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REVIEW ARTICLE

Current studies on the degradation of microplastics in the terrestrial and aquatic ecosystem

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Abstract
Soil and water are two important basic ecosystems for the survival of different organisms. The excessive microplastic pollutants in soil have been directly discharged into the terrestrial ecosystems. Microplastic pollutants (MPs) constitute a ubiquitous global menace due to their durability, flexibility, and tough nature. MPs posed threat to the sustainability of the ecosystem due to their small size and easy transportation via ecological series resulting in the accumulation of MPs in aquatic and terrestrial ecosystems. After being emitted into the terrestrial ecosystem, the MPs might be aged by oxidative degeneration (photo/thermal), reprecipitation (bioturbation), and hetero-accumulation. The mechanism of adsorption, degradation, and breakdown of MPs into unaffected plastic debris is accomplished by using several biological, physical, and chemical strategies. This review presents the importance of ecosystems, occurrence and sources of MPs, its toxicity, and the alteration in the ecology of the ecosystems. The inhibitory impact of MPs on the ecosystems also documents to unveil the ecological hazards of MPs. Further research is required to study the immobilization and recovery efficiency of MPs on a larger scale.

Keywords Microplastics · Pollutants · Adsorption · Ecosystems

Introduction

Microplastics (MPs) are solid, synthetic plastic particles that are insoluble in water. They are irregular in form and range in size from 1 µm to 5 mm (Frias and Nash 2019). Food and water have been shown to contain microplastics in the natural environment. Additionally, they are found in human faeces (Mintenig et al. 2019; Schwabl et al. 2019). Globally, the production of plastic was more than 426 MMT (million metric tons) including resins (359 MT), and synthetic fibers (67 MT), according to the PlasticsEurope and *The Fiber Year*, respectively. The production of plastic is likely to increase in the future to sustain the living standards of the world's population. Though, approx. 85% of these plastics products are not reprocessed and flow into the ecosystems. Small MPs (< 5 mm) have turned out to be an immense problem illustrating universal alarm as they adsorb contaminants or other organic substances on their surface. MPs could also be consumed and amassed in the food chain by biota resulting in direct exposure of MPs-contaminated ecosystems to humans and threatening worldwide biodiversity.

Terrestrial soil serves as a significant microplastics reservoir (Rillig 2020). After being introduced into the

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soil, microplastics have the potential to remain there and accumulate, ultimately having an impact on the development, reproduction, and overall biodiversity of soil organisms (Chae and An 2018; de Souza Machado et al. 2018a). The MPs caused a deleterious impact on the terrestrial ecosystem at a physical, cellular, and molecular level. MPs affected the soil aeration and porosity, alter microbial populations, and may result in reduced soil fertility, which can affect agricultural seed germination and seedling growth. Soil acts as a sink for MPs and also enables its transport from one site to groundwater systems through numerous methods such as agricultural practices, soil erosion, surface runoff, and waterlogging further disturbing the groundwater levels and complete aquatic system (Nizzetto et al. 2016a; Rillig et al. 2017a; He et al. 2018a; Wong et al. 2020; Yao et al. 2020). The variation in the MP characteristics in terms of shape, size, type, charge, specificity, density, surface chemistry, and many other environmental attributes have been notified to directly impact their transport as well as the distribution within soils (Zhang et al. 2019). Moreover, the horizontal transfer of microplastics within the soil is impacted by various soil activities, microbiota, and soil physicochemical properties such as soil aggregates and soil pores (Rillig et al. 2017b; Chae and An 2018). Wu et al. (2020) depicted the behavioral transport of polystyrene microspheres in three categories of soils and observed that MPs declined with the presence of higher soil minerals such as Fe/Al oxides. This is mainly attributed to electrostatic interactions among negatively charged MPs and positively charged oxides present in the soil. The hetero-aggregates formed with soil mineral particles and organic matter also induce the transport of MPs.

In aquatic ecosystems, microplastics are reported to be present as suspended sediments in the water column, in sediments, or floating on water surfaces, majorly synthetic plastics that contaminate the aquatic environment include low- and high-density polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET), polypropylene (PP), and polyvinyl chloride (PVC) (da Costa et al. 2016). The direct ingestion of nanosized and microplastic particles results in physical damage to feeding structures, the digestive tract, and concerned organs (Harmon et al. 2018).

Ubiquitous and highly resistant nature of microplastics (MPs) makes them difficult to eliminate from the environment. Almost all the water bodies have been polluted by MPs, so to regulate the transport of MPs in water some methods should be applied for the degradation of MPs and combat the pollution. The rate of MPs degradation depends upon the type of polymer produced. Polystyrene (EPS) particles are quickly degraded into smaller fragments by mechanical abrasion but polyethylene (PE) and polypropylene (PP) are not completely degraded by this process (Song et al. 2017). In biological methods, the potential organisms are introduced to degrade and eliminate the MPs in the aquatic ecosystems. In a majority of experiments, certain microbial populations are implemented to neutralize these MPs (Harrison et al. 2011). These microbes are capable to disintegrate the complex MPs polymers into monomeric constituents. Aerobic microbe's degradation actions result in water and CO_2 while anaerobic forms result in water, CO_2, H_2S, and methane as byproducts (Chandra and Singh 2020). The immobilization and degradation of MPs in terrestrial ecosystems was done by using biological, coagulation, agglomeration, and nanomaterials. Corona et al. (2020) evaluated the potential of mushroom coral isolated from Magoodhoo, Maldives, to minimize the pollutants associated with bio-fueled plastics and are found to eliminate 97% of the particles of nearly 200–1000 μm in size in the laboratory environment. Also, scientists are working on the isolation and identification of multiple microorganisms associated with MPs hydrolyzing enzymes, mostly the depolymerases which are effective in the breakdown of MPs are yet to be identified (Wei and Zimmermann 2017). Whereas, other methods adopted by Sturm et al. (2020), follow the step systematic processes of adsorption, agglomeration, and finally filtration was implemented to remove MPs. This method undergoes the application of alkyl trichloro silanes (linear and branched) which efficiently remove the MPs like polypropylene, low and high density- polyethylene, etc. Also, the carbon nanotubes with magnetic potentials show 100% efficiency in removing certain microplastics under marine ecosystems. These tubes effectively adsorb materials like PET, polyamide, and PE and these tubes are recyclable.

