Chapter 10
Ecological Impacts and Toxicity of Micro- and Nanoplastics in Agroecosystem

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Abstract Micro- and nanoplastics are fragments of small plastics that are of sizes 1–5000 microns and <1 μm and consist of carbon and hydrogen atoms chained together by polymer. Micro- and nanoplastics are environmental pollutants, and their degradation depends on the properties of plastics, soil type, environmental condition, and microbial community. Their presence in the agricultural system is an emerging concern, which is basically attributed to the ability of the plastics to penetrate the soil and contaminate the soil plants, and microflora and fauna which thereby affect the food chain and security. Micro- and nanoplastics pollution in agrosystems originates from human activities (agricultural practices and anthropogenic sources) and natural sources (atmospheric inputs and flooding). Micro- and nanoplastics contamination of soil plants alters the chemical, physical, and biological properties of the soil ecosystem due to increased adsorption capacity when in combination with another organic contaminant. In agricultural ecosystems, micro- and nanoplastics affect soil microbial activity, microbial biomass, functional diversity, and the cycling process of plant nutrient elements in the soil, which have an indirect effect on plant seed germination and growth. When ingested or in association with the soil biota, micro- and nanoplastics can influence the agro-functionality through effects on soil root-associated microbiome and root symbionts, soil

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structure, nutrient immobilization, contaminant adsorption, and diffusion which can directly impact the fertility of the agricultural soil, plant qualities, and its yield. Microplastics excessive accumulation can directly result in toxic risk effects, including the interruption of the nutrient transport system by the obstruction of the pores in the cell wall, alter the community diversity, activity of the soil biota, and inhibition of nitrification. Microplastics and nanoplastics contribute to a major distribution of toxic and harmful compounds to soil plants, soil fauna, and photosynthetic organisms.

Keywords Environment · Contamination · Microplastics · Nanoplastics · Agriculture · Soil

10.1 Introduction

It is undoubtedly true that the need for hygienic products and equipment for people's daily lives has led to an astronomical increase in the demand for plastics. It is also evident that the problem will only grow as almost 400 million tons of plastics are produced annually, with a mass projected to be more than double by 2050 (Lim, 2021; Auta et al., 2022). Though plastics are discarded within 3 years of their production, above one-third of the plastics is used in disposables (Paul et al., 2020). Indiscriminate disposal of these materials recently become an issue of concern globally because of their potential environmental hazard due to their resistance to degradation and long-term persistence in the environment. Doubtfully, if all plastic production were magically stopped from now on, the existing plastics; that is, a sizeable number of debris that has already accumulated in landfills and the ecosystem would continue degrading into tiny fragments that are impossible to collect or clean up, constantly raising micro and nanoplastic levels. This global problem affects probably all ecosystems as well as the complete food chain (Abioye et al., 2015a).

Officially, there is no published definition for micro and nanoplastics but they are generally considered to vary in size from 0.1 to 5000 mm and 1–100 nm respectively (EFSA, 2016; Hardy et al., 2018). Microplastics are primary and secondary by classification according to their source into the environment. The key source of primary microplastics is the raw materials used in the manufacture of plastic items, poor handling, accidental loss, run-off from processing facilities, and residues from the production process while secondary microplastics comes from fragmentation of larger plastic particles when exposed to the physical, chemical, and biological processes (Gouin et al., 2015). The first part of the environment at the receiving end of micro and nanoplastics is soil. Farming remains an important activity on soil, as food is the main sustenance of human beings. However, farmland may be particularly vulnerable to accumulation of micro and nanoplastics (Nizzetto et al., 2016) because agricultural plastics remain valuable items in farming, particularly in sustainable agriculture (United States Government, 2018). Applications include mulch films, high tunnel coverings, drip tape, row covers, silage films, packaging use for seedlings, fertilizers, etc. (Scarascia-Mugnozza et al., 2011; Steinmetz et al., 2016). In practice, these agricultural plastic materials employed are mostly polyethylene and non-biodegradable. After some time, the plastics become brittle because of weather-related effects and form small fragments that disperse in the soil that house plants and living organisms. More so, pesticides can adsorb plastic fragments which could be used in plasticizers or production by plastics manufacturing companies that may be released during breakdown of plastics, resulting in soil contamination (Bouwmeester et al., 2015).

