Chapter 5
Persistence of Micro- and Nanoplastics in Soil

N. Chaitanya, Suresh Babu Bastipati, and D. Bhagawan

Abstract Plastic pollution has been a heavy drawback for a number of years; these plastics (MNPs) have gathered notice from researchers all over the world. The fate, determination, and properties of microplastics (MPs) and nanoplastics (NPs) in soil are not well-known. In fact, yearly three hundred million plastics are created within the environment, and due this plastic trash, the soil acts as a logterm sink. In soil, the fate of MPs and NPs is powerfully determined by plastic physical properties, considering negligible impact is applied by their chemical structures. The derivative of plastic, termed deteriorate, other than generating micro- and nano-size waste, can produce marked changes in their properties (chemical and physical) with applicable impact on their reactivity. Further, these processes might cause the discharge of harmful monomeric and oligomeric components from plastics, likewise as cyanogenic additives, which can enter within the food chain, constituting a potential harm to human health and affecting the flora and fauna within the environment. In relevance their persistence in soil, soil inhabiting list, plastic uptake bacterium, fungi and insect are increasing daily. One among the most ecological functions due to MPs is expounded to their aim as vectors for microorganisms through the soil. However, the most ecological effect of NPs (limited to the fraction size <50 nm) is their capability to suffer the membrane of each being and organism cells. Soil biota, significantly earthworms and order Collembola, are often each MPs and NPs carriers through profile. The utilization of molecular techniques, particularly omics approaches, will gain insights into the results of MPs and NPs on composition and activity of microorganism communities inhabiting the soil and into those living on MP surface and within the gut of the soil plastic-ingesting fauna.

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5.1 Introduction

Plastics, easy to supply, strong, and flexible, were exponentially growing in production and consumption over the previous few decades worldwide (Jambeck et al., 2015). More than 300 million tons of plastics are manufactured every year wherein 50% of which are primarily single use (Chen et al., 2020). In maximum parts of the world, this plastic waste was mismanaged because the decomposition takes place more than 1000 years because it's more chemically stable and corrosion-resistant and degradation is very hard (Shen et al., 2019). About 6300 million metric tons of global plastic waste had exceeded by 2015, and the current production and waste management trends will attain 12,000 million metric tons by 2050 (Geyer et al., 2017). Due to the ubiquity, persistence, and less management, plastic wastes are scarcely recycled (Barnes et al., 2009; Dris et al., 2015; Nizzetto et al., 2016). Due to this the accumulation of plastic was covered inside the aquatic, terrestrial, and atmospheric environments or all types of environmental media, inclusive of aquatic ecosystems, landfills, and agricultural ecosystems together with mulching and biofilm in addition to air (Shen et al., 2019; Kumar et al., 2021; Wang et al., 2021; Adam et al., 2021). Plastic pollution contributes to a rebellion problem faced by the sector today. The plastic waste can break into smaller particles that can affect the terrestrial and aquatic surroundings significantly. These particles are known as microplastics (MPs) (0.1 μm–5 mm) and nanoplastics (NPs) (0.001–0.1 μm) (Gigault et al., 2018).

Microplastic pollution in soil became first addressed by Rillig (2012), and there have been an increasing number of studies centered in this crucial subject matter as soil and environmental scientists alike have realized its gravity (Chae & An, 2017; De Souza Machado et al., 2018a; Hurley & Nizzetto, 2018; Mai et al., 2018; Ng et al., 2018; Rillig et al., 2017). On World Environment Day in 2018, the United Nations Environment Programme (UNEP) referred to more research on the effects of microplastic pollutants in the soil environment (UNEP, 2018). One critical factor influencing the UNEP's decision was the fact that soil is probably a greater essential sink for microplastics than marine environments. It's far envisioned that plastic released yearly to the terrestrial environment is 4–23-fold greater than that released to the marine environment (Horton et al., 2017).

In general, the researchers of the studies make a special focus on MPs, ignoring the reality that NPs, the much less-explored plastic fragments, can also have an effect on the soil system (Revel et al., 2018) due to the fact NPs can act as the carriers for pathogens and serve as habitat for microorganism and virus. NPs are more dangerous than MPs as they could penetrate through the biological membranes (Ng et al., 2018). Notwithstanding the significance of MNPs in terrestrial environments, maximum of the MNPs research has focused on the marine environment (Horton et al., 2017; Mofijur et al., 2021; Soares et al., 2020). The enormous amount of MNPs present in the soil leads to unveiling pathways to the microorganisms and human health (Hurley & Nizzetto, 2018).

MNPs impact the soil plant system extensively because they accumulate in the soil and interact with PTEs and organic pollutants, concentrating the soil (Chai et al., 2020). MNPs can have an effect on the increase of plant life and its chlorophyll content material. Besides, MNPs can have interaction with soil organic particles and survive in soil for 100 years which may additionally contaminate the soil properties (physicochemical) and groundwater (Wahl et al., 2021). The crop yield of agricultural soil contaminated with MNPs could be affected negatively due to low pH levels and much smaller number of productive earthworms. Further, MNPs can act as the organic pollutant and pathogens carriers because of their excessive surface area-to-quantity ratio and hydrophobicity (Atugoda et al., 2021; Tiwari et al., 2020).

Microorganisms connected to MNPs can pose threats to the surroundings as they are able to act as the medium in transferring MNPs from the soil to plants and eventually to other living things through the food chain (Chai et al., 2020). The consuming of MNPs by human have a higher threat to several problems, such as reproductive harm, cancer, developmental postpone or organs issues. Visual exam, vibrational spectroscopy, and mass spectrometry are the analysis techniques of MNPs in the soil samples; however these analytical methods are most applicable to identify MPs in place of NPs because of the particles size of NPs that make the detection process tough. Moreover, those analytical methods commonly use samples from marine surroundings, creating the doubt whether that analytical equipment can be utilized in soil samples. Prior to the identification of MNPs, pretreatment and isolation of plastic particles from the samples, which includes soil matrices, are essential to avoid confusion. Nevertheless, there is loss of strong separation and pretreatment techniques from complex environmental samples and this may be a chief impediment (Hurley & Nizzetto, 2018). MNPs can interact with PTEs in soil, inflicting soil toxicity (Antoniadis et al., 2017, 2019; Palansooriya et al., 2020). The control or removal of MNPs particles in the soil is very difficult and hard (Oke et al., 2020; Hou et al., 2020). Currently, the soil and environmental scientists are trying to adjust and invent new techniques to assess the presence of MPs and NPs in soil (Qi et al., 2018). To reduce the impacts of MPs and NPs within the soil systems, there is a need to manipulate MNPs which includes microbial remediation, biotechnology use of biodegradable bioplastics, and public education.