Microplastic sources, pathways, and their fate

Multiple sources are accountable for the discharge of microplastics into the environment. Included among these sources are individuals, transportation, and industries. Sources of microplastics are listed in detail in Table 1. When released, microplastics enter the ocean via direct discharge or river transport systems. After release, they accumulate, degrade, and move through the environment, eventually entering the human body by ingestion, inhalation, and skin contact (Prata et al. 2020). Microplastics are introduced into the environment in two distinct forms: primary and secondary. The origins of these major and secondary forms are listed in Table 2.

Air

After being expelled from the atmosphere, these microplastics settle in sediment or soil, where they may pose a threat to human lung health (Chen et al. 2020). Table 1

Table 1 Sources of microplastics in different spheres of the atmosphere

S. no.	Sphere	Sources	References
1.	Air	Synthetic textiles, urban dust, erosion of synthetic rubber tires, industrial emission, building material, particle resuspension, plastic fragments from house furniture, traffic particles, landfills, tumble dryer exhaust, waste incineration, sewage sludge used as fertilizer and synthetic particles used in horticulture	Dris et al. 2017; Dris et al. 2016
2.	Freshwater	Primary microplastics are released from industries in the form of plastic resin powder, microbeads present in personal care products, pellet spillage from air blasting machines and material from plastic producing products. Secondary microplastics are released from breakdown of larger plastic debris	Horton et al. 2017b Fischer et al. 2016
3.	Soil	Debris in sewage sludge, microplastic fibers, compost fertilizers, fragmentation of plastic items, plastic waste in landfills, weathering, breakdown of plastic films on farmland, atmospheric deposition, littering, wastewater irrigation and surface runoff	Blaesing and Amelung 2018; Rochman 2018
4.	Ocean	Indirectly from atmospheric transport, beach littering, and rivers. Directly from shipping, fishing activities and aquaculture Also released from cosmetics, air-blasting media, pellets, water treatment plants, tourism, marine industry and leisure	GESAMP 2016 Chatterjee 2017 Sun et al. 2019 Cole et al. 2011

Table 2 Sources of primary and secondary microplastics

Type of microplastics	Sources	References
Primary microplastics	Facial cleansers, cosmetics, vectors for drugs, air-blasting media, virgin plastic manufacturing pellets	Auta et al. 2017
Secondary microplastics	Breaking of larger particles into smaller fragments by physical, chemical, and biological methods	Sundt et al. 2014

lists the sources of microplastics in the atmosphere. It has been observed that the concentration of microplastics in indoor air is greater than that in outside air (Dris et al. 2017). It has been noticed that the concentration of outdoor microplastics differs in different locations of the world (Cai et al. 2017). In outdoor conditions, the fate of microplastics relies on wind direction and speed, precipitation, vertical pollutant concentration gradient, and temperature (Prata 2018).

Soil

Soil is an extremely important microplastics reservoir. It has been observed that once these microplastics are introduced into the soil, they persist and accumulate, thereby inhibiting the growth and reproduction of soil-dwelling microorganisms. Consequently, they impact the biodiversity of these microbes (Rillig 2012; Chae and An. 2018). These microplastics also act as pollution carriers, damaging the soil environment (He et al. 2018b). According to research conducted by Wang et al. 2020a, microplastics in the soil also originate from fertilizers and contaminated irrigation water. Additionally, microplastics have been found in agricultural, suburban, urban, coastal, and floodplain soils (Liu et al. 2018).

Freshwater and ocean water

Microplastics that remain in sludge or are not filtered out during sewage treatment are discharged into freshwater (Horton et al. 2017a). As freshwater provides humans with drinking water, humans can directly inhale microplastics from freshwater (Novotna et al. 2019). According to findings by Fischer et al. (2016), the transmission of microplastics is dependent on wind, water body size, particle density, and current. Additionally, water retention time, urbanization, closeness to urban centers, proximity to a dense human population, sewage spills, and waste management influence the occurrence of microplastics in water systems (Horton et al. 2017b). After entering waterbodies, microplastics create biofilms through the colonization of algae, bacteria, and fungi, which are then consumed by fish, so altering their fate in freshwater (Hoellein et al. 2014).

It has been observed that wastewater treatment plants directly or indirectly contribute to plastic pollution in the ocean (Sun et al. 2019). In the ocean, the fate of microplastics is governed by phytodegradation, biodegradation (external influences), and microplastic characteristics (Li et al. 2016). Microplastics degrade completely in more than 50 years. Michels et al. (2018) reported that when microplastics enter the ocean, they create biofilm which, within 7 to 14 days, is turned into a plastic surface. The altered buoyant density of polymers causes the transfer of microplastics to deeper water and soil.

Uptake of MPs

MPs are being introduced into water bodies and soil on a large scale through different sources as mentioned above. As these MPs are non-biodegradable, they make entry into the living systems in their vicinity through various processes such as absorption, adsorption, ingestion, etc. many research studies supported the uptake of MPs by aquatic animals through their respiratory organs, i.e., gills (Siegfried et al. 2016). The transfer of food and energy as a result of linked food chains in the ecosystem further results in the bio-magnification of these toxic pollutants within the bodies of living organisms at higher trophic levels (Gigault et al. 2016). The plants have been reported to absorb these tiny MPs through their roots from the soil as well as from the microbes with which they interact during their vegetative and reproductive growth. Also, the adsorption or entry of MPs within any living component is inversely linked with the size of the former. The larger the size of MPs will be adsorbed with difficulty in comparison to the small-sized ones (Eriksen et al. 2013; Corcoran et al. 2015). Hence, with different modes of movement through different sources, MPs get accumulated within both terrestrial and aquatic biota (Rillig et al. 2017b; Rodriguez-Seijo et al. 2018; Wang et al. 2019a).

Inhalation is one of the routes of microplastic exposure for humans. Ingestion and cutaneous contact are yet other sources of human exposure. The effects of microplastic exposure on humans are reported in Table 3 (Prata et al. 2020). Microplastics have been detected in the human diet, including seafood, sea salt, sugar, honey, beer, and drinking water (Smith et al. 2018; Kim et al. 2018; Liebezeit and Liebezeit 2013, 2014 and Mintenig et al. 2019). The respiratory tract is thought to be a major pathway for exposure to microplastics. Reports indicate that humans can inhale approximately 272 particles per day from indoor air (Vianello et al. 2019). After the respiratory system, skin contact is the second mode of exposure and is regarded as less significant (Prata et al. 2020). According to Sykes et al. (2014), microplastics (size less than 100 nm) can pass through human skin. Microplastics penetrate human tissues via endocytosis and paracellular absorption. It depends on microplastics' surface functionalization, size, protein corona formation, surface charge, and hydrophobicity (Wright and Kelly 2017).

