17] reported that organic pollutants (OPs) can be assimilated onto the surface of MPs through electrostatic, hydrophobic, non-covalent, partition effects, and multiple interactions. Perhaps the molecule size, polarity, ageing, functional group, crystallinity, and surface area of MPs impacts their potential to adsorb OPs (Table 2). Different types of contaminants might exert antagonistic or synergistic influence on another present in the natural ecosystem. The association of MPs with contaminants develops in an extremely multifaceted way with persistent changes in the environment [17]. Microplastics are highly hydrophobic (water resistant), therefore chemical contaminants can easily be adsorbed onto the surface of plastics, making them a reservoir of hazardous contaminants in the ecosystem [18,48].

MPs are hydrophobic polymers possessing a greater surface area, which makes them competent carriers. Pesticides significantly adsorb pesticides onto the surface of MPs and ultimately reach each trophic food chain of the ecosystem (Table 2) (Figure 1) [37,47,48]. Previous studies comprehensively provide significant inferences that the lethal chemicals present in the MPs can persistently migrate within the MPs surface and have the potential to disseminate in the soil [10]. Microplastics can serve as drivers of chemical pollutants, either used as additives during polymer manufacturing or directly assimilated from the environment [47]. Wang et al. [49] investigated the adsorption behavior of diflubenzuron, carbendazim, malathion, diptrex, and difenoconazole pesticides with polyethylene MPs, and showed that all pesticides adsorbed onto the MPs surfaces posed a potential risk to the ecosystem. This is due to the exclusive surface adsorption mechanism between pesticides and MPs, entirely regulated by intermolecular van der Waals forces and microporous filling mechanisms [50]. According to Mohana et al. [51], the adsorption and interaction mechanisms of MPs with various other existing pollutants are mostly unknown since the prevailing literature has focused on the existence of the MPs in the ecosystem [51]. However, it is crucial to study the fate and interactions of MPs with existing co-contaminants to ameliorate the impact on soil biodiversity [37]. Therefore, an imperative study is required to assess the combined interaction and impact of MPs with other pollutants present in the environment [49]. While recent studies have reported that MPs can affect the degradation process of pesticides in the aquatic ecosystem, there is still little relevant research on MPs in soil [47]. Table 2 shows a list of the combined effect of several types of MPs on existing soil pollutants.

Table 2. Impact of microplastics on existing pollutants in the soil.

Microplastic Types	Size	Soil Pollutants	Effects	Geographic Zones	References
LDPE	25–100 µm	Deltamethrin	More pesticides accumulated on the mulch films	Netherland (WUR)	[52]
PVC	NA	Heavy metal (As)	Lowers toxicity in the *Lumbricus terrestris*. L (earthworm)	China	[37]
Polyurethane foam	<75 µm	PBDE (POP)	Accumulation of worms 3740 mg/kg PBDE burdens	Virginia, US	[53]
HDPE	<5 mm	Heavy metal (Zn)	Bioavailability of zinc increases	United Kingdom	[54]
LDPE	<150 µm	Glyphosate	Combined negative effects on earthworm weight	China	[55]

Table 2. *Cont.*

Microplastic Types	Size	Soil Pollutants	Effects	Geographic Zones	References
LDPE	5 mm, 0.25–1 mm	Chlorpyrifos	The more chlorpyrifos transfer to the soil base	Spain	[56]
PE, PS	250 µm, 300 µm	PAHs, PCBs	After MPs invasion, the conc. of PAHs and PCBs in the tissue reduced	China	[37]
PS, PE, PP	100 –150 µm	Nitroanthracene (9-Nant): NPAH:9-	NA	China	[57]
PV, PS, PE	200 ± 10 µm	17β-estradiol (E2)	NA	China	[58]
PS, PP	spherical shape 3–5 mm: PP, cylindrical shape 3.5 mm length and 2.2 mm thickness: PS	Aromatics: benzene, toluene, ethyl benzene, and xylene; BTEX fuel ethers: Methyl tert-butyl ether: MTBE, tert-amyl ethyl ether: TAME	NA	Berlin	[59]
PS, PVC, PE	<75 µm	(DEP); Dibutyl phthalate (DBP), PAEs: Diethyl phthalate.	NA	Korea	[60]
HDPE, PS, PS-COOH	3–16 µm, 10 µm, 10 µm	PFAS	NA	Spain	[61]
PVC-S, PVC-L	<1 µm, 74 µm	Triclosan	NA	China	[62]
PVC, PE, PP	<0.15 mm	PHCs: 3,6-dibromocarbazole (3,6-BCZ); 3,6-dichlorocarbazole (3,6-CCZ); 2,7-dibromocarbazole (2,7-BCZ); 3-bromocarbazole (3-BCZ):3,6-diiodocarbazole (3,6-ICZ).	NA	China	[63]
PE, PS, PVC, PA	152.53 ± 57.92 µm, 57.64 ± 26.50 µm, 109.44 ± 44.53 µm, 168.55 ± 57.50 µm.	Chlorobenzene, Naphthalene n-Hexane, Toluene, Cyclohexane, Benzene,	NA	Austria	[64]
PE	0.85–0.71 mm	Difenoconazole, Imidacloprid, Buprofezin,	NA	China	[50]
PVC, PE	1–5, 0.425–1, 0.125–0.425, and 0.045–0.125 mm.	TCEP—Tris(2-chloroethyl) phosphate; TBP—Tri-n-butyl phosphate	NA	China	[65]
PE, PVC	<125 µm	Simazine	Induction of MPs decreases density and a shift in soil microbial communities.	China	[66]
PP powder	NA	Glyphosate	Respiration of soil and enzymatic actions related to P4, N2, and C cycles altered during the incubation.	China	[55]
LDPE and biodegradables	0.85–2.00 mm	Prothioconazole	Prothioconazole impacts the desorption/adsorption of heavy metals on both MPs.	China	[67]
PE fiber, PE beads, and tire fragments	<5 mm, 250–300 µm, <5 mm	2,4-D Atrazine DDT Glyphosate	The mixture of (pesticides + MPs) with sediments, changes the pesticide assimilation, neither in river water nor in deionized, in contrast with the sediments.	Canada	[68]
PE powder	40–48 µm,	Epoxiconazole Myclobutanil Tebuconazole Simazine Azoxystrobin Metolachlor Terbutylazine Atrazine	Floating of PE in water, its interaction with the sediment is inadequate and does not change the pesticide half-life that persists in the deposits.	China	[26]