5.2 Scenario of Plastic and Its Waste in the World and in India

The petrochemical sector is seemed as the backbone of plastic production; it is also considered a yardstick for measuring global monetary growth, wherein plastic processing and manufacturing are important. Only 2 million tons/year (worldwide) of plastic was produced in 1950. Since then, it was increased nearly 200-fold and

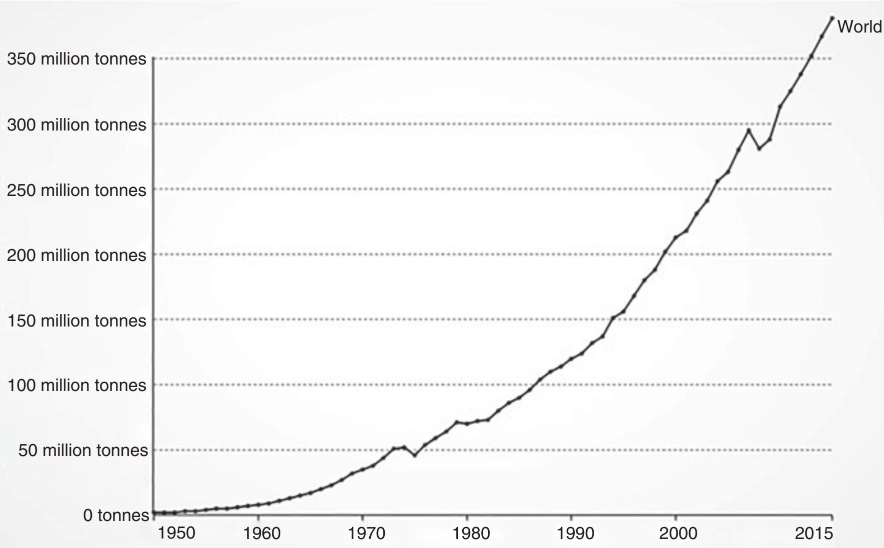

Fig. 5.1 Global plastic production, 1950 to 2015. (Modified from Geyer et al., 2017)

reached to 381 million tons/year in 2015 (Fig. 5.1). It's far predicted that inside the current financial year 2020, exports would cross 8 billion USD with an extended increase of 9.5% within the first half of FY 2018 as compared to the past year. Over 6.3 billion tons of plastic waste were generated globally up to now. That level is alarmingly high, and there are fears that if this situation isn't addressed, the world will turn out to be "drowning" in plastic. Plastic use has appreciably increased through the years; particularly, as it's a reasonably a cheap form of material, it could effortlessly be molded, and unlike paper, plastic keeps ingredients sparkling for longer intervals. Of late, there was a growing trend of making much less long-lasting plastic materials which makes it hard to reuse. But, at a matching rate, the quantity of plastic waste has also grown through the years, no longer just in India, but globally. The overall plastic produced almost 79% entering into the environment as wastes. Only 9% is recycled from the total global plastic waste. The Central Pollution Control Board (CPCB) reports (2018–2019) that 3.3 million metric tons/year of plastic wastes were generated in India. Even this information, horrifying as it is, might be sarcasm. While India's plastic waste trouble isn't always as massive as that of other countries, it's really growing. Some rich states like Delhi and Goa produce 37 grams and 60 grams/capita/day, respectively, against a national average of 8 grams/capita/day. These plastics are referred to as single-use plastics and are said to account for 40% of all plastics manufactured. Statistics also show that from the entire plastics produced globally, a measure 9% has been recycled. Prior to 1980, recycling and incineration of plastic was negligible; 100% was therefore discarded. For incineration in 1980 and recycling in 1990, rates increased on average by about 0.7 percent per year. An estimated 55% of global plastic waste was discarded in 2015, 25% was incinerated, and 20% was recycled (Fig. 5.2).

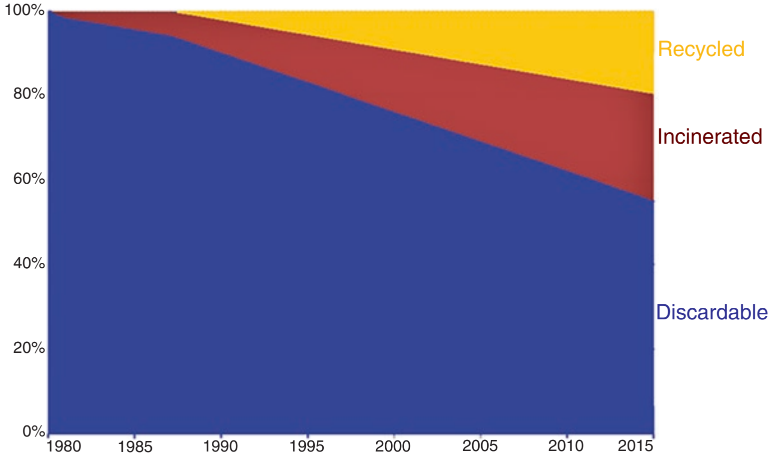

Fig. 5.2 Global plastic waste by disposal, 1950 to 2015. (Modified from Geyer et al., 2017)

The predominant task, however, is segregation and re-aggregation of plastic waste streams together with packaging waste, consisting of laminated plastic. As a lot as 79% of the plastic manufactures in the world ends up in landfills or in the environment in our oceans and our water bodies. We want to be aware of the plastic usage and need to find other alternative energy supplies for the recovery of the material immediately in order to save the environment.

