Risks of Microplastics and Nanoplastics in Agricultural Ecosystems

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Contributor: Naga Raju Maddela , Balasubramanian Ramakrishnan , Tanvi Kadiyala , Kadiyala Venkateswarlu , Mallavarapu Megharaj

In all the agroecosystems, the transformation, migration, and transferring of MNPs, along with other contaminants, and the trophic transfer of MNPs can threaten the food web. MPs can exhibit negative and positive effects, or none, on the physical/chemical properties of soil, soil microbiota, invertebrates, and plant systems, depending on the polymer compositions, additives, and exposure time. Difficulties in comparing the studies on the effects of MNPs, as well as the discrepancies among them, are mostly due to variations in the methods followed for sampling, detection, quantification, and the categorization of particles, abundance, and exposure time. Since agricultural soils are important environmental reservoirs for diverse chemicals and contaminants, they provide milieus for several types of interactions of MNPs with soil biota.

microplastics nanoplastics soil biota toxicity and fate plant uptake additives
farmland soils regulatory guidelines

1. Introduction

The term “plastic,” which originally meant “pliable and easily shaped,” has been now used for a chain of synthetic polymers [1], but “plastic” is historically known as “celluloid” and “bakelite.” The mass production of synthetic plastics has continually increased since the 1950s. The current global production is about 370 Mt (Megatons; million metric tons), reflecting a similar rise in plastic waste generation. In 2050, the global annual primary plastic production can reach about 1-billion metric tons [2]. Interestingly, China is the world’s largest producer of plastics (31% of the overall production), while other Asian countries, including India, synthesize about half the amount of plastics in the world. Plastics are used in different sectors: packaging (~40%), building and construction (~20%), automotive industries (~10%), electrical and electronic industries (~6%), agriculture (3 to 4%), household, leisure, sports (~4%), and others (~17%; this includes plastics for furniture, medical applications, machinery and mechanical engineering, technical parts, etc.) [3]. Although direct usage of plastics in the agricultural sector is lesser than in other sectors, the accumulation of plastics in the agricultural soils is steadily increasing due to intentional uses and unintentionally through contaminated water and manure [4]. Almost half of the global usage of plastics in agricultural production is in Asia.

The intensive global production of resins and fibers, with an increase of 8.40% in compound annual growth rate (CAGR) from 1950 (2 Mt) to 2015 (380 Mt) [5], resulted in the release of enormous quantities of plastic wastes from different sectors. Nearly no or slow degradation rates are the key drivers of plastic accumulation in the environment. One of the important receivers of plastics in the environment is agricultural soil. By 2050, global projected plastic waste generation is expected to reach 26,000 Mt, of which 45% is not expected to be recycled or incinerated [5][6]. Based on the size, these particles can be of two types: MPs and nanoplastics (NPs), which have sizes that can be <5 mm and <100 nm, respectively [7]. Plastics of a size ˃5 mm are considered “macroplastics”.

2. Sources of MNPs in Agricultural Soils

Plastics are omnipresent in modern agricultural farms and food production systems. Annually, the agricultural value chains and food packaging use about 12.5 Mt and 37.5 Mt of plastics, respectively [8]. Crop and livestock production accounts for over 80% of plastic use, followed by fisheries and aquaculture (18%) and forestry (2%) in the agricultural value chains. The plastic protective films for fumigation, silage,bale wrap, mulching, nursery, wind tunnel, greenhouse, direct cover and non-woven floating cover, nets (ant-hail, anti-bird, wind-breaking, and shading), twine, and pipes for irrigation and drainage are extensively used in the production of agricultural and horticultural crops and livestock. The breakdown process of plastics begins with the action of handling, soil abrasion, water, wind, and UV light. The breakdown products of varying sizes, including macroplastics, MPs, and NPs can last long in these production systems.