However, toxicological effects of micro and nanoplastics on humans and animals have become a great concern to researchers globally because of their interconnection with the food chain in relation to the environment (Verma et al., 2016). On the terrestrial animals, recent reports suggest that microplastics in soil affect soil geochemistry and microorganisms (de Souza Machado et al., 2017). Earthworms and collembolans (hexapods) exposed to MPs underwent increased mortality and reduced growth and reproductive rates (Huerta et al., 2017; Zhu et al., 2018), and this will deprive the soil of its fertility and retard the plant growth. In all studies, terrestrial micro and nanoplastics have received less attention and their occurrence in soil is at higher levels than in marine systems, by at least a factor of four (Nizzetto et al., 2016; Horton et al., 2017; Alimi et al., 2018). In this regard, since everyone eats foods and inhales sand and dust, and it's not clear if an extra diet of plastic specks will harm us, it has become imperative to reveal the findings on the threat the micro and nanoplastics would have on plant-based food. This article also provides information into sources of micro and nanoplastics in soil, the potential effect on soil microflora and fauna, soil properties and toxicity, and evaluating the plant performance in a soil containing micro and nanoplastics.

10.2 Sources of Micro and Nanoplastics in Soil

Soil is a critical component of nearly every ecosystem but is often taken for granted. It plays a significant role in sustaining life on earth. More importantly, most of the foods that humans consume, except for what is harvested from marine environments, are grown in the earth's soils. The soil consists of chemical, physical, and biological environment leading to material transformation, possibly rendering initially harmful materials less dangerous and immobilizing others as a result of the interactions between these added materials and the organic and inorganic soil constituents (Nortcliff, 2012). However, numerous human activities result in different forms of soil pollution when materials are indiscriminately disposed on the soil.

10.2.1 Micro- and Nanoplastics in Soil

Globally, the pollutants of major concern in soil are micro and nanoplastics. In recent years, most of the reports in the scientific and popular press have focused upon the accumulation and fate of micro and nanoplastics in marine environments, particularly oceans whereas micro and nanoplastics are usually transported from land to other parts of ecosystems. Our major interest is on micro and nanoplastics in soil, and this chapter addressed the sources of micro and nanoplastics in soil. The problem of microplastic pollution in the soil is extremely serious. Horton et al. (2017) summarized the sources and hazardous maturing of micro and nanoplastics in the soil environment in recent years. However, one of the most serious risks is that microplastics may be ingested by humans and other organisms via the food chain. It is important to note that micro and nanoplastics are easily transported from their sources into soil environment and get transformed via the soil chemistry and impact negatively (Fig. 10.1).

Around the world, various sources of micro and nanoplastics in the soil have been identified to include agricultural production activities; that is, the use of agricultural films, and the addition of organic fertilizers, the industrial production activities, urban construction, daily life, atmospheric subsidence, automobile tire wear, among others.

(a) *Micro- and Nanoplastics from Industrial Activities*

About 9.7 billion people would share the world by 2050 (United Nation, 2019) with food supplies needed globally projected to increase by 50% (Guillard et al., 2018). As a result of this geometric increase in population, there will definitely be

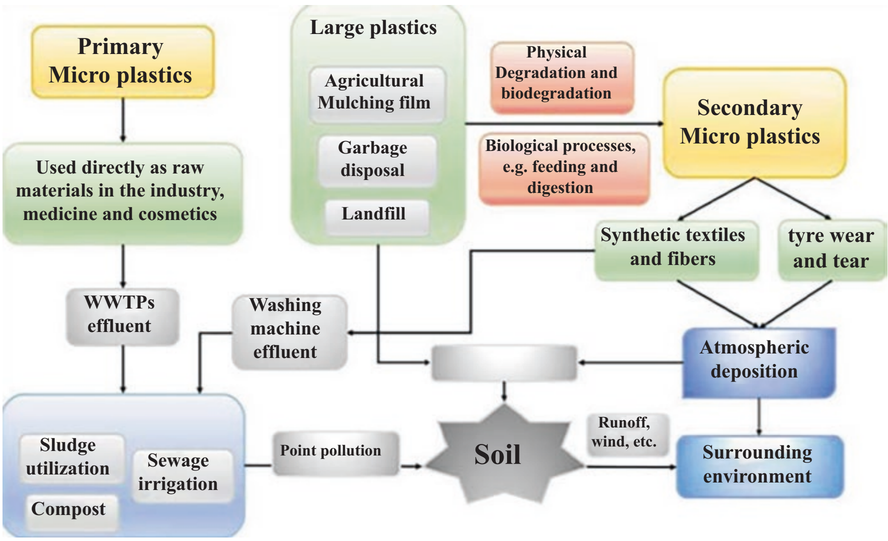

Fig. 10.1 Schematic diagram of the sources of microplastic in soil ecosystem (Yu et al., 2022)

an increase in food demand, which could drastically lead to an increase in food packaging material usage (Ncube et al., 2021).