5.3 Different Categories and Uses of Plastic

A main classification of plastics is based on the durability or non-durability of their shapes, or whether they are thermosets or thermoplastics. Thermosets consist of polyurethane, epoxy, and alkyd, and they are regularly used as insulators, adhesives, and plywood. The thermosetting procedure is based on heat-prompted go linking to form new and irreversible covalent bonds, which makes the thermosets strong and not easy to decompose (Rudyak, et al., 2018). On the contrary, thermoplastics have no newly shaped chemical bonds and may be recycled and remolded, making them extra broadly used than thermosets in patron goods (Mattsson et al., 2015; Battulga et al., 2019; Xu et al., 2019; Raddadi & Fava 2019). There are different types of thermoplastics, which are polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). PE is used in a wide range of less expensive plastic products, consisting of plastic bags and bottles. There are two typically used subtypes of PE: (1) the high-density polyethylene (HDPE), which is generally used in milk cans, detergent bottles, and molded plastic cases; and (2) the low-density polyethylene (LDPE) used in outside furniture, siding, ground tiles, clamshell packaging, and bath curtains. PP is mainly used to prepare ingesting straws, bottle cap appliances, yogurt containers, car bumpers, fishing traces, and plastic pressure pipe systems. PS is the mainly chemical used to provide food containers, foam peanuts, disposable cups, plastic tableware, plates, cutlery, CD discs and cassette bins. PVC is an essential element of plumbing pipes and guttering, shower curtains, window frames, and flooring. In addition to the everyday plastic classifications listed above, microplastic fibers (MFs), which might be made of polyester (PES) or PP, are one of the most common types of MPs located within the environment (Hü-er et al., 2018; Cole, 2016). MFs are generally used in an expansion of fibrous substances, inclusive of textile, industrial, agricultural, and household semi-finished or ancillary products used in different fields (Liu et al., 2019).

Generally, PE, PS, and PVC are three important forms of MPs used in scientific research. PE and PS are the popular plastic materials used in customer products, and they have shorter carrier lives than different types of plastics. Moreover, PVC is primarily used for plastic wire insulation or the cable jacket of data cables. Once the life cycle of a cable ends, the metals within the cable could be recycled, but the plastic elements containing PVC are commonly discarded into the environments because of the expensive for separation and recycling value. It was reported that 82% of PVC waste is discarded in landfills, 15% incinerated, and most effective 3% recycled (Suresh et al., 2017). This courting between the large output, brief life cycle and plentiful environmental discharge of these plastics makes them the primary recognition of scientific research (Deng et al., 2015; Yang et al., 2019; Deng et al., 2018; Wu et al., 2019).

5.4 Sources and Formation of MNPs

There are many viable routes through which microplastics can enter soil, along with soil amendment with compost and sewage sludge, plastic mulching, irrigation and flooding, littering, and atmospheric deposition (Bleäsing & Amelung, 2018). Compost and sewage sludge are extensively used as fertilizers, which may serve as a significant source of soil plastic pollutants in these areas. For example, in Ireland, 79.3% of sewage sludge became reused in agricultural lands (EPA, 2015). In Asia, China South Korea, and Japan accounted for 80% of world plastic mulching (Espı et al., 2006). Similarly, in China, plastic mulching increased fourfold from 0.64 million tons in 1991 to 2.60 million tons in 2015 (NBSC, 2019). Fragmentation of massive plastics result in the formation of MPs (>100 nm and <5 mm) Or NPs (<100 nm) (Horton et al., 2017). Larger plastics can be degraded in two mechanisms which are abiotic (mechanical method, solar irradiation, warmth, chemical substances) and biotic degradation (Chamas et al., 2020; Zhang et al., 2021). Plastics can be broken down mechanically through external forces, for instance, freezing and thawing of plastics in the marine environment. Wind and waves can cause plastics to collide with rocks and sands, ensuing in mechanical degradation (Fiend et al., 2018). The impact of external forces is determined by the plastic mechanical properties. Moreover, photodegradation mainly by UV radiation (UV-A and UV-B) is one of the vital procedures to degrade most of the plastics that require free radical-mediated reactions and are brought on by way of solar irradiation (Liu et al., 2019). There are few techniques to assess plastic degradation charge including the mass loss, evolution of carbon dioxide, chemical analysis, thermal analysis, surface analysis, and so on. The MPs in the environment can be leached from the agriculture practices, runoff, unintentional direct disposal, and fragmentation of larger plastic waste. These sources are then split into direct and indirect sources. Microplastics and nanoplastics input agro ecosystems either as primary (synthetic) micro and nano materials (e.g. in medical applications, waterborne paints, coatings, electronics, adhesives), or secondary microplastics and nanoplastics generated by the breakdown indirectly of large plastic debris (Koelmans et al., 2015; Duis & Coors, 2016; Rillig, 2012). Later, it turned into photodegradation of recovered marine microplastic debris (Lambert & Wagner, 2016), 1-cm2-portions of disposable polystyrene espresso cup lid (Lambert & Wagner, 2016) generated nanoplastics. Direct resources in agriculture consist of plastic mulches and soil conditioners and greenhouse materials (e.g., polyurethane foam and polystyrene flakes). Oblique assets consist of fashionable littering and the usage of dealt with wastewater and biosolids (Duis & Coors, 2016; Horton et al., 2017). Microplastic and nanoplastic emissions per capita vary greatly between regions because of populace affluence, size, presence, and efficacy of waste control practices (Ziajahromi et al., 2016; Nizzetto et al., 2016). However, we consciousness on plastics that become in agro ecosystems. Using present statistics and estimates, we have derived capability annual and maximum plastic loadings in agro ecosystems for Europe, United States of America and Australia to illustrate the capability scale of the plastic hassle. MNPs are broadly used within the electronics, plastic goods, automotive, textile, 3D printing, personal care, and cosmetics sectors (particularly toothpaste and exfoliating merchandise) (Tiwari et al., 2020; Carr et al., 2016) at which can be discharged (MNPs) into soil, affecting the soil environment. MNPs may be categorized into two companies which are primary and secondary MNPs (Fig. 5.3). Primary MNPs are processed plastics which are commonly delivered to personal care products (Auta et al., 2017; Anderson et al., 2016; Godoy et al., 2019; Guerranti et al., 2019; Praveena et al., 2018). These PE microbeads are extensively used as exfoliants in detergents, cosmetics, toothpastes, scrub facial cleansers, and drug carriers. Due to this, the primary MNPs especially cleansers serve as stimulus (physical) and after use, it was discharged into the environment (Cheg et al., 2018; Yurtsever, 2019). In addition, a recent study also suggested that glitters that are usually utilized in crafts, cosmetics, and textiles are some other essential supplies of plastic infection caused by primary MNPs (Yurtsever, 2019). The secondary MNPs are plastic debris that degrades from the massive portions of plastics because of UV radiation, physical wear, and biodegradation within the environment (Sharma & Chatterjee, 2017; Lehner et al., 2019; Adawi et al., 2018; Auta et al., 2017; Deng et al., 2017; Yurtsever, 2019).