The essential sources of MNPs in agricultural ecosystems are the standard practices, such as the application of biosolids (processed sewage sludge) [9] and compost [10], the use of plastic mulching films [11], water pipes, plastic greenhouse covers [10], polymer-based fertilizers [12], and pesticides [13]. Aerial deposition and transport from landfills are other considerable sources of MNPs in agricultural soils [14]. The plastic film mulching technology is popular among farming communities to conserve soil moisture, regulate soil temperature, and prevent weed growth. Light-density polyethylene (LDPE) has been applied to millions of hectares of agricultural soils across the world [15]. Polyvinyl chloride (PVC), as the plastic film, has improved water use efficiency and crop growth yield. However, the mechanized cultivation and the use of thin film generate higher residual levels of plastic mulch, which disturb the moisture and nutrient transport, decrease seed germination, hinder root growth, induce salinization, and accumulate harmful chemicals such as phthalate esters, aldehydes, and ketones in soils [16]. Thus, the “white revolution” of plastic film mulch technology is becoming “white pollution” in the agricultural production systems. The dumping of municipal wastes in open farm fields, parks, or landfills has been an important factor in spreading MPs to soils in several tropical and subtropical countries [17]. Though many factors like wind and water are involved in the removal of plastics present on the soil surface, substantial MNPs are expected to reach the soil layers [18]. Nearly 40% of MNPs that reach agricultural soils cannot be recovered. Instead, these contaminants break down into a continuum of smaller fragments [19].

Plastic contaminants can enter the agricultural production systems from damaged, degraded, or discarded agricultural plastic products, and the leakage from non-agricultural sources such as contaminated water, air, and waste. The available technologies remarkably control the entry of MNPs into aquatic systems, but not into soil systems. The current wastewater treatment (WWT) plants can remove ~99% of MNPs from wastewater, which results in mitigating aquatic systems’ pollution from MNPs [10]. However, the recovered MNPs remain in the sludge

[20], contaminating the agricultural soils upon the sludge amendments [21]. Polymer coatings for fertilizers for improved nutrient use efficiency and reduced risk of runoff and emissions, and those for seeds for improving germination, serve as the primary sources of microplastics, in addition to plastic mulch films in modern agriculture [22][23]. The widespread and regular application of polymer-coated fertilizers and seeds in the soil systems will eventually change the physical, chemical, and biological processes.

Most agricultural plastics are single-use products; with short life spans, they become waste within 12 months. For example, the plastic mulching films decompose due to weathering, and the microplastics that fall off from them remain in the soil. Improper disposal and mismanaged waste plastics will increase soil pollution by secondary microplastics. The abundance of MPs and NPs can vary depending on the sampling sites and other factors related to plastic usage (agricultural intensification) and climate. The abundance values of plastics at the sampling sites can serve only for reference. The types of plastics and additives used for different purposes make toxicological and risk assessments a necessity. In quantitative terms, the main polymers used for the agricultural sectors are polyethylenes (PEs) of both low- and high-density, polypropylene (PP), and PVC, followed by others such as expanded polystyrene (PS), ethylene-vinyl acetate copolymer, and polyethylene terephthalate (PET) [24]. The numerous types of polymers and the additives used in agricultural plastics present a high degree of variability in the toxicological properties and the risks of MNPs to plants and animals. At the end of each crop growing season, the plastic migration begins from soil to aquatic environments through erosion and surface runoff.