Long ago, polymers have been beneficial to man and plastics appeared as the most important polymer helping human to survive (Al-Salem et al., 2009; Rahimi & García, 2017; Payne et al., 2019; Horodytska et al., 2019; Papadopoulou et al., 2019; European Bioplastics, 2021; Auta et al., 2022). These waste plastics are discarded indiscreetly, leading to soil contamination (Aarnio & Hämäläinen, 2008; Aransiola et al., 2013, 2021). Plastics used in packaging of materials often served a purpose but many are discarded and become post-consumer waste (Tencati et al., 2016; Ragaert et al., 2017). Discarded plastics find their way into incinerating plants, landfills, recycling plants, or the environment (Geyer et al., 2017; Abioye et al., 2015b). However, during recycling of plastics by mechanical operations, micro and nanoplastics could escape by contaminant separation, cutting/shredding, milling, floating, drying, washing, extrusion, quenching, and agglutination into the soil (Kumar et al., 2016).

(b) *Micro- and Nanoplastics from Agricultural Activities*

Farmlands have been identified to be vulnerable to accumulation of micro and nanoplastics (Nizzetto et al., 2016). Because most agricultural activities nowadays involve valuable uses of plastics, particularly in sustainable agriculture (United States Government, 2018). Agricultural film manufactured from polyethylene and polyvinyl chloride is commonly employed in agriculture. Applications include mulch films, high tunnel coverings, drip tape, row covers, silage films, packaging for seeds, seedlings, or fertilizers, among others (Scarascia-Mugnozza et al., 2011). Most plastics used for this purpose of production are non-biodegradable. The plastics become brittle due to sunlight and other weather-related effects and form small fragments that disperse in the environment due to flowing water and wind (Benedict, 2018). Often, plastic fragments become incorporated into the soil due to incomplete retrieval of the mulch film when it is being removed or recovered prior to disposal. Fragments of polyethylene are frequent in the soil in high concentrations of up to 60–-300 kg/ha, which could rise to 500 kg/ha as reported in China (Bloomberg, 2017; Tremblay, 2018**;** Bouwmeester et al., 2015). The long-term fate of plastic fragments in soil is unknown. Recent reports predict that plastic fragments may reside in soils for over 100 years due to the near absence of oxygen and ultraviolet radiation from the sun (de Souza Machado et al., 2017).

Another aspect of agriculture that introduced micro and nanoplastics into soil is irrigation of farmland with wastewater and sewage sludges. Wastewater serves as a medium that transfers a large part of micro and nanoplastics materials from the sources; soil, industrial environment, roads to surface water bodies, and domestic environment (Carr et al., 2016; Ziajahromi et al., 2017; Mahon et al., 2017; Sun et al., 2019). Comparatively, more than 90% of microplastics found in wastewater are accumulated in sewage sludge, which in turn is used for land applications: the annual amount of microplastics entering the soil in this way is greater than that entering the oceans (Zhang et al., 2020a, b; Hurley & Nizzetto, 2018). Microplastic sources in domestic sewage are detergents and personal care products. About 20 million hectares of arable land worldwide are reported to be irrigated with untreated or partially treated sewage, and an estimated 10% of the world's population depends on food grown with contaminated wastewater (Abioye et al., 2021).

(c) *Micro- and Nanoplastics from Other Sources*

Runoff from roads or urban areas that is not captured by sewer systems can contaminate surrounding soils. Moreover, atmospheric transport has the potential to move plastics in the smallest size classes over long distances and likely contributes to a proportion of micro and nanoplastics in soils. Atmospheric deposition has been demonstrated in urban environments (Dris et al., 2016) and the transport of particles from landfill sites to soils has also been discussed (Rillig, 2012; Rocha & Duarte, 2015). More so, overbank deposition likely enriches alluvial soils with micro and nanoplastic particles. It has been shown that fluvial sediments comprise of high concentrations of microplastics (Castañeda et al., 2014; Leslie et al., 2017) which gathered during flooding (Veerasingam et al., 2016). This leads to accumulation of plastics in the soils. This likely represents a significant, albeit localized, source of microplastics.