Once the plastic enters into the environment, these plastics become brittle because of UV radiation that catalyzes the photooxidation. Similarly due to the wind, waves, and other abrasive interactions, the structural integrity of the

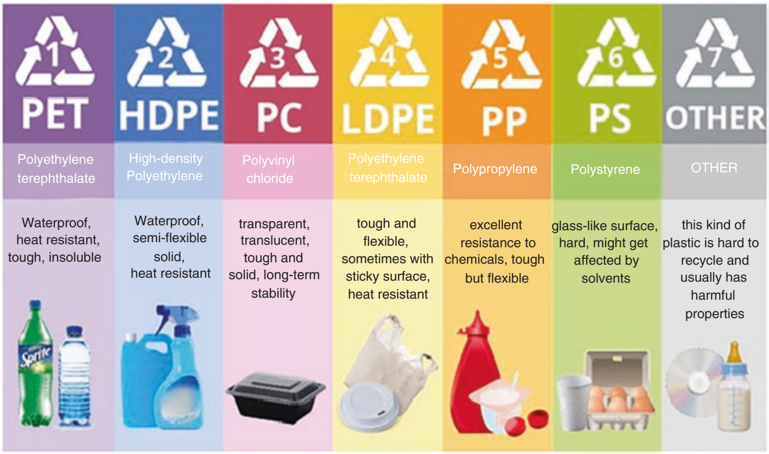

Fig. 5.3 Different categories of plastic

plastics further break and form MNPs (Sharma & Chatterjee, 2017; Lehner et al., 2019; Adawi et al., 2018; Auta et al., 2017; Deng et al., 2017; Yurtsever, 2019; Au et al., 2017; Hebner & Maurer-Jones, 2020; Weinstein et al., 2016; Wright & Kelly, 2017). Those outcomes suggest that both MPs and NPs can be produced within the degradation process of disposable plastic waste and accumulate over time (Lambert & Wagner, 2016; Sommer et al., 2018; Kole et al., 2017).

5.5 General Soil Properties

The properties of soil are determined by the structure of the soil, depending on different amounts of biotic and abiotic components. The combinations of these components determine the properties (physical and chemical) of soil.

5.5.1 Physical Properties

The following physical properties of soil are:

(a) *Soil Texture*

- Soil texture depends on the soil particle size that is based on the related components of minerals like silt, sand, and clay.
- Soil texture is an addition to the soil infiltration, porosity, and water retention capacity.
- The texture of soil differs with soil type; silt feels smooth, sandy soil feels gritty, and clay is sticky and moldable.

(b) *Soil Structure*

- The components of soil structure, together with sand, silt, and clay, might develop in aggregates because of their clumping and after together to form peds.
- This soil structure gives information on the matter content, soil texture, and biological activity.
- Soil structure is formed by physical processes that are probably improved or destroyed by the farming practices.

(c) *Soil Density*

- The common soil density ranges from 2.60 to 2.75 grams/cm^3, which generally remains unchanged for a given soil.
- The soil particle density is lower for soils with high organic matter content and higher for soil with higher mineral content.
- Soil particle density varies from soil bulk density which is less than soil particle density.
- Soil density usually depends on the soil structure and texture of the composition of the soil.

(d) *Soil Porosity*

- Soil porosity means the number of pores present within the soil.
- The determination of air and water movement within the soil is known as porosity.
- Usually, more number of pores between and within soil aggregates mean this soil is healthy, whereas few pores or cracks soil mean poor quality soils.
- The structure and texture of soil influence the soil porosity. Based on these pore sizes, the food substances like water, oxygen, and other gases/minerals will enter into the plants and other organisms.

(e) *Soil Consistency*

- Soil consistency refers to the ability of the soil to stick to itself or other objects and to resist deformation and rupture.
- Three moisture conditions define soil consistency: air-dry, moist, and wet.
- The consistency of dry soil ranges from loose to hard, whereas that of wet soil ranges from non-sticky to sticky.
- Soil consistency is an important property that determines the ability of soil to support buildings and roads.

(f) *Soil Color*

- Soil color is determined primarily by the organic composition of the soil.
- Soil color is one of the factors that help in the prediction of other soil characteristics within a soil profile.
- The quality of soil can be identified by the color; it means measuring organic matter, iron oxide, and the clay contents of the soil.
- Besides, soil color is also influenced by the mineral content of the soil as the color might change as a result of oxidation of degradation.

5.5.2 Chemical Properties

(a) *Cation Exchange Capacity (CEC)*

- At particular pH, the maximum holding capacity of total cations that a soil sample is known as cation exchange capacity.
- In soil, the cation exchange capacity is taken as an indicator of nutrient retention, soil fertility, and the ability of soil to protect groundwater from cation contamination.