3. Transformation of MNPs in Farmland Soils

The transformation of MPs, which can be due to mechanical, chemical, and biological processes, is slow, by decades or hundreds of years, and is poorly understood in the agricultural ecosystems [25]. In the heterogeneous and porous medium of soils, the MPs and NPs can aggregate homogenously or heterogeneously with other solid particles. The homo-aggregation of MNPs can be described by the DLVO (Derjaguin, Landau, Verwey, and Overbeek) theory, which states that the interaction force between particles is due to van der Waals and electrostatic forces. The presence of heavy metals and other organic contaminants facilitates the hetero-aggregation of MNPs by sorption. The hetero-aggregation of MNPs with heavy metals and adsorption/desorption with organic pollutants are more than the homo-aggregation in soils with increased environmental risks. The exposure of plastic particles to light (UV rays), high temperature, and oxygen concentrations on the soil surface can accelerate photoaging, which can change the physical/chemical properties, especially the release of additives and monomers. The aggregated and aged MNPs in soils may get absorbed, degraded, and transported by biological organisms, wind, or runoff. Uptake, ingestion, biomagnification, and biodegradation are the major processes of the soil organisms by which MNPs undergo significant changes in the agricultural soils.

The degradation and transformation rates of MNPs in soil environments are minimal, and MNPs highly persist in freshwater, marine, and terrestrial environments [26]. There was a 0.40% degradation of PP after one year of soil incubation, whereas PVC was unaffected even after 10–35 years of soil incubation [27]. Under laboratory-simulated conditions, a maximum of 14–16.70% of PE strips were degraded in 5–5.50 months [28]. Compared to the MPs of PE and PP, PS was transformed easily, as confirmed by an indoor simulated weathering experiment [29]; this is attributed to a faster transformation propensity (likely to crack and break) of PS by friction heat. Thus, the degree of the physical transformation of MPs is greatly influenced by the type of constituents that they have. The physical transformation of MNPs in the agroecosystems is quite common by mechanical tillage and crop rotation; both accelerate the fragmentation of MNPs in soils [18]. The photo- and thermally initiated oxidative degradations are the primary types of abiotic processes, resulting in the transformation of MNPs in the soil environment. UV radiation and thermal oxidation cause several changes in MNPs in the soil ecosystem [30]. For instance, tensile strength, hydrophobicity, contact angle, and molecular weight were reported to decrease. In contrast, surface roughness, micro-cracks, crystallinity, polarity, functional groups, carbonyl index, leachates, and sorption capacity increased with aging [30]. The soil texture and composition are essential determinants in the degradation of MNPs in the soil environment. Due to higher organic matter content, polymers' degradation in clay soils is more rapid than in sandy soils [31].

4. Release and Fate of Additives from MNPs

Various chemical substances are added intentionally during the production and processing of plastics. For example, the additions of antioxidants, plasticizers, and flame retardants improve and impart specific properties, while polymerization catalysts, solvents, or lubricants are used as processing aids. In addition, byproducts, breakdown products, and contaminants are the unintentionally added substances in plastic products. More than 10,000 chemical substances have been identified with varying persistence, accumulation, and toxicity levels from scientific, industrial, and regulatory data sources [32]. Thus, the MNPs contain several chemical congeners/additives, such as dioxins, polycyclic aromatic hydrocarbons, heavy metals (e.g., lead, tin, and cadmium), phthalates, brominated flame retardants, bisphenol A (BPA), and BPA dimethacrylate [33]. Such additives are often mixed to expand final plastic products' utility and specific properties. Several of these additives (e.g., BPA and nonylphenol) are endocrine-disrupting chemicals (EDCs) [34]. The most detected EDCs in the leaching from particulate plastics were estrogen, BPA, bisphenol S, octylphenol, and nonylphenol; the second-most-often detected EDC was plastic additive, i.e., BPA with an identified mean concentration of 475 ± 882 µg kg^{-1} [35].

The additives in plastics can migrate from the plastics to the surrounding medium (i.e., air, water, or soil) they are in contact with, or they can also migrate within the plastics [36]. Additives are covalently or non-covalently linked with plastics, and these chemicals are easily leached from the source materials subjected to the environmental deterioration [37]. Desorption and UV-degradation are critical mechanisms in the leaching of additives from MNPs. Nevertheless, the additives are released from the parental material at any time, i.e., the production phase, use phase, and end-of-life phase [33]. The plastic waste that is subjected to landfilling and littering is subsequently degraded (i.e., chemical, mechanical, and biodegradation) and then fragmented to MPs or mineralized to CO_2 or inorganic molecules [33]; in all these events, there is a possibility for the release of additives from plastics. Notably, the composition of additives decides which chemical is to be released first during leaching. However, the migration potential is also essential in the leaching of additives, i.e., availability versus solubility behavior. Generally, polymers have three-dimensional porous structures inside, allowing additives to migrate. Therefore, more minor additives move freely in the polymers containing larger porous structures [38].