10.3 Effects of Micro- and Nanoplastics to Soil Microflora and Fauna

Microflora plays a major role in biogeochemical transformation in the soil ecosystem. The activities carried out by soil microflora helps in the availability of nutrients to soil biota and also affect the physical and chemical properties of the soil ecosphere (Rillig et al., 2017b; Huerta Lwanga et al., 2018; Li et al., 2020). The microflora is affected when the soil environment is contaminated with plastics such as macro and nano.

Microplastics act as a vector for transport of harmful substances and microbes in soil. The movement of microplastics will affect the soil microflora as microbes attach to the plastics, colonize the surface area of the plastics, and interact with the pollutant. The harmful interaction of the plastic-microbial association will affect the ecological functions of the microflora, retard the growth of some organisms and alter the microbial community composition and density (Judy et al., 2019; Chai et al., 2020; Atugoda et al., 2021). In addition to microbial dispersal and DNA transfer in biofilm formation on microplastics, microbial attachment to microplastics can act as a vehicle of transport of plastics to plants (Hoellein et al., 2019; Chai et al., 2020). Soil contaminated with nanoplastics affect the metabolic activities and function of the microflora when the plastics (nano) enters the lipid membrane of the microflora (Rossi et al., 2014), which can be prevented by the microbes through protection mechanisms such as secretion of extracellular molecules that degrades the plastics contaminant or through changes of cell membrane structure (Henriques & Lov, 2007). In addition, nanoplastics can induce redundancy and resilience in the functional properties of the microorganism in the soil flora, which can impact the ecological activities including nutrient cycling, decomposition of organic matters, energy flow, and biofilm formation of the organism (Tang et al., 2018; Wang et al., 2020).

Microplastics can affect soil microflora via changes in the soil structure. Changes in soil structure can have direct effects on soil parameters, which can result in a shift in microbial community composition, abundance, and distribution. Microplastics contamination of the soil can change the soil porosity through oxygen flow and can also alter the soil profile (soil pore space), leading to loss of inherent soil microbes and an alteration in microbial structure (Machado et al., 2018; Judy et al., 2019).

Micro and nanoplastics are high in carbon content and contribute to carbon sources in the soil which impact the microbial biomass and also result in microbial immobilization (Rillig, 2018). The carbon in the plastics is relatively inert, which is due to slow decomposition of the plastics, especially microplastics. When degraded, the C:N ratio increases, this will lead to increase in microbial activities (Qi et al., 2018). As reported, increase in abundances and activity of Ascomycota fungi in the presence of readily degradable microplastics (polylactic acid).

Micro- and nanoplastics impact the symbiotic relationship between plant and microorganism in the soil. The plant growth, reproduction, and cycling of nutrients depend heavily on the interaction of soil biota and the root of a plant, especially on root colonizing microbes, which include mycorrhizal fungi-fixers and pathogens (Wagg et al., 2014; Powell & Rillig, 2018). The change caused by micro and nanoplastics in soil structure, affects the community diversity of the soil, rate of decomposition, and also the community abundance and distribution of root symbionts (Vallespir Lowery & Ursell, 2019). For instance, nanoplastics contamination affect the soil-borne stage root symbionts of arbuscular mycorrhizal fungi via toxic effects and functional activities of mycorrhizal. (Feng et al., 2013). Macro- and nanoplastics association in the rhizosphere affect root exudate quality and quantity by altering the length of the root, the weight, and oxidative responses to stress, cell wall pores disruption, and cell-to-cell relationship used for transport of nutrients (Jiang et al., 2019). Plastics also impact the ability of plants to uptake some soil microbiome and promote the expression of genes, including those required for chemotaxis and biofilm formation (Jing et al., 2014).