(b) *Soil pH*

- The reactivity of soil is expressed in terms of the soil pH, which determines the acidity and alkalinity of the soil.
- It is the measure of the concentration of hydrogen ion in the aqueous solution of soil which ranges between 3.5 and 9.5.
- Usually, the higher amounts of manganese and aluminum present in the soil have high acidity, and higher concentration of sodium carbonate has higher alkalinity.
- In terms of soil fertility, agricultural production tends to be more in acidic soil.

(c) *Soil salinity*

- Salts in the soil are transported from salt tables in water resources that then accumulate due to evaporation.
- During irrigation processes the salinization of soil also occurs from drainages. The salt accumulation affects the degradation of organic matter in soil and the vegetation on the soil.
- The most common salts that are present in soil include magnesium sulfate, potassium sulfate, and carbonates.

5.6 Impact on Soil Properties

Once in soil, MNPs accumulation may cause a series of adverse effects in soil ecosystems. MNPs may alter soil physical properties, decrease soil fertility, and disrupt resident microbial groups, therefore affecting soil quality and nutrient cycling (Awet et al., 2018; De Souza Machado et al., 2018b; Wan et al., 2019; Zhu et al., 2018). Moreover, these MNPs ingested by way of earthworms had been observed to be transferred through the food chain, which may also pose a potential threat to terrestrial predators and even human beings (Huerta Lwanga et al., 2017). Several research have simulated the abiotic transport of microplastics, especially nanoplastics, in soil using column experiments packed with porous media (Alimi et al., 2018; He et al., 2018; O'Connor et al., 2019). The movement of earthworms also can provide a pathway for downward microplastic transport, potentially into groundwater systems (Yu et al., 2019). Similarly, microplastic generally tends to adsorb various classes of potentially toxic chemicals, which include polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), hexachlorocyclohexanes (HCHs), pharmaceuticals and personal care products (PPCPs), pesticides, perfluoroalkyl substances (PFASs), and heavy metals (Engler, 2012; Holmes et al., 2012; Lee et al., 2014; Liu et al., 2017; Llorca et al., 2018; Seidensticker et al., 2018; Velzeboer et al., 2014; Wu et al., 2019; Xu et al., 2019). Significantly, due to the sorption of contaminants (e.g., organic and inorganic compounds) onto microplastics (in particular nanoplastics), the migration of plastic debris likely enables the transport of absorbed contaminants throughout soil and contributes to a more ecological chance (Liu et al., 2018; Liu et al., 2019).

5.6.1 Soil Chemical-Physical Properties

The presence of MPs and NPs in soil aggregates can alter biological, chemical, and bodily properties of soil (Rillig et al., 2017; Moreno & Moreno, 2008; Atuanya et al., 2012; Kasirajan & Ngouajio, 2013) and have an effect on the estimation of soil carbon sequestration (Santos et al., 2017). The effect of plastics on soil combination formation and humic acid properties are shown in Fig. 5.4. Certainly, Atuanya et al. (2012) observed that the addition of plastic granules to soil improved the whole natural carbon content of soil because the modern-day methods used to quantify the soil organic carbon also determine the invisible MP fraction of soil aggregates (e.g., polystyrene or polyethylene incorporate almost 90% carbon) (Atuanya et al., 2012). Consequently, Riling advocated re-comparing what's the "actual" soil carbon storage in plastic-polluted soils. De Souza Machado et al. (2018a, 2018b) studied the results of MPs with shape, density and chemical composition on the bulk density, water conserving capability, water strong aggregates, and microbial sports of the soil.

As previously mentioned, the interactions of MNPs with soil reactive components and with the main extracellular biological molecules may affect soil functionality, which could directly affect the soil fertility and consequently yield and quality of crops. But, only a few reviews confirm the environmental relevance of MPs in soil. MPs and NPs can interact with various practical of the dissolved fraction (dissolved organic count number, DOM), which can be associated with inorganic pollution (Chen et al., 2014, 2017; Sun et al., 2017). The end result would be the formation of natural complexes being probably very toxic and shifting thru the soil profile (Chen et al., 2018a). Certainly, humic substances interacted with MPs (phenanthrene) and heavy metals (Pd and Cd) while being adsorbed on a clay mineral (bentonite) (Zhang et al., 2015). MPs can have interaction with the fragrant DOM structure via conjugation and then with carboxyl organizations and C=O bonds (Chen et al., 2018a). Microplastics assume to act as electron donors to humic materials main to highly conjugated co-polymers with an improved electron density (Fig. 5.4). Those consequences depend on the plastic size and the pH of the

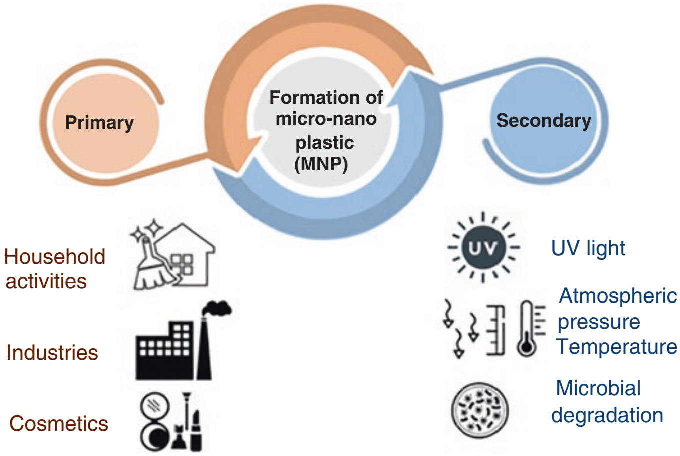

Fig. 5.4 Formations of MNPs. Primary MNPs are produced for a specific purpose, for instance, microbeads in cosmetics, microfibers in textiles, etc. On the other hand, secondary MNPs are produced due to "environmental actions": sunlight, wave actions, and microbial degradation

soil answer. On the other hand, NPs can boost up the kinetic assembly rate of DOM through susceptible electrostatic interactions and hydrophobic interactions as a consequence forming the particulate natural count (Chen et al., 2018b). The interaction of MPs with natural compounds also relies upon at the plastic's age, but contradictory variations in reactivity among the elderly and the relative unique plastics were observed (Hü-er et al., 2018; Liu et al., 2019). Interactions of MPs with natural matter can also affect the nutrient availability to biota in soil, as an instance, with the aid of reducing the dissolved organic N and dissolved natural P forms (Liu et al., 2017).