Toxicity of MP pollutants

The process of plastic deterioration is extremely sluggish, and it might take more than 50 years for the plastic material to completely degrade (Müller et al. 2001) which further enhanced its toxicity. Direct toxicity of microplastics is caused by the ingestion of microplastics by terrestrial and aquatic creatures. In various aquatic species, direct ingestion of microplastics induces inflammation through the destruction of their filtering mechanisms (von Moos et al. 2012; Anbumani and Kakkar 2018; Wang et al. 2020b), damages the feeding apparatus, digestive tract, lower assimilation capacity, reduced swimming velocity and resistance time (Barboza et al. 2018; Meng et al. 2020), disrupts reproduction cycle, and enters the food chain (Barboza et al. 2018a). In addition to this, microplastics aggregate on the surface

Table 3 Uptake and effect of microplastics on soil microbes, plants, and humans

S. no.	Category	Effects	References
1	Soil microbes	-Destroy filter mechanism of marine biota and thereby cause inflammation. -Algae feeding is disrupted. -Fertility is decreased. -Mortality of copepods is increased. -Abrasion -Ulcers -Liquid stores are reduced	von Moos et al. 2012 Cole et al. 2019 Rillig et al. 2019
2	Plants	-Affects growth -Affects biomass -Inhibits weight and number of grains	Zhu et al. 2019 Kumar et al. 2020
3	Humans	- Generate reactive oxygen species -Activate antioxidant-related enzymes -Increase glutathione S-transferase activity -Activate mitogen-activated protein kinase signalling -Neurotoxicity -Reduce digestion of lipids -Inhibits activity of digestive enzymes -Impacts cell health and immune system	Alomar et al. 2017 Jeong et al. 2017 Yu et al. 2018 Tan et al. 2020 Browne et al. 2008

of algal cells interrupting gaseous exchange and photosynthesis. In higher plants, microplastic blocks photosynthetic processes, minerals, nutrients, water uptakes and starts various other growth-inhibitory processes.

The fact that microplastics cause indirect toxicity could not be ignored either as these toxicities are much more dangerous and complicated as compared to the direct toxic effects. During the production of plastics goods integration of chemical additives is very frequent such as such as bisphenol A (BPA) and bis (2-ethylhexyl) phthalate, acid scavengers, antistatic agents, antioxidants, flame retardants, plasticizers, lubricants, pigments, and thermal stabilizers that possibly resulting in combined toxicity. These additives are actually added to increase the performance of plastic materials (Hahladakis et al. 2018). Additional research has shown that many plastic-related monomers, oligomers, and other chemicals (for example, di-n-octyl phthalate, di (2-ethylhexyl) phthalate, polybrominated diphenyl ethers, and tetrabromobisphenol A) show adverse effects in humans through various exposure routes, such as through food, air, and water (Wang et al. 2021). Microplastics have been shown to be capable of absorbing heavy metals such as cadmium, zinc, nickel, and lead (Brennecke et al. 2016). As a result, microplastics are now thought of as potential vectors for these co-existing pollutants (Zhao et al. 2020), which raises the hazards associated with them. For example, it has been said that combining organic pollutants (like phenanthrene, 4,4'-DDT, and PBDEs) with microplastics could make them more bioavailable along food chains, which means they could end up in the human body (Zhao et al. 2020; Wang et al. 2021).

Impact of MPs on the terrestrial ecosystem

Terrestrial soil serves as a significant microplastics reservoir (Rillig 2020). After being introduced into the soil, microplastics have the potential to remain there and accumulate, ultimately having an impact on the development, reproduction, and overall biodiversity of soil organisms (Chae and An 2018; de Souza Machado et al. 2018b). In addition, microplastics can serve as vehicles for the transmission of different contaminants to soil biota, causing damage to the soil ecosystem (He et al. 2018a). According to the findings of a study carried out by Liu and colleagues, microplastics can live not only in the topsoil but also in the deeper subsurface soils (Liu et al. 2018). Microplastics have the potential to alter the characteristics of soil as well as its biophysical environment, which may influence the microbiological activity in soil (Wang et al. 2021). The most common way for soil microplastics to get into deep soil and even groundwater is through leaching (Rillig et al. 2020). Furthermore, soil organisms (such as earthworms) have a significant role in determining the accumulation and destiny of microplastics in soil, either by ingesting or excreting them (Wang et al. 2021). Soil organisms may help transfer microplastics across strata (from shallow to deep soil, or vice versa). A recent study showed that terrestrial plants can take in nano-size plastics (55 5 nm and 71 6 nm) depending on their surface charge (Sun et al. 2020). Therefore, remains of plastic, both large and little, have a deleterious impact on the vegetative and reproductive stages, interrupt nutrients, minerals, water uptake, reduce photosynthesis of the plant, alter soil microbial community, and root symbionts. Moreover, it also causes cellular and molecular alterations inside the bodies of terrestrial organisms (also shown in the Fig. 1).

MP inhibitory effects on higher plants

Microplastics cause direct toxicity mainly by limiting plant performance and development by reducing nutrients, minerals, water uptake, blocking photosynthesis, damaging cellular organelles, and suppressing various genes involved in the growth of plants (detailed experimental reports shown in Table 4). Whereas indirect toxicity is caused due to the weak bond between the additives and the basic polymers, as the additives were easily leached and released, causing toxic effects to the organism. Such as microplastic additive leachate from shoe soles hindered the photosynthesisin *Vigna radiata* (Lee et al. 2022). Similar to this lactic acid, the degradation products of polylactic acid (PLA) cause an adverse effect on *Lolium perenne*shoot length (Rozman et al. 2021). Polycarbonate (PC) granulate was also reported to inhibit *Lepidium sativum* seed germination by 60% compared to the control (Pfugmacher et al. 2021). Another investigatory report also shows that polystyrene (PS) microspheres are transported from roots to leaves, where PS microspheres decompose and produce benzene which causes a disruption in chlorophyll and sugar metabolism (Li et al. 2020). Microplastics may indirectly affect plant development by altering soil parameters, soil microorganisms and by affecting other pollutant bioavailability (Li et al. 2022).