The type of degradation products released depends on multiple factors, such as polymer type, the degradation mechanism, and environmental factors (i.e., temperature and oxygen) [39]. Even by a single degradation mechanism, different polymers release different additives. For example, during thermal degradation, nitrogen-containing polymers (e.g., nylons, polyacrylonitrile, PU) release hydrogen cyanide (HCN), but chlorine-containing polymers (e.g., PVC) release hydrogen chloride and dioxins [40]. Since the chemical substances that are released from the plastics may have different hazardous properties, such as endocrine disruption, carcinogenicity, mutagenicity, chronic, acute toxicity, bioaccumulation potential, and persistence, their fate depends on several soil factors and the exposure potential to the biota for their uptake, ingestion, and biomagnification.

5. MNPs as Vectors of Other Contaminants

The contaminants, such as hydrophobic- and persistent organic compounds, heavy metals, and microbial pathogens, are adsorbed onto MNPs as hetero-aggregates in the soils. Hence, the MNPs act as potential vectors by bringing different contaminants (e.g., pharmaceuticals, polyaromatic hydrocarbons, agrochemicals, and engineered nanomaterials) to agricultural soils [30][41]. Thus, there is a significant concern about the co-transport of MNPs with the sorbed pollutants of farm soils. MNPs relocate the immobile contaminants, which have a strong propensity to interact with the soil matrices [41]. Thus, the hetero-aggregates of MNPs threaten the groundwater resources [42]. Several characteristics of MNPs, such as type, specific surface area, porosity, number of adsorption sites on the surface, and hydrophobicity, as well as soil physical/chemical properties like pH, ionic strength or salinity, texture, and metal cation concentration, influence the initial adsorption of contaminants by MNPs [30]. Regarding the transportation of organic contaminants along with MNPs, the critical conditions include a high abundance of particles, the type of contaminants, a greater mobility of particles than the contaminants, and a lower desorption of contaminant from the MNPs during the travel time of MNPs [41].

MNPs play a significant role as vectors in the accumulation and transport of heavy metals (HMs), organic contaminants, and engineered nanomaterials. HMs are adsorbed to the MNPs' surface by chemical interactions, such as electrostatic attraction, surface complexation, and precipitation. There was an adsorption of 0.091 (Cu^{2+}) to 0.470 (Pb^{2+}) mg kg^{-1} of HMs on PP and PE-type MPs in the aquatic environment through electrostatic attraction [43]. The principal mechanisms behind the interactions between organic pollutants and MNPs are the π–π interactions, van der Waals, electrostatic interaction, hydrogen bonding, hydrophobic interactions, pore filling, and cation ligand interactions [30]; structures and properties of MNPs generally determine these mechanisms. On the other hand, the engineered nanoparticles (ENPs) that are released to the soil ecosystem from different sources (e.g., cosmetics, textile industries, and wastewater treatment facilities) are readily adhered to MNPs by physical adsorption (e.g., π–π interactions).