Table 2. *Cont.*

Microplastic Types	Size	Soil Pollutants	Effects	Geographic Zones	References
LDPE	0.60–2850 cm^2	Chlorpyrifos Endosulfan Deltamethrin Procymidone Trifluralin	Applied pesticides on the mulches contacted the soil later 24 h. Migration of pesticides to the inside the plastic, more for thicker plastics, and then partially released in the soil and to the environment.	Argentina	[52]
PE	125–250 µm	Atrazine 2,4-DB	The MPs lowered the adsorption of herbicides due to the low mol. interaction with the PE (aliphatic). Likely condensed the mobility of components due to a decreased soil holding capacity.	Austria	[69]
PS-50, PVC-42000 and PVC-10	2–110 µm, 100–290 µm, 0.5–1.4 µm	Thiacloprid	Irrelevant effect of various microplastics compositions and size on the assimilation.	China	[33]
Pristine, PBAT, and aged PE (bio-MPs)	NA	Flumioxazin Imidacloprid	The deterioration of pesticides was enhanced with pristine MPs and overdue with aged, bio-MPs and above at greater MPs conc.	China	[70]
PE powder	180 and 120 µm: powder, 3000–2000 µm: pellets	o,p′-DDT, p,p′-DDT, p,p′-DDE, p,p′-DDD, β-HCH, γ-HCH, α-HCH, δ-HCH	MPs assimilate more pesticides. This MP could enhance the strength of non-polar pesticides in soil.	China	[71]

PBDE: Polybrominated diphenyl ethers, POPs: Persistent organic pollutants, PE: Polyethene, LDPE: Low-density polyethylene, HDPE: High-density polyethylene, PS: Polystyrene, PP: Polypropylene, PAHs: Polycyclic aromatic hydrocarbons, PCBs: Polychlorinated biphenyls, PFAS: Perfluoroalkyl substances, PBAT: Polybutylene adipate co-terephthalate, MPs: Microplastics, P4: Phosphorous, C: Carbon, N2: Nitrogen, As: Arsenic, Zn: Zinc, PHC: Polyhydrocarbons.

3. Microplastic Pollution as a Threat to Soil Ecosystem Sustainability and the UNSDGs

Microplastic pollution can have a significant impact on soil sustainability. One of the ways that MPs impact soil sustainability is through their ability to alter the soil's physical properties, such as reduced soil porosity, decreased water holding capacity, and increased soil compaction [26–28]. This can limit the movement of water, air, and nutrients in the soil and make it harder for plant roots to penetrate the soil and absorb nutrients, which can negatively affect plant growth and development. Changes in the soil's physical properties can negatively impact soil fertility and reduce the ability of plants to grow in the affected soil [23]. Another way that MPs can impact soil sustainability is through their potential to alter soil microbial communities. Microbes are essential for maintaining soil functions such as nutrient cycling, and any disturbance to these communities can have significant consequences on soil health. Recent research has shown that MPs can alter the abundance and diversity of soil microbial communities (Table 1). These changes can lead to a reduction in soil nutrient availability and negatively impact soil fertility [37]. Microplastics can inhibit the growth of beneficial microorganisms in the soil which are crucial for maintaining soil fertility. This can lead to reduced nutrient availability and lower crop yields. In addition to their impact on soil physical properties and microbial communities, microplastics can also pose a direct threat to soil organisms [35,37]. Several studies have shown that MPs can be ingested by soil organisms, such as earthworms, and cause physical damage or even the death of the organism [16,23]. This can have significant implications for soil biodiversity and ecosystem functioning. Further, as discussed in previous sections, MPs can also contribute to soil pollution. They can absorb and accumulate toxic pollutants such as heavy metals and pesticides, which can contaminate the soil and pose a risk to human health and the environment.