MP impact on soil rhizosphere

MPs have been found to modulate the contents of dissolved organic C, N, and P present within the soil thereby affecting its physicochemical properties (Dai et al. 2021; Liu et al. 2017; Machado et al. 2018b). In addition to this, the water holding capacity, microbial activity, and bulk density of soil particles are also adversely affected by major occurring MPs such as polystyrene and polyethylene (Dai et al. 2021; Machado et al. 2019). An increase in the contents of humic and fulvric acid in soils was reported as a result of MPs incidence making them fertility boosters (Wang et al. 2020c; Wong et al. 2020; Zhang and Zhang 2020). These dynamics in soil porosity and moisture caused by MPs pollution affect

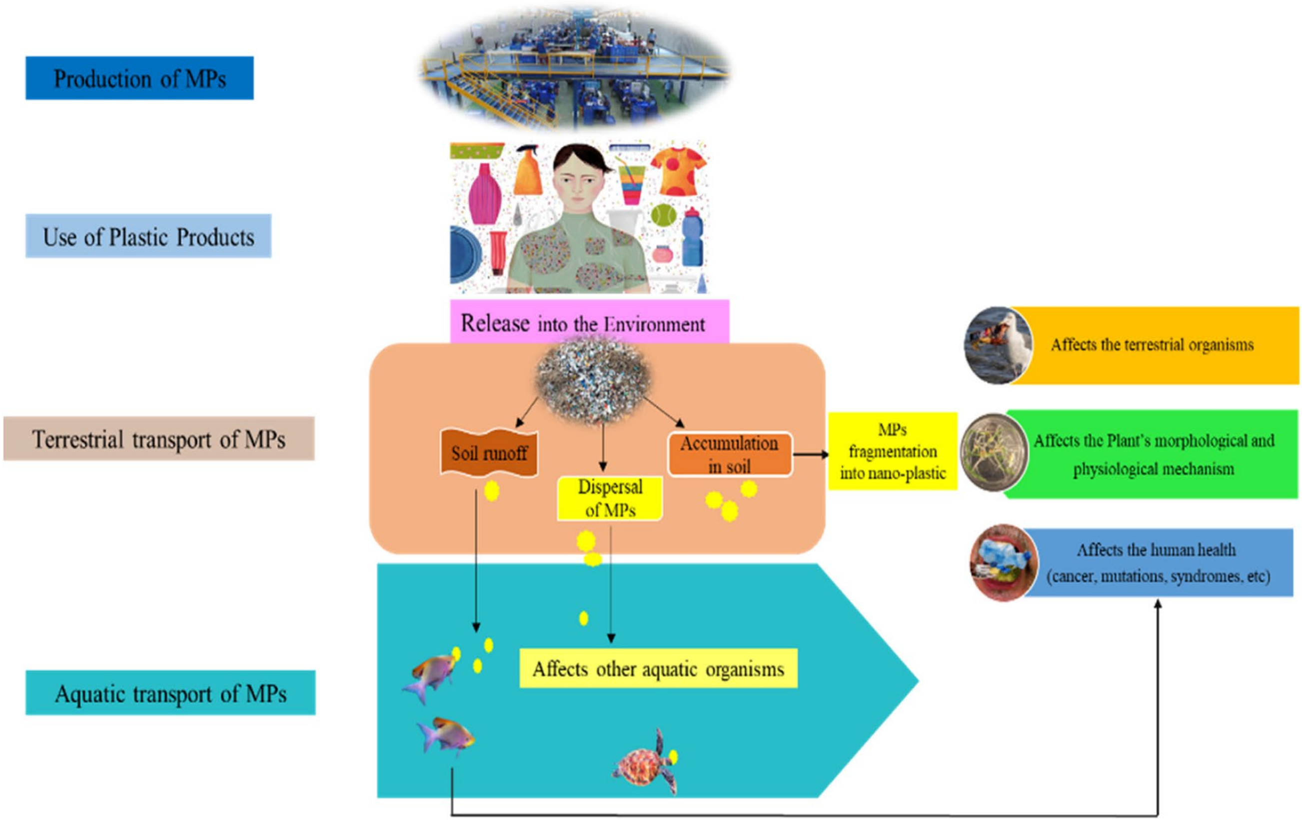

Fig. 1 Terrestrial and aquatic ecosystems are affected by the release of MPs (microplastics) into the environment

the process of gaseous exchange between the soil and the microbes flourishing in the rhizospheric zone (Zhou et al. 2020; Rillig et al. 2019; Lu et al. 2020; Imran et al. 2019). Soil microbes which are the foremost component of the rhizospheric soil get incorporated with significant amounts of MPs, owing to their small size and highly adsorbent nature (Horton et al. 2017a; Huerta et al. 2016). In addition to these, the persistence of MPs within soil may lead to the aging of MPs making them active sites for the adsorption of other pollutants within soil especially the heavy metals and organic matter (Nizzetto et al. 2016b).

MP influence on terrestrial organisms

The MPs get accumulated in biotic components of an ecosystem from the soil via plants thereby affecting the organisms at different trophic levels to varying extents depending upon the quantity that is being transferred in the food web. The very minimal concentration of these MPs is excreted by these organisms while most of the accumulated MPs gets retained within their body and pose serious threats to biological and metabolic processes within the organism owing to its indigestible nature (Nizzetto et al. 2016c; Futter et al. 2016). Some of the harmful effects reported in living organisms due to MP uptake are infertility, blockage of the respiratory and digestive tract, and increased mortality (Dris et al. 2016). Another lot of deteriorating symptoms reported in plants as a result of MP accumulation includes poor seed germination, water uptake, root growth, and gaseous exchange limiting the primary metabolic process of photosynthesis (Vickers. 2017; Alam et al. 2018; Balestri et al. 2019). Similarly, the adsorption of MPs over the microbial surfaces leads to biofilm formation altering the species composition of microbial communities in the soil (Dussud et al. 2018; Wang et al. 2017; Jiang et al. 2018). In human beings, the noxious effects of MPs have been reported such as poor reproductive health, skin ailments, decreased immunity, cancer, etc. (Barboza et al. 2018; Peixoto et al. 2019; Schwabl et al. 2019). However, these aspects of MP pollution remain controversial sometimes; hence detailed studies on their persistence and affection need to be carried out.