Soil microfauna plays an important role in decomposition of organic compounds, nutrient cycling, and food sources for lower trophic levels and are major drivers of chemical and biological processes in the soil. Micro and nanoplastics pollution of the soil microfauna can impede the growth rate, reproduction, lifespan, and survival of the fauna biota through ingestion, bioaccumulation, oxidative stress, DNA damage, neurotoxicity, genotoxicity, reproductive toxicity, histopathological damage, gut microbiota dysbiosis, and metabolic disorders. Micro and nanoplastics interact with other soil contaminants to produce combined toxicity to soil fauna; their presence reduces the abundance of microfauna such as soil microarthropod, nematodes, and protists. Higher concentration of plastics and continuous exposure have a greater negative impact on the soil fauna composition (Zhu et al., 2018). The exposure of Collembola and Nematodes to increased concentrations of microplastics results in high mortality and decreased growth and rate of reproduction (Zhu et al., 2018). Nematode's consumption of plastics (microplastics) results in oxidative and intestinal damage that leads to a reduction in the level of calcium and an increase in the oxidative stress gene gst-4 in nematodes (Liu et al., 2018; Zhu et al., 2018). Earthworms are vehicles of movement for plastics especially, microplastics. Their burrowing activities transport plastics from the soil surface to the in-depth layers, promoting distribution and pollution which stunts their growth and development resulting from obstruction and irritation of the digestive tract, limiting nutrient absorption. A study reported by Cao et al. (2017) indicated that the growth of earthworms was significantly inhibited at concentrations of 1% and 2% and posed a toxic effect to them. A study carried out by Rodriguez-Seijo et al. (2017) reported an increase in lipids, polysaccharide and protein content, histopathological damage and immune system of earthworms at 10% concentration of polyethylene. In microarthropods, microplastics can prevent migration by filling up soil pores, while protists can easily absorb plastic fragments (nanoplastics) and colonize their surface and increase their abundance in the soil. But for microplastic, their uptake rate depends on the type, age, nutritional status, and the microplastics concentration (Rillig & Bonkowski, 2018; Lin et al., 2020).

10.4 Soil Properties and Micro- and Nanoplastics Toxicity

Nanoplastics are the smaller nanoscale fraction of plastics (defined as particles with a diameter below 100 nm) and are most likely to be incidentally produced from the fragmentation of larger plastic debris. The fragmentation of plastic debris down to the nanoscale may be caused by mechanical wear, heat, UV degradation, and, in some cases, biological factors (Ekvall, 2019; Hernandez, 2019; Lambert and Wagner (2016); Dawson, 2018). Microplastics (MPs), as defined by Frias and Nash (2018), are "synthetic solid particles or polymeric matrices, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water." Nanoplastics have traditionally been treated as a size-dependent extension of microplastics, but their size-dependent properties distinguish them from microplastics in terms of transport properties, interactions with light and natural colloids, analytical challenges, bioavailability, potential toxicity, and additive leaching times. In contrast to engineered nanomaterials (ENMs), which can include polymer formulations, accidentally produced nanoplastics in the environment are essentially debris from the environmental fragmentation of larger plastic objects (Gigault et al., 2021).

MPs are common contaminants that are causing increasing concern in aquatic and terrestrial ecosystems (Zhang et al., 2021a, b). MPs can harm organisms if they are released into the environment (Teuten et al., 2009). Depending on the properties of the microplastic, microplastics accumulation in soil could have an impact on the characteristics of the soil (Liu et al., 2017; Yi et al., 2020; Lozano et al., 2021a). The shape of microplastics may influence how it interacts with soil particles; for example, once fused into the aggregate soil, fibers have the ability to undermine the structure of the soil due to their linear shape (de Souza Machado et al., 2018; Rillig et al., 2017a; Lehmann et al., 2020; Rillig & Lehmann, 2020). Furthermore, microplastics' chemical properties, such as molecular chain arrangement and functional group, may affect their ability to absorb other chemicals, like antibiotics and toxic elements (Fred-Ahmadu et al., 2020), with potential consequences for the properties of soil and the activities of microorganisms (Pathan et al., 2020). For example, polyethylene (PE) had a high sorption capacity for phenanthrene (Wang & Wang, 2018), which could inhibit the activities of microorganisms in soil when combined with its nitrogen heterocyclic analogs (Zhao et al., 2021). Similarly, PVC, PP, and PE could have dissimilar capacities of chemical sorption according to research (Teuten et al., 2009; Wang et al., 2018). PE, for example, had a higher hydrophobic sorption capacity for organic compounds like pesticides and solvents than PE, PVC, or PET (Teuten et al., 2009; Fred-Ahmadu et al., 2020), while PS had a higher sorption capacity for Polycyclic Aromatic Hydrocarbons than PVC, PET, PP, or PE (Teuten et al., 2009; Fred-Ahmadu et al., 2020). PVC, on the other hand, could absorb more Cu than PS. As a result, the polymer type of microplastics may influence their effects on soil enzymatic activities. A Similarly, different polymer types (e.g., PE, PP, and PVC) may have different chemical sorption capacities, according to research (Teuten et al., 2009; Wang et al., 2018). PE, for example, had a higher sorption capacity for hydrophobic organic compounds like pesticides and solvents than PET, PVC, PE, or PP (Teuten et al., 2009; Fred-Ahmadu et al., 2020), while PS had a higher sorption capacity for Polycyclic Aromatic Hydrocarbons than PET, PVC, PE, or PP (Teuten et al., 2009; Fred-Ahmadu et al., 2020). PVC, on the other hand, could absorb more Cu than PS. As a result, the polymer type of microplastics may influence their effects on soil enzymatic activities. Soil properties: little is known about microplastics' effects on soil pH, a key soil parameter that could impact a range of microbial processes (Zhao et al., 2021).