5.6.2 Soil Microbial and Enzyme Activities

Recent studies have focused on the potential of microplastics to affect or disturb soil microbial communities and enzymatic activities, but the findings of these studies disagree on the magnitude of the impact of microplastic pollution on these endpoints. Polyacrylic and polyester microfibers (0.1% w/w) significantly decreased soil microbial activities (De Souza Machado et al., 2018b). Polystyrene (PS) nanoplastics at 100 and 1000 ng g^{-1} significantly decreased soil microbial biomass and increased basal respiration, respectively (Awet et al., 2018). An intensely enhance the rate (28% w/w) of microplastics PP expanded up to 3 times of respiration rate of soil basal (Yang et al., 2019). And the presence of PS nanoplastics (100 ng g^{-1}) in silt loam soils may reduce the enzyme activity which are involved in the C, N, and P cycles (Awet et al., 2018), while PP microplastics (28% w/ w) mainly stimulated the activity of fluorescein diacetate hydrolase in sandy loam soils and hence increased nutrient availability to plants by enhancing microbial hydrolytic activity on SOM (Liu et al., 2017; Yang et al., 2019). Likely the effect of microplastic on soil physical properties and soil microbial and enzyme activities also depend on size, shape (linear vs. nonlinear), addition rate, soil texture, and polymer composition. Plastic film residues (67.5 kg ha^{-1}) can cause significant declines in soil microbial community diversity and decrease soil microbial C and N, as well as decrease the activity of fluorescein diacetate hydrolase and dehydrogenase by 10% and 20%, respectively (Wang et al., 2016). However, it determined that these negative effects might be related to concomitant phthalate pollution and not to the occurrence of plastic film residues (Wang et al., 2016). Overall, anthropogenic microplastic pollution may alter soil microbial community diversity, as well as the activity of enzymes and microbiota in the soil and thus disturbs microbial ecosystems and affects soil nutrient cycles. Due to the environmental stresses exerted on soil microbial communities, the adaptation and evolutionary response of soil microorganisms to microplastics in soil should be considered and addressed in future research (Rillig et al., 2018).

5.6.3 Soil Microbial Community

The transport of microbial species through plastic waste, specifically the function of MNPs in transporting microorganisms, was poorly identified because of methodological issues. Pesticides can pass through the soil with MNPs as hypothesized (Horton et al., 2017). The concern on those problems should suggest destiny studies with the intention to aware on MNPs role not only as vectors of microorganisms however also as vector of pollutants. MPs can affect a few microbial residences along with MNP-associated microorganism, which confirmed higher plasmid transfer costs than free-living microorganism (McCormick et al., 2014). Because the elimination of biofilm through bacterial community can collect a large antibiotic resistance potential, it is important to hypothesize that MPs might also act as vector for antibiotic resistance (McCormick et al., 2014). In the biofilm, the DNA transfer is involved by both transformation and conjugation (Li et al., 2001). The cell function is affected by the NPs through the cell's lipid membranes (Rossi et al., 2014). But the prevention of NPs from the cells through microorganisms by means of adopting exceptional self-protective mechanisms, which include secretion of molecules, changes of intracellular membrane and neutralizing the contaminants (Henriques & Love, 2007; Leriche et al., 2003) and any biofilm matrix and other the bacterial cell wall barriers (Jing et al., 2014; Tang et al., 2018). Perhaps the motion of cells from a biofilm state which is in a planktonic state will contact with NPs (Jing et al., 2014). The biofilm action for the protective towards toxicity of NPs is exerted with the aid of active and passive mechanisms. The passive safety is because of the biofilm matrix properties (physical-chemical), consisting of practical agencies and the high density at the extracellular polymeric materials that are efficient of binding and entrapping NPs on the surface of biofilm layer, respectively (Feng et al., 2018). Further, NPs separate from biofilms and after they penetrate on the surface of biofilm (Jing et al., 2014), which is probably because of tendency NPs to form hetero-aggregates within the presence of natural organic matter and inorganic colloids the bacterial pastime (Jing et al., 2014). But the NP presence may result in resilience and useful redundancy houses within the bacterial network inhabiting the biofilm (Tang et al., 2018). There is no exact information about the soil MNPs because of the soil microbial composition. So, further researches should fill those gaps by way of monitoring the relative consequences via figuring out microbial diversity via metagenomics or amplicon sequencing (Schöler et al., 2017; Vestergaard et al., 2017).

5.7 Soil Fauna

Soil biota plays a significant role in soil ecosystem techniques and gives a number of environment services such as decomposition of natural count, nutrient biking, bioturbation, and suppression of soil-borne illnesses and pests (Brussaard, 1997). According to the body width of soil fauna, they're categorized into three categories, i.e., microfauna (<0.1 mm), mesofauna (0.1–2 mm), and macrofauna (>2 mm) (Orgiazzi et al., 2016; Wardle, 2002).

5.8 Soil Quality

5.8.1 Soil Physical Environment

Numerous studies have supplied restricted statistics concerning the have an effect on of MNPs on soil physical homes. The prevailing proof has revealed that the impact of MNPs on soil residences depends on plastic type. Those with a shape and size extra just like soil debris have a much less pronounced effect on soil structure and water cycle. as an example, polyester fibers (0.4%,w/w) appreciably reduced soil bulk density and water-strong aggregates, and extended water-conserving capacity and evapotranspiration, at the same time as other kinds of microplastics, together with PE fragments or polyamide (PA) beads (2.0%w/w) prompted results with a lower significance (De Souza Machado et al., 2018a, 2018b, 2019; Lau et al., 2018). Furthermore, polyester fibers had been found to significantly decrease the bulk density of sand soils (0.4% w/w), however not clay loam soils (0.3% w/w) (De Souza Machado et al., 2018b; Zhang et al., 2021).