Table 4 Inhibitory effects of microplastics on higher plants

S. no.	Microplastic type	Plant part affected	Inhibitory effects of microplastics on higher plants	References
Morphological levels inhibitory effects of microplastics				
1	Polystyrene (PS)	Leaves	Foliar exposure to PS directly reduced lettuce yield output by blocking photosynthetic processes	Lian et al. 2021a b
2	Polystyrene (PS)	Roots	Affect the uptake and transport of nutrients, water, and mineral elements (e.g., K and Fe) by roots, or influence the distribution and reuse of mineral elements in plants	Jiang et al. 2019; Urbina et al. 2020; Wu et al. 2021; Xu et al. 2021; Li et al. 2020
3	Massive microplastics	Roots	Collect on plant roots. As a result, microplastics, particularly those with rough surfaces and sharp edges, may mechanically injure plant roots, limiting root activity and impeding root development	Gao et al. 2021; Rozman et al. 2021
4	Polystyrene (PS) and polytetrafuoroethylene (PTFE) microplastics	Roots	Induce mechanical damage to rice roots that results in the production of reactive oxygen species (ROS)	Dong et al. 2020
5	Remains of plastic, both large and little	Wheat plants	deleterious impact on the vegetative, reproductive stages of the wheat plant	Qi et al. 2018
6	Polystyrene (PS)	Seed	Able to build up inside the pores of seed capsules thus intake of water by the pores will be inhibited, which will in turn affect the germination rate of plant seeds	Bosker et al. 2019
Cytotoxic inhibitory effects of microplastics				
7	Polystyrene (PS) particle sizes smaller than 3.0 µm	Leaf cells	Microplastic particles gather in leaf vessels and can block cell junctions or cell wall pores	Sun et al. 2021
8	Polystyrene (PS)	Plant cells	Impact on protein synthesis-related gene expression thus significant decrease in the amount of soluble protein in the *Utricularia vulgaris*	Yu et al. 2020
Molecular level inhibitory effects of microplastics				
9	Polystyrene (PS)	*Arabidopsis thaliana* whole plantlet	Decreased *Arabidopsis thaliana*'s resistance to disease by turning down the expression of disease-resistance genes	Sun et al. 2020
10	Polystyrene (PS)	Root	PS had a negative effect on the expression of genes involved in the activation of antioxidant enzyme activity thus, decreased the antioxidant enzyme activity in rice roots	Zhang et al. 2021
11	Polystyrene (PS)	Grain	Suppressed the expression of genes encoding proteins involved in the tricarboxylic acid cycle in the rice grains	Wu et al. 2022a
12	Polystyrene (PS)	Rice plant	Prevent the creation of lignin and jasmonic acid through altering the gene expressions of *Oryza sativa*	Zhou et al. 2021a

Impact of MPs on the aquatic ecosystems

The literature serves as a source of many recent reports that highlight the devastating effect of these MPs on the biota of aquatic ecosystems. Ingestion of polyamide fibers by amphipod *Gammarus fossarum* suffered reduced assimilation efficiency (Blarer and Burkhardt-Holm 2016). Interestingly, altered fish behavior on revelation to polystyrene nanoparticles was documented by Mattsson et al. (2015). His observations included alterations in brain morphology, reduced feeding rates, and disruption in cellular processes. Apart from the direct impacts of MPs, the metals that adhere to their surfaces also increase the toxicity levels (Turner and Holmes 2015; Wang et al. 2017). An experimental setup was used by Brennecke et al. (2016) to demonstrate and study the release of heavy metals such as Cu and Zn from the antifouling paint that got adsorbed to virgin polystyrene beads and polyvinyl chloride fragments in water. Further, we have discussed the effect of MPs in alerting microbial populations and triggering altered gene expressions. Figure 2 represents the diagrammatically injurious effects of MPs on the sustainability of aquatic flora and fauna.

Alters microbial population

Aquatic microbial populations (phytoplankton, zooplankton, algae) are of prime importance for aquatic ecosystems not only due to their autotrophic capabilities, oxygen releasing nature but also because they are primary producers supporting the entire food chain. The theory was proposed and experimentally tested by Bhattacharya et al. (2010). His team exposed *Chlorella* and *Scenedesmus* to positively charged plastic nanoparticles, they observed a decline in photosynthetic activity after these particles adhered to the cell surfaces. Zhang et al. (2017) also tested the above-proposed theory by exposing *Skeletonema costatum* to polyvinyl chloride microspheres and reported the deleterious effect of MPs on photosynthetic efficiency, chlorophyll content, and growth. Many laboratory toxicities studies were conducted to assess the effects of microplastics on algal strains. After the application of Polyethyleneimine PS nanoparticles (0.1–1.0 mg/L for 72 h) on *Pseudokirchneriella subcapitata*, its growth got constrained (Casado et al. 2013).

Stimulates the gene exchange

Microplastic biofilms are referred to as hot spots of horizontal gene transfer (HGT). These sites have high cell densities resulting in increased interaction levels among the cells (Aminov 2011; Sezonov et al. 2007). The studies conducted by Arias-Andres et al. (2018) describe the impact of microplastics on the ecology of aquatic ecosystems, bacterial evolution, and growing hazards to environmental and human health. They observed that the bacterial population associated with microplastics has a greater frequency of plasmid transfer in comparison to free-living bacterial strains. In addition, they reported that enhanced gene exchange occurs in phylogenetically diverse bacterial communities that were grown on polycarbonate filters. Furthermore, it was observed by Grossart et al. (2003) that under conditions of high dissolved organic carbon, plasmid transfer frequencies increase. Hence, microplastics have an impact on the evolution of aquatic bacteria finally leading to neglected hazards for human health (Fig. 3).