Microplastics could alter the soil microbial communities (Huang et al., 2019; Fei et al., 2020), suggesting potential effects on soil respiration (Lozano et al., 2021a, b), affecting enzymatic activities. Microplastics have been shown to affect nutrient and/or substrate availability, most likely due to microplastic absorption or competition for physicochemical niches with microorganisms (Lozano et al., 2021b). The shape of the microplastics and the type of polymer it is made of may also play a role. According to the polymer type, PE and polyvinyl chloride (PVC) microplastics can enhance enzymes like urease and acid phosphatase (Huang et al., 2019; Fei et al., 2020), whereas PP, PES, and PVC can inhibit or enhance soil fluorescein diacetate hydrolase activity depending on the polymer type (Liu et al., 2017; Fei et al., 2020). Likewise, enzymes such as β-D-glucosidase and cellobiosidase (involved in cellulose degradation), N-acetyl-β-glucosaminidase (involved in chitin degradation), and phosphatase, which are related to C, N, P-cycling, could be negatively affected by microplastics (Lozano et al., 2021b).

10.5 Micro- and Nanoplastics Toxicity and Plant Performance

MPs pose a risk to human health because they are harmful to soil flora, which could affect plant growth and development. Sludge composts may act as a vehicle of MPs into soils and then enter soil biota, which in turn can influence the spread of MPs in the environment (Zhang et al., 2020a, b). Meanwhile, MPs can change the structure and properties of soil and the performance of plants. The effects of MPs on the physicochemical properties of soil adversely affect the root properties, growth, and nutrient absorption of plants (de Souza Machado et al., 2018).

Numerous studies validated that MPs delayed the germination of seeds, reduced plant growth, and induced the ecotoxicity and genetic toxicity of plants (Jiang et al., 2019), depending on the amounts of MPs present in the soil (Wang et al., 2020). Plants are the initial source of energy and organic matter in all ecosystems. MPs in the soil are migrated and accumulated in plants, and then transported into humans through the food chain, ultimately posing risks to the ecological environment and human health.

In general, toxicity mechanisms of MNPs hinge on the polymer size, surface characteristics, and type of the polymer. Plausible toxicity mechanisms mainly include membrane disruption, extracellular polymeric substance disruption, reactive oxygen species generation, DNA damage, cell pore blockage, lysosome destabilization, and mitochondrial depolarization. Positively charged nanoplastics accumulated in the root tips at lower levels than negatively charged sulfonic-acid-modified nanoplastics, but they induced a higher accumulation of reactive oxygen species and inhibited plant growth and seedling development. Negatively charged nanoplastics, on the other hand, were found frequently in the apoplast and xylem, implying that nanoplastics can accumulate in plants based on their surface charge (Sun et al., 2020).

10.6 Conclusion

In agricultural ecosystems, micro and nanoplastics affect soil microbial activity, microbial biomass, functional diversity, and the cycling process of plant nutrient elements in the soil which have an indirect effect on plant seed germination and growth. When ingested or in association with the soil biota, micro and nanoplastics can influence the agro-functionality through effects on soil root-associated microbiome and root symbionts, soil structure, nutrient immobilization, contaminant adsorption, and diffusion which can directly impact the fertility of the agricultural soil, quality of crops, and its yields.

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