Consequently, it is speculated that soil texture is an important aspect to decide the impact of MNPs on soil properties; however extra research are required to test this speculation. Polyester fibers (0.3% w/w) have additionally been observed to affect the pore shape of a clay loam soil (Zhang et al., 2019). PE movie (1% w/w) has been observed to increase the rate of water evaporation in a clay soil to a full-size diploma (Wan et al., 2019). In addition, plastic-film residues (15 kg ha^{-1}) instigated significant changes to preliminary gravimetric water content, bulk density, total porosity, and soil water distribution (Jiang et al., 2019). These deviations from a natural state suggest that the presence of microplastics should pose a capacity hazard to soil ecosystems.

5.8.2 *Soil Chemical Fertility*

Microplastics may also affect the soil chemical properties. An amendment rate of 28% (w/w) microplastics significantly increased the concentrations of dissolved organic C, inorganic N, and total P in a sandy loam soil, but these changes were not observed at a reduced amendment rate of 7% (w/w) over 30 days (Liu et al., 2017). Soils with a range of textures and long-term effects need to be considered in future research to gain a better understanding of these phenomena in the field. Due to the presence of plastic residues, the soil organic matter (SOM) and alkali-hydrolysable N at 500 kg ha^{-1} and available N and P by 55% and 60%, respectively, at 2000 kg ha^{-1} (Dong et al., 2015). Those findings recommend that plastic-mulching residues certainly decrease soil fertility and possibly result in decreased plant growth while the impact of microplastic under environmental conditions isn't properly understood (Fig. 5.5).

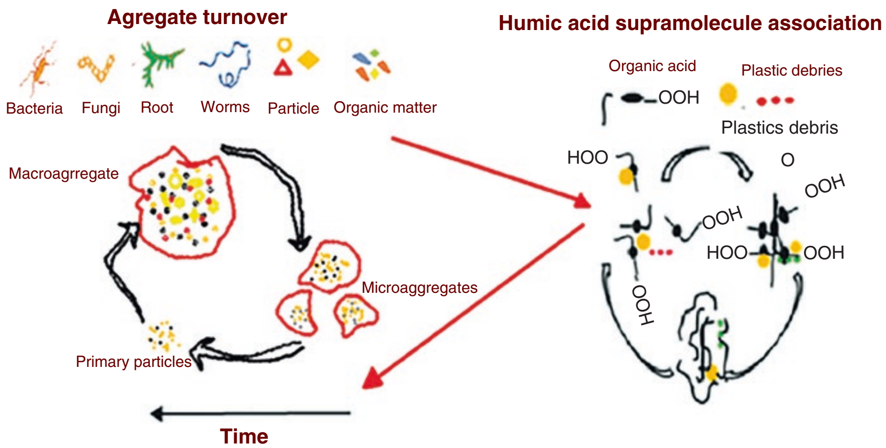

Fig. 5.5 Plastics effects on humic acid properties and soil aggregate formation (OM Organic Matter)

5.9 Soil Pedogenesis

An interesting issue mentioned above is the effect of MNPs on the soil properties, due to an extended residence time and excessive reactivity along with the soil pedological procedures. It's far feasible to hypothesize the presence of MNPs characterizing thing to categories the soil horizons (surface and subsurface). Furthermore, how should this debris alter the pedological processes isn't discussed within the research study to our expertise. This feasibility is preeminent and harbinger of thrilling trends. In this context, it's far crucial to don't forget these days observed pyro-plastics originating from the regularly burning waste particles (Ehlers & Ellrich, 2020; Turner et al., 2019). These plastics may also emerge as part of the soil's geological cycle due to their recalcitrance to degradation.

5.10 Plants

The contamination of soil plastics could apply a direct and indirect influence developed plants as an outcome of their root take-up or impacts on soil substance physical-chemical and organic characteristics individually. Concerning the direct impacts over the most recent 2 years, there were various studies of MNPs' effect in plants (Huerta Lwanga et al., 2017); the pollutants in plant metabolism or their stockpiling of headstrong pollutants could be the primary issue (Sandermann, 1992). The plant take-up of MNPs depends upon the physiological and anatomical characters of the plant on plastics properties, particularly those of the eco-corona and environmental ageing affecting surface chemistry and behavior (Ng et al., 2018). Li et al. (2019) have established that plastic material with size up to 0.2 μm can be absorbed by roots (lettuce) intercellular presence of plastics as a "grape-like" group. As of late, Sun et al. (2020) revealed that take-up of NPs altogether relies on their surface. The researchers showed that collection and take-up of adversely charged NPs was a lot higher in attaches contrasted with emphatically charged NPs, due to their high restricting proclivity with extremist adhesive and their size expanding through the hetero-conglomeration acceptance by root's exudates. Nonetheless, these outcomes do not bar the danger of the MP section into the human pecking order for food as a result of their grip to the surfaces of root vegetables and salad (Sun et al., 2020). Smith et al. (2018) studied on MPs from modern created fertilizer could aggregate in plants compost.

The immoderate accumulation of plastic in the root can cause various problems for the plants which include the disruption of the transport system (nutrient) via the interference of the cell connection and/or the pores in the cell wall (Jiang et al., 2019) and the extreme production of reactive oxygen species (ROS) (Jiang et al., 2019), and the plant disease resistance can reduce by inducing down regulation of disease resistance genes (Sun et al., 2020). Further these plastic particles enter into the roots, stems, and leaves through the vascular system following the transpiration and finally detected at intercellular level as "string-like" cluster and dispersed forms, respectively (Li et al., 2019). The NPs (<0.1 um) can normally enter in the cell membrane, but the MPs cannot enter inter the cell membrane because of their particle size (from 0.1 μm to 5 mm).