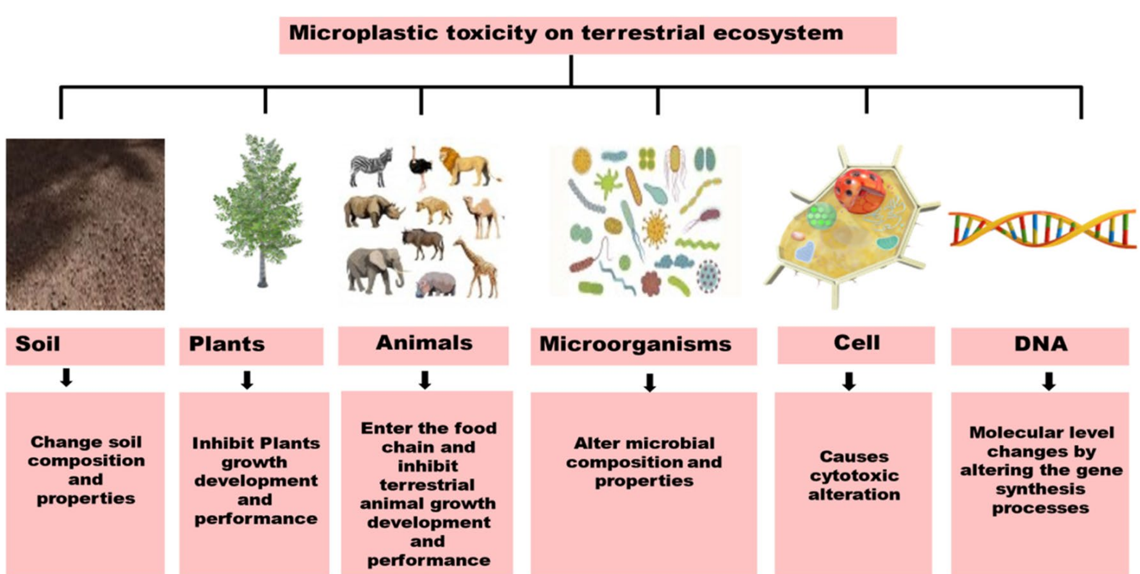

Fig. 2 Microplastic toxicity on terrestrial ecosystem

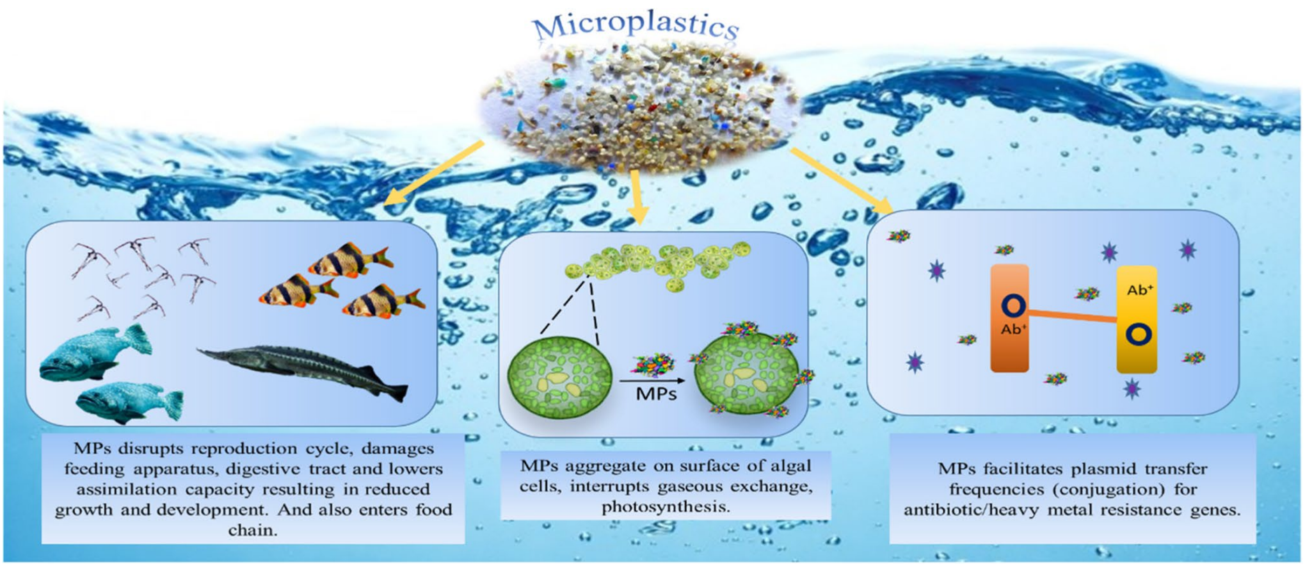

Fig. 3 Deleterious effects of MPs on the aquatic ecosystems

Mechanism of environmental degradation of MPs

The degradation of MPs can be divided into four basic processes mechanical, chemical, and biological. Firstly, macroplastic/synthetic polymer chains are converted into shorter molecular units, i.e., oligomers, dimers, monomers MPs, and then finally degraded into inorganic components (Eubeler et al. 2009).

Mechanical methods

MPs are degraded mechanically by abrasion in which solid particles come in contact with various natural (sediments, debris) and manmade (transportation vehicles, barriers) substances in the terrestrial and aqueous environment (Klein et al. 2018). Small rounded grains with surface textures of grooves and conchoidal cracks produced by abrasion are similar to quartz grains of natural sediments (Corcoran 2022). It was also reported that polymer degradation was increased by mechanical pressure as a bottle with sand containing plastic pieces was continuously rotating for 24 h and the weight of plastic was decreased to 14% indicatingthe abrasion process degrade the polymer (Kalogerakis et al. 2017). Due to wind, wave action, and tidal currents beaches are considered a favorable place for MPs degradation. It was studied that PE microbeads used in facials were found in wastewater and then subjected to shear stress through stirring, pumping, etc. These shear stress forces converted PE microplastic into nanoplastic particles (Enfrin et al. 2020).

Chemical degradation

The chemical breakdown of MPs depends on the type of polymer, medium used, chemical composition, and deposition of a particular type of sediment (Gewert et al. 2015; Brandon et al. 2016; Song et al. 2017). MPs absorb a greater amount of UV radiation on beaches as compared to particles hidden under benthic sediments. Chains with smaller molecular units are generated when MPs are photodegraded through exposure to UV radiation and oxygen. But the C-C bonds of PE, PP, and polyvinyl chloride (PVC) do not break completely through photooxidation and require some additives for degradation in comparison to polymer polyethylene terephthalate (PET) (Chamas et al. 2020). After the photodegradation of C-H bonds in PE and PP, the free radicals react with oxygen which leads to the formation of inert products with a low molecular weight of these polymers (Gewert et al. 2015). The generated polymers are then disposed off or mechanical abrasion/biological degradation. The chlorination process is also used to degrade MPs by which old bonds are broken and new ones introduce between chlorine and hydrogen. Big-sized particles of MPs are formed by adding salts of Fe and Al or other coagulants through the processes of agglomeration or flocculation for degradation. One of the advanced oxidation processes for the degradation of contaminated particles is photocatalysis as this green technology uses immeasurable solar energy for the oxidation of microplastics. This process is based on the photocatalytic properties of certain materials such as TiO_2 which have been used to transform solar energy into chemical energy to oxidize/reduce pollutants in hydrogen or hydrocarbons. Upon the absorption of UV light, high energy electrons from the valence band are transferred to the conduction band on the TiO_2 surface, and then holes are produced in the valence band, therefore both the holes and electrons react with OH˙, O_2, or H_2O to generate reactive oxygen species (ROS). These ROS then involved in the process of microplastic degradation (Nakata and Fujishima 2012).