6. Influence of MNPs on Soil Physical/Chemical Properties

MNPs seriously affect the soil's physical/chemical properties (e.g., water retention capacity, pore size, pore availability, hydraulic properties, and soil conductivity) and biological properties, especially those of soil microbial community. At environmentally relevant nominal concentrations (i.e., 2%), polyester, polyacrylic, and polyethylene MPs decreased the soil bulk density and caused changes in the structure and function in a loamy sand soil within 5 weeks [44]. The changes in the soil bulk density are mainly due to the low density of MPs, relative to those of many natural soil minerals. The PS-based MNPs changed the chemical properties and functional groups in dissolved organic matter aromatic rings [45]. Up to 6% of PP MPs (20, 200, and 500 µm) decreased the Ks values (saturated hydraulic conductivity) of loam, clay, and sandy soils by 70, 77, and 96%, respectively [46]. Especially in clay soils, the addition of MPs caused a more significant reduction in water retention capacity than in the loamy and sandy soils [46].

Compared to larger-sized MPs, relatively smaller-sized MPs significantly reduced soil porosity and aeration [47]. There is an inverse relationship between the number of MPs and the number of micropores in soil. Zhang et al. [48] found a reduction in pore-size distribution upon mixing MPs with the soil; this subsequently reduced the hydraulic conductivity of saturated soils. MPs can affect the distribution of soil water–stable aggregates and impair water infiltration by decreasing soil stability [49]. The properties of MPs are altered upon their entry into the soil matrix. There is a hetero-aggregation of MPs with the soil inorganic elements, such as Fe, Mg, Si, and Al [50]. Having a positive charge, Fe oxides readily interact with the negatively charged MPs by electrostatic attraction. The hetero-aggregation of MPs with soil minerals and OM enhances the density and zeta potential of MPs. Depending on the shapes (fibers, films, foams, and fragments) and polymer types, MPs can change soil pH, with those of foam and fragment shapes decreasing initially and then increasing the pH as observed in the laboratory incubation studies [51].

7. Toxicity of MNPs to Different Soil Biota

7.1. Microbial Diversity

The ecological interactions between the microorganisms and MNPs are complex and have received enough attention from researchers to identify suitable bioremediating agents. The microorganisms can adhere, colonize, and form biofilms, depending on the surface rugosity and hydrophobicity of MNPs [52]. The MNPs influence the soil microbial community structure, metabolism, and functions. After 90 days of incubation in Cinnamon soil, LDPE (76 mg kg^{-1}) caused an alteration in the bacterial community composition [53]. In another study, LDPE, and PVC at concentrations of 1–5% reduced both the richness and diversity of the bacterial community after 50 days of incubation. However, relative bacterial abundance was affected in a community-dependent fashion (i.e., based on phyla and families; increased *Burkholderiaceae* and decreased *Sphingomonadaceae* and *Xanthobacteraceae*) [54]. There was an enrichment of *Acidobacteria* and *Bacteroidetes* in loamy and sandy soils dosed with 2% of PE and PP and incubated for 29 days. However, the same experimental conditions depleted the populations of *Deinococcus, Thermus* and *Chloroflexi* [55]. The richness (Chao1 and ACE) and diversity (Simpson's and Shannon's) of bacterial communities were significantly affected by MPs in an acid, cropped soil. In an Ustic Cambosol type soil co-amended with PE (1%) and ciprofloxacin, the bacterial community diversity was reduced within 35 days of incubation [56]. However, the members of *Serratia* and *Achromobacter* were abundant in this co-amended soil. The abundance of ammonia-oxidizing bacteria and the copies of nitrite reductase (*nirS*) gene were reduced in clay loam soil treated with LDPE at different concentrations (0.10, 0.50, 1, 3, 6 and 18%) for 30 days [57]. However, MPs also have certain positive effects on soil microbial community structure. In the soil environments, microbial communities, rather than individual members, may apply diverse biofilm-mediated degradation processes involving penetration, leaching, and enzymatic action to transform and degrade MPs/NPs. The combination of biological and nonbiologically mediated processes influenced by the soil properties, such as organic matter and mineral contents, pH, and ionic strength, and the environmental factors, including temperature, rainfall, and irradiation, determine the biotic transformations of MNPs. The abiotic and biotic transformation mechanisms will determine the dispersion, accumulation, and the fate, thus, the lifespans, of MNPs in agricultural soils.