Following the inauguration of the United Nations Sustainable Development Goals (UNSDGs) in 2015, the goals were used widely by governments and organizations to develop sustainability. There are 17 SDGs containing 169 targets, which are assessable against 247 unique indicators [72]. While the extremely critical risks to our globe are addressed through 17 SDGs, only a definite indicator under Goal 14 is particularly concerned with mitigating plastics [72]. Therefore, the UNSDG report for 2022 estimated that about 17 million metrics of plastics invaded the oceans in 2021, and it assumes that the quantity will double/triple by 2040 [9]. The production of MPs on land is for anthropogenic utilization and will ultimately end up in the oceans. Therefore, the major sources of oceanic MPs pollution on land are the inefficient management of land-based pollution, such as plastic dumping, pharmaceuticals, and cosmetics, dumping of fabrics (microfibers) [19], tire wear particles [21], and all waste run-off into the sea. These land-based pollutants are the major cause of pollution in aquatic ecosystems as well [72]. Microplastics have emerged as a major environmental concern, particularly in terrestrial ecosystems, due to their potential negative impacts on biodiversity and human health [11,28]. Microplastics in soil can harm the soil microorganisms which play a critical role in maintaining soil fertility and supporting plant growth [27]. This can lead to reduced crop yields, ultimately impacting food security and contributing to hunger, thereby affecting the targets of Goal 2: Zero Hunger. Additionally, MPs in soil can also impact the quality and safety of food produced on it [9,72]. Consumption of contaminated food can lead to respiratory issues, cancer, and hormonal imbalances, which can undermine the overall objectives of Goal 3: Good Health and Well-being [9,72]. Moreover, MPs released in soil can cause point source contamination through runoff and leaching, polluting surface, and groundwater sources [29], thereby impacting water quality and availability and affecting the targets of Goal 6: Clean Water and Sanitation [9,72]. Furthermore, MPs in terrestrial ecosystems can have negative impacts on biodiversity, including insects, other animals, and soil microorganisms [28]. This can ultimately impact ecosystem health and resilience, contributing to the loss of biodiversity and undermining the sustainability of terrestrial ecosystems, affecting the targets of Goal 15: Life on Land [9,72]. Moreover, MPs in soil can end up in marine water bodies, significantly impacting marine ecosystems and the animals that inhabit them [19]. This can disturb the health and biodiversity of marine ecosystems, thereby affecting the targets of Goal 14: Life Below Water [9,72]. The production, consumption, and disposal of plastics contribute significantly to plastic pollution and the generation of MPs in terrestrial ecosystems [72]. Therefore, addressing plastic waste and reducing plastic consumption are essential to reducing microplastic pollution in terrestrial ecosystems and meeting the targets of Goal 12: Responsible Consumption and Production [9,72]. Additionally, the study inferred that greenhouse emissions from plastics globally will reach 1.34gigaton per year by 2030 [72]. Subsequently, unsustainable utilization of plastic debris for energy recovery has been extensively criticized for liberating GHG emissions, therefore utilizing plastic surplus for energy retrieval conflicts with SDG 7: Ensure access to affordable, reliable, sustainable, and modern energy for all [72]. The achievements of the SDGs and the well-being of anthropoids are under threat due to the unsustainable applications and overproduction of plastic that results in environmental pollution, loss of biodiversity, and climatic change [72]. Proper waste management practices can help reduce the amount of plastic that ends up in the environment, including soil. In summary, microplastic pollution in terrestrial ecosystems can have significant negative impacts on multiple UNSDGs, highlighting the urgent need to address this issue through sustainable consumption and production patterns, responsible waste management, and improved environmental policies and practices.

4. Way forward for Future Research

Limiting the expanding production and utilization of MPs could provide a better solution to several environmental threats caused by MPs. Globally, research on MPs is a persistently progressing field, and while researchers emphasize separation, identification, and quantification of MPs in soil, there are still some system-level research gaps that must be addressed [23,27]. There is a dearth of in-depth studies on the combined effect of different potential sources of MPs with existing co-contaminants in the soil ecosystem and how this can modify the properties and efficacies of MPs by altering their fate in the environment. Despite the rapid growth in MPs, prevailing scientific research might not have comprehensively related the combined interactions between MPs, co-pollutants, and the soil microbial community of the environment The rapid production, emission, and outflow of plastics into the ecosystem could lead to a further increase in the concentration of MPs in the near future [73]. If we proceed on the existing developmental pathways, the finite capacity of the earth will be incapable of sustaining the resources for immediate and upcoming generations. Hence, the participation of all citizens would be essential to enhance resource efficacies and develop a new economic circle by reducing waste and pollution from the ecosystem [9]. Additionally, further quantitative, and qualitative assessment might be required in the terrestrial environment to mitigate MP pollution and their impacts on shifting soil biodiversity. Mitigating soil pollution may also lead to a decrease in aquatic pollution.

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