Biological degradation

In biodegradation, a complex community of microorganisms which have the ability to adapt to various environmental fluctuations forma biofilm on the surface of organic pollutants including MPs, and change their properties (Muthukumar et al. 2011). After the formation of biofilm, the polymer structure is disturbed and bonds are weakened. The weakened bonds are then attacked by extracellular enzymatic secretions of microorganisms. At last, the assimilated MPs monomers are completely mineralized by cellular enzymes into smaller components like CO_2, H_2O, N_2, and biomass which are then available as energy sources for microorganisms and then recycle to the atmosphere (Du et al. 2021). The extent of biodegradation depends on the surrounding ecosystems (terrestrial or aquatic), the structure of the polymer (degree of polymerization, branching, chemical bonds, crystallinity, and hydrophobicity), and environmental factors (pH, temperature, moisture) (Klein et al. 2018). Microorganisms such as bacteria (*Azotobacter* sp. and *Pseudomonas* sp.), fungi (*Aspergillus* sp., *Penicillium* sp.), and actinomycetes (e.g., *Amycolatopsis* sp., *Actinomadura* sp.) can degrade both synthetic and natural plastics (Bose 2020). It has been reported that bacterial strains (*Bacillus* sp. 27 and *Rhodococcus* sp. 36) obtained from mangrove sediment degrade the polypropylene MPs efficiently as the weight of the polymer was reduced to 7% by *Bacillus* sp. 27 and 5% by *Rhodococcus* sp. 36, respectively (Auta et al. 2018). Figure 4 summarizes these three processes of MP degradation.

Immobilization of MPs from terrestrial ecosystem

Polymers like polyethylene (PE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) are the major plastic particles found in the terrestrial ecosystem. Irradiated or cracked polymers have been degraded under the influence of various microorganisms (Miri et al. 2022). It was observed that earthworms can increase the degradation of MPs as in the gut of earthworms, low molecular polyethylene particle size was reduced within four weeks (Lwanga et al. 2018). It was also stated that using polymers as carbon sources microalgae degrade MPs through the synthesis of some toxins or enzymes and biodegradable plastic can be made using protein and carbohydrate-based polymers by microalgae. The growth of algal cells is faster than in higher plants which can be enhanced through genetic engineering, so algal-based plastics can replace synthetic plastics (Chia et al. 2020).

Immobilization of MPs from aquatic ecosystem

To restrict and eliminate these MPs, advanced approaches should be implemented in combating these pollutants (Fig. 5). Synthetic textile industries are found to generate microfibers of microplastics which are drawn into the surface of waste and act as a pollutant around the globe (Mishra and Ahmaruzzaman 2022).

Immobilization of microplastics using biological methods

Mangrove-derived *Bacillus* species such as *Bacillus gottheilli* and *Bacillus cereus* are typically used in minimizing microplastic polymers like PS, PE, and PP (Auta et al. 2017). However, some other algae and fungal populations are also helpful in minimizing the MPs from the aquatic ecosystems. Paco et al. (2017) found that the application of *Zalerion maritimum*, a fungus, has a higher potential to

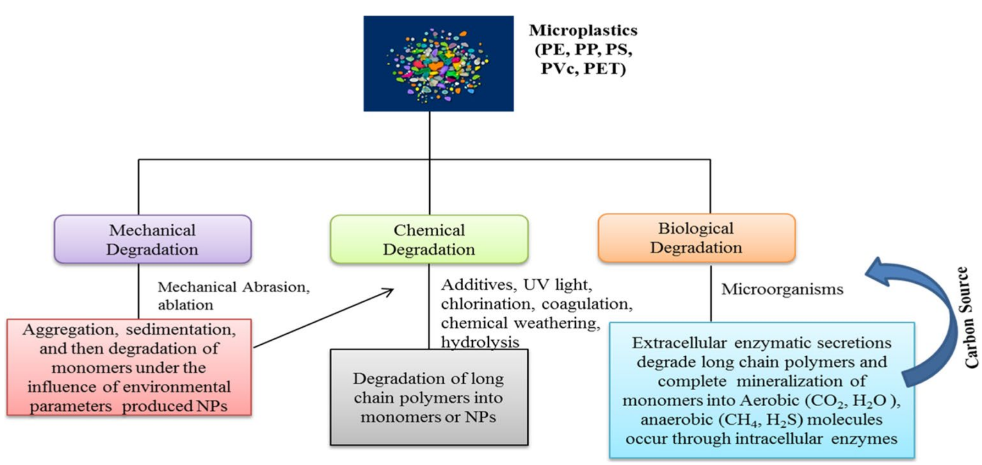

Fig. 4 Environmental degradation processes of microplastics (MPs). Abbreviations: PE, polyethylene; PP, polypropylene; PS, polystyrene; PET, polyethylene terephthalate; PVC, polyvinyl chloride; NPs, nanoplastics

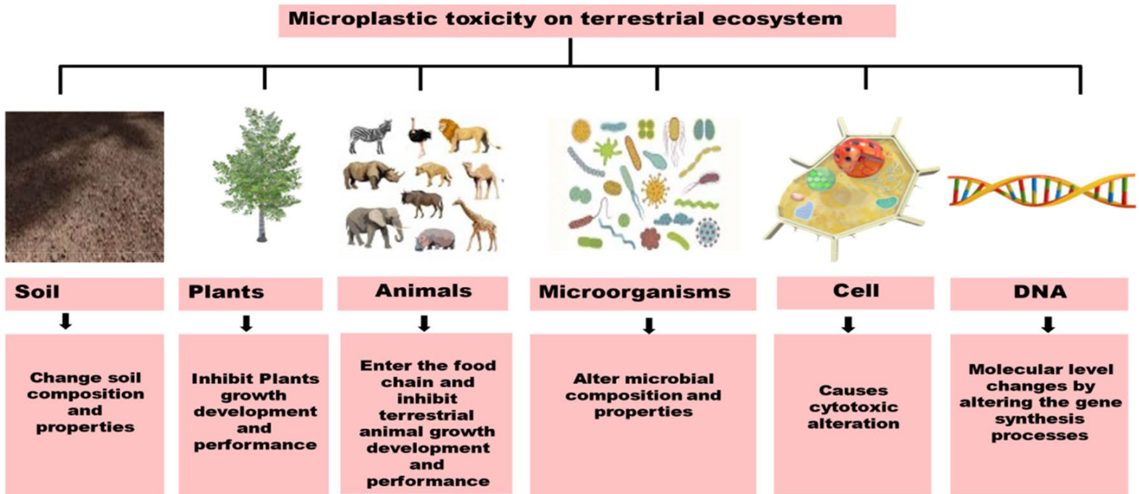

Fig. 5 The general mechanism adopted for the immobilization of microplastics (MPs) from the aquatic ecosystem

degrade or convert these MPs or polyethylene chemically and morphologically. Also, researchers have identified some other MPs sinks for aquatic ecosystems, one among such are organisms like *Tridacna maxima* generally known as the Red Sea giant clam, some corals, and crustaceans like *Euphausia superba* (Arossa et al. 2019; Corona et al. 2020).