7.2. Invertebrates

Earthworms, which play significant roles in the soil food web, are the central focus of research on the effect of plastic pollution on soil animals. Species of earthworms, such as *Lumbricus terrestris*, *Eisenia fetida*, and *Eisenia andrei,* can ingest and digest MNPs, with variable effects on the growth rate, reproductive rate, and mortality [58]. The activities of earthworms increase the transport and incorporation of MNPs into the soil matrix. The meta-analysis of the effects of MNPs on earthworms and nematodes showed dose-dependent responses [59]. MNPs, even at 0.10% (*w*/*w*), can reduce the growth and survival of earthworms. Increased mortality and decreased growth rates in *L. terrestris* were observed in litter containing higher concentrations (28, 45, and 60%) of MPs of PE than at lower concentrations (7%) and control (0%) [60]. Many functions in soil animals were known to be influenced (decreased/increased) by MPs. The gut microbiomes of invertebrates can be significant sources of microorganisms capable of plastic degradation. The larvae of mealworms (*Tenebrio molitor*) and wax moth (*Galleria mellonella*) cut plastic pieces by grinding, and their gut microbiome with *Bacillus* sp. strain YP1 and the members belonging to *Citrobacter* and *Kosakonia* aided in the degradation of PS and PE [61][62][63]. MNPs have also been identified as critical factors that adversely affect different functions in soil invertebrates, such as reproductive fitness and success [64], ingestion behavior [65], oxidative stress response [66], locomotion [67], and gene expression [68].

7.3. Plants

Higher plants absorb materials or particles of 3–4 nm in size, or up to 40–50 nm in some cases. Bandmann et al. [69] provided the first report on the uptake of PS nanoparticles of 20–40 nm in size by tobacco BY-2 cells attributed to endocytosis. MNPs in the terrestrial ecosystem are known to be accessible to plant systems and cause phytotoxicities upon root uptake and translocation. Subsequently, MNPs enter the food chain, and, thus, “food safety” becomes an issue. In the recent past, several investigations have confirmed that MNPs are subjected to root uptake and translocation to the edible tissues of several food crop species such as wheat [70], carrot [71], cucumber [72], rice [73], maize [74], and lettuce [75]. Several adverse effects of MNPs on plant functionalities have been reported. For instance, a reduction in the root length, the fresh weight of the plant and chlorophyll content [76], decrement in shoot/root ratio [70], induction of genetic changes [77], reduction in seed setting and root/shoot ratio [78], altered metabolic pathways [79], decrement in seed germination rate [80], dry biomass and plant height [81], reduction in the photosynthetic metabolism of leaves, and interference in the mineral nutrition metabolism in the roots, stems, and leaves [82]. Importantly, MNPs can also exhibit indirect negative effects on plant growth and performance by altering the soil's physical/chemical properties [64], soil microbiome [83], and invertebrates [84]. The charge of the MNPs is also an essential factor in inducing different phytotoxicities. The positively charged PS NPs (PS–NH_2) were less accumulated in the root tips in *Arabidopsis thaliana* but caused a higher accumulation of ROS and, thus, affected plant growth and seed development worse than the negatively charged NPs of PS (sulfonic-modified; PS-SO_3H) [76]. Conversely, the negatively charged NPs of PS showed a higher accumulation in the apoplast and xylem. Very recently, it was observed that NPs of PS could significantly alter the gene expression pattern in a tissue-specific manner in *Triticum aestivum* L. [77]. In a hydroponic condition, 0.01–10 mg L^{-1} of NPs of PS (100 nm) altered several plant functions, such as carbon metabolism, amino acid biosynthesis, mitogen-activated protein kinase (MAPK)-signaling pathway, plant hormone signal transduction, and plant–pathogen interaction pathways. Cress seed germination was reduced dose-dependently in treatment with MNPs at 10^{-3} to 10^{-7} particles mL^{-1} [80]. When MNPs are with co-pollutants, the phytotoxicities are even worse. For example, photosynthesis and antioxidant activities in rice were adversely affected by the combination of NPs of PS (0.20 g L^{-1}) and As(III) (4.0 mg L^{-1}) than As(III) treatment alone [85]. However, there are also positive and non-significant effects of MNPs on plant functionalities [86], which makes it difficult to conclude the impact of MNPs on plants.