On the other hand, microalgae are gaining much importance as a biological tool in removing the MPs. Peller et al. (2021) found that the macrophytic algae *Cladophora* is efficient in the elimination of microplastics due to their high sorption potential as they have a high surface area and shows effective associations among algae and microplastics. Whereas on the other hand Wu et al. (2022b) identified a green-algae namely *Chlorella vulgaris* which shows its potential in the normalization of the toxic PS-microplastics which are however capable of endocrine disruption like Levofloxacin an antibiotic present in wastewater from aquaculture. Also, the microalgae, Diatoms namely *Phaeodactylum tricornutum* have been employed to remove multiple microplastics ranging from PVC, PE, PET, and PP, etc. (Song et al. 2020). However, an edible marine sea-weed, *Fucus vesiculosus* shows effective adsorption of microplastics mainly PS-microplastics on their surfaces. Thus, the algae show an efficiency of up to 94.6% for the PS microplastics as they contain gelatinous compounds like alginates a kind of polysaccharide that helps in PS adsorption (Sundbaek et al. 2018).

Immobilization of microplastics using nanomaterials

Nanomaterials are another breakthrough in the research field and are kept in use over conventional methods, such as microalgae and sponges. Mishra and Ahmaruzzaman (2022) have employed certain iron nanoparticles with hydrophobic, cost-effective, and large surface areas. These nanomaterials are having the ability to interact with microplastics and mediate their removal through ferromagnetic properties with a high potential to act against polymeric microplastics such as PP, PVC, PE, PS, PU, and PET. They have an efficiency of 93% in seawater whereas show 84% of its efficiency to remove PP, PVC, PS, PU, PE, etc. Another nano-catalyst cesium oxide (CeO_2) shows excellent adsorption of microplastics which mainly depends on the large surface area, its oxidation state as well the sorption capacity of the microplastics (Ho et al. 2021). Zinc oxide nanorods are applicable in removing low-density PE microplastics (Tofa et al. 2019). Au-doped Ni-TiO_2-based micromotors are developed and are well used to eliminate microplastics by using certain UV light irradiations for wastewater treatments. But due to low selectivity, this particular technique is not of much use for wastewater treatments (Wang et al. 2019b). However, Yuan et al. (2020) have developed graphene oxide-based adsorbents having three-dimensional structures that are much more effective against PS microplastics. The π-π bonding between the C- atoms in reduced graphene oxide and the benzene in PS are important to mediate the effective adsorptions of the pollutants. Also, researchers have developed certain nanomaterials like magnetic-nano- Fe_3O_4 to eliminate marine contaminating magnetized MPs (Shi et al. 2022).

Immobilization of microplastics using coagulation and agglomeration

These effective methods are employed to deal with the enlarged MPs in aquatic ecosystems. The contaminants are captured by the Fe and Al salt-based catalysts through ligand-based interactions. Arzia-Tarazona et al. (2019)

demonstrated the elimination of certain PE microplastics by employing the Fe and Al-based salt catalysts through ultrafiltration and coagulation mechanisms. In different studies, the Al^{3+} ions were found to be more effective with respect to Fe^{3+} ions to eliminate the MPs. However, an alteration in the pH of the solution did not change the activities of the Al coagulation with a size of 0.5 mm MP particles, whereas an increase in pH impacts and limits the elimination of MPs below 0.5 mm in diameter. However, Zhou et al. (2021b) have developed a method that utilizes ferric chloride and polyaluminum chloride as coagulants to treat the MPs from the wastewater. These +vely charged coagulants are made to interact with the -vely charged microplastics and other pollutants which finally get settled at the surfaces via gravity. Furthermore, the sediments were collected and the supernatants were allowed to undergo mechanisms like filtration and drying. Finally, the characterizations of the MPs' flocs were done. On the other hand, Akarsu et al. (2021) implemented electrocoagulation techniques to eliminate the PE -microplastics from the reactors containing sludge which are mainly used in wastewater treatments and are thought to be more cost and energy efficient. The researchers emphasized the factor stabilization of suspended microplastics through effective van der Waals forces in action under electrocoagulation techniques (Akbal and Camci 2011). This technique is found to be 90% efficient to trap microplastics suspended on surfaces.

Conclusion

MPs are found to have high persistence and a very slow biodegradable nature. They pose direct physical and nutritional complications post ingestion, also the presence of plasticizers associated with these MPs often aggravates the toxicity. Also, if these plastic pieces get smaller, i.e., nanosized, they have more surface area, which means they can absorb more chemicals and change chemically on the outside, which could make them more dangerous and gain scientific attention. However, the recent studies accompanying MP transport through bioturbation in regard to various soil fauna may not reflect real-world conditions due to the fact that experimentation is being conducted using model organisms in laboratory conditions. Therefore, the transport pathway of MPs in diverse organisms and their impact on the entire soil ecosystem is considered in the near future research. There is an urgent need of investigating the behavior and mechanism of microplastic degradation in terrestrial and aquatic ecosystems because it will not be feasible to evaluate the risk of MPs to human health and the environment.

Future perspectives

The microplastic pollution in the environment and its long-standing effects are less implicit. The reported documentation of MPs in the aquatic ecosystem should address the abundance of polymers like PE, PET, PE, PP, and PS. It is important to examine their fate in the environment. There is a knowledge gap in understanding the exact nature and long-term effects of MPs on both ecosystems. Competent and reliable ecosystem models should be developed to evaluate the fate of free-floating and plummeting MP waste in aquatic systems. The mechanism of migration and degradation of MPs into other products is still unclear for which the generalized approach should be developed. There is doubt about the volume, configuration, and diversity of MPs penetrating the environment because there is no quantified data about the release rate of MPs either accidentally or purposely. However, MP litter and its accidental discharge is considered as one of the utmost uncertainties for discharge predictions. This review documented to understand the subtleties and effects of MPs as a pollutant, especially in a terrestrial and aquatic ecosystems context. There is a need of extensive study to determine how MPs in wastewater leached out in the cropland and hence enter the food chain of the ecosystem. MP effects on the formation of biofilms and the expansion of infective microbes mainly with potable sources of water need to be discovered. Field research on the environmental effects of MPs presently remains at the level of species which demands research at the level of ecosystem also. More investigations are needed to study the direct MP impressions on the ecosystems' food chain flow and distribution. It is necessary to follow and relate existing crumbled data to advance the knowledge gap about impacts of MPs on various processes like sequestration of carbon, nutrient cycling, etc. This study reviewed some research extents associated with MP impacts and degradation that further needs an urgent advancement to understand the possible environmental risks and offers some references to recover and control the MP management system into the environment.

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