8. Regulatory Guidelines for Mitigation of MNPs

Framing regulatory guidelines for controlling MNPs in different environments is a challenging issue. The two main cumbersome reasons are: the intentional/unintentional release of MNPs, and the classification and quantification of MNPs. One of the reasons is that certain MPs are not included intentionally to the products. Instead, the degradation of plastics generates them. In this case, it is challenging to set regulations on unintentionally released MPs, and it would not be possible to regulate such MPs under the existing chemicals legislations. On the other hand, certain MPs are deliberately manufactured and intentionally added during the manufacturing of certain products (e.g., fertilizer coatings, phytosanitary products, cosmetics, household and industrial detergents, cleaning products, cosmetics, and paints, and products used in the oil and gas industries).

The following are some of the proposed regulatory measures for controlling the release of intentionally added MNPs: (i) prohibit the products containing MNPs on placing in the markets; (ii) restrict the use of MNPs in natural/biodegradable polymers; (iii) use products without foreseeable microplastics release; (iv) recommend product labelling to minimize the release of MNPs; and (v) implement mandatory reporting requirements on the identification, description of use, tonnage, and the release of MNPs [87]. The classification of NPs is controversial, and there are three possibilities to regulate NPs by considering them as MPs, nanomaterials, or polymers [88]. Based on the size (i.e., <100 nm), NPs can be considered as "nanomaterials." However, NPs mainly contain polymeric substances and could be regulated under "polymers."

9. Conclusions

The intensification of industrialization led to a higher use of intentional, and an accumulation of unintentional, plastics in the agroecosystems. There is a high level of burden of MNPs in agricultural soils, with their quantities detected up to 43,000 particles kg^{-1} [89], and the rate of burden is expected to be a maximum of 300,000 tons of MNPs yr^{-1} [90]. Both agricultural practices and amendments are the principal causes of soil contamination by MNPs. The available technologies are not 100% effective in removing MNPs from agricultural inputs, especially from biosolids [90]. The efficient WWT technologies can remove ~99% of MNPs from wastewater and leave them in the sludge, which takes the MNPs from the aquatic system to the soil systems through agricultural practices. MNPs are unaffected for a reasonably long period in the soil environment (e.g., PVC is unchanged after 10–35 years). However, agricultural activities (e.g., mechanical tillage and crop rotation) can accelerate the fragmentation of MNPs, which results in the unintentional release of MNPs in the soil ecosystem. MNPs further can contaminate soils in two ways: firstly, by releasing toxic additives that they contain, and secondly, by acting as vectors for several contaminants. Likewise, MNPs interact with soil biota in a complex environment that contains several contaminants, including but not limited to dioxins, PAHs, HMs, phthalates, BFRs, BPA, pharmaceuticals, agrochemicals, and engineered nanomaterials. In addition, aging causes several changes in MNPs in the soil ecosystem [91]. Therefore, the results of investigations carried out with the pristine forms of MNPs are not comparable with the scenarios that occur in agroecosystems by MNPs. According to laboratory analyses, MNPs have exhibited positive [92][93][94] and negative effects, in addition to having no effects, against the physical/chemical properties of soil, soil microflora, and invertebrates. The mixed impact of MNPs against abiotic and biotic factors is attributed to a wide range of variations in the experimental conditions in different investigations, such as MNP type and dose, soil types, and incubation time. MNPs exhibited adverse effects on plants either directly by direct phytotoxicity or indirectly by altering the soil physical/chemical characteristics and soil biota.

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