NPs can take up by the plant cell endocytosis, through ion transport channels along with the aquaporins or carrier proteins. The particle size of NPs is important for plant uptake due to nano-beads (polystyrene) with a diameter of 20 to 40 nm were entered into tobacco cells, but not those of 100 nm (Bandmann et al., 2012; Kettler et al. (2014) advised that the threshold value is 50 nm. And it also depends on physiological and anatomical properties of the plant; plant species; properties of nanoparticle; plant parts, especially the eco-corona; environmental ageing; and activity of NPs, affecting the surface chemistry. More investigations is need to well known MNPs translocation, toxicity and storage on plants and the defense mechanisms of plants against NPs (Wang et al., 2013).

In indirect MP and NP effect on cultivated plants, the primary form to be considered is their effects on nutrient immobilization, soil structure, impurities in diffusion and adsorption, soil microbial community root-associated microbiome, and root symbionts. The toxicity of plastic waste could cause degradation in soil; and this may evidence the plants' high enantioselectivity, which is as recently investigated for hexabromocyclododecanes (HBCDs) and pentabromocyclododecenes (PBCDEs) monomers (Huang et al., 2018).

5.11 Biological Indicators in Soil

Plant growth and seed germination (ISO 11269-2 Soil Quality–Part2, 2012), focusing on the inhibition of nitrification and toxicity to earthworms (Bandmann et al., 2012), act like biological indicators of plastic toxicity. As previously indicated, these soil filtering earthworms can accumulate both MPs and NPs into the soil, and thus these earthworms can extract plastics from the soil (Zhu et al., 2018). The microbial degradation of MPs can produce volatile compounds (VOCs), includes ethylene and methane, MPs indicators presence in the analyzed sample (Huerta & Wanga et al., 2018; Kyaw et al., 2012; Royer et al., 2018) . However, the application of this process is aimed by the lack of awareness by (such as those due to microbe-microbe and plant-microbe interactions) producing VOC mechanism during the degradation of plastic and by various factors, such as moisture, pH, clay minerals and organic carbon content, and different microbial diversities affecting this production in soil (Serrano et al., 2006; Heribert, 2014).

5.12 Environmental Risk of MNPs in Soil

MNPs entering the soil pose a potential environmental hazard to terrestrial ecosystems. Those anthropogenic substances may also pressure environmental changes in soil that cause pressure to soil fauna (De Souza Machado et al., 2018a; Rillig et al., 2017). But few research have documented the environmental effect of MNPs on the soil environment. It is critical to conduct further studies on the risk of these classes of pollutants so one can direct efforts to address their presence inside the environment.

5.13 Environmental Management of MNPs

Micro-nano plastics (MNPs) are very hard to degrade within the soil. So, we must mitigate or minimize the impacts of MNPs at the soil environment and human beings, which are legislation (regulation on the plastic waste management and plastic manufacturing in various industries), technical (biodegradable bioplastics and microbial biotechnology) and social (public education on reducing using single-use plastics or disposable plastics, adopting recycling habits, use of biodegradable products).

First, biological technology using organic retailers (bacteria and fungus) and metabolic enzymes has been advised and explored due to their competencies to degrade natural and synthetic polymers. Microbes will adhere to the plastic surface, which bring about the formation of microbial biofilm. Following that, microorganisms secrete extracellular enzymes and exopolysaccharides to adhesion of biofilm on the plastic surfaces, biodeterioration triggering, and breakdown of the plastic substances into monomers, dimers, and oligomers. Ultimately, mineralization takes place with microbial biomass, carbon dioxide, and water as the end products (Ganesh Kumar et al., 2020). From the past research, microorganisms that have proven to degrade plastics were *Streptomyces setonii*, *Pseudomonas aeruginosa, Rhodococcus ruber*, *Pseudomonas stutzeri, Streptomyces badius, Aspergillus niger, Aspergillus flavus,* and *Fusarium lini* (Pathak & Navneet, 2017). Liang et al. (2016) isolated a bacterial strain *Pseudomonas tamsuii* TKU0155 from Taiwanese soil, to reduce PLA, fibrinogen, and tributyrin successfully, except casein, triolein, and poly (β-hydroxybutyrate). Gajendiran et al. (2016) demonstrated the biodegradable capability LDPE (*Aspergillus clavatus)* of an aqueous medium. The degradation of LDP E became observed through the burden and morphological changes through microscopy and CO_2 evolution test (Sturm test). Mor and Sivan (2008) proved the potential of biofilm-producing *Rhodococcus ruber* in inducing partial degradation of PS. The biodegradation of plastic substances can be influenced by the microorganism species involved, resources of carbon, and size and types of plastic substances. Microorganism can utilize the plastic substances for the carbon sources through biodegradable procedure, but the high stability of MNPs in the environment is making them hard to be used as carbon resources. Consequently, biodegradation of MNPs necessitates the suitable conditions, which are not always possible in field conditions (Shen et al., 2019). Biotechnology, for example, enzyme engineering, stress engineering, and metagenomics, can be used to enhance microbial generation or boost up enzyme activity within the biodegradation of plastic materials or MNPs. Wei et al. (2016) confirmed the residual exchange of amino acid of polyester hydrolases, Tf Cut2 from *Thermo bifidafusca* KW3 with LC-cutinase

(LCC) elevated the PET degradation. Islam et al. (2019) investigated the cutinases from *Thermomonospora curvata* through the combination peptide tachystatin A2 which facilitated the enzyme kinetics and biodegradation rate of polyester-polyurethane nanoparticles (NPs). Huang et al. (2018) utilized a strain by means of inactivating dual arginine translocation complexes and expanded the secretion of PETase by 3.8-fold in *Bacillus subtilis* strain to increase the MP/NP degradation, specifically PET. Moog et al. (2019) used *Phaeodactylum tricornutum* (a photosynthetic microalga) as a chassis to produce engineered model of PETase within the bacterium *Ideonella sakaiensis* to degrade PET. Apart from the microbial generation, physicochemical-biological treatments also may be used to degrade MNPs. Siipola et al. (2020) studied on the production of low-price biochar from the bark of Scots pine (*Pinus sylvestris) and spruce (Picea sp.) trees in the remediation of chemical contaminant complexes from MPs or immobilize larger MPs particles. Cunha et al. (*2020) determined the bioflocculant *from Cyanothece* sp, which can EPS to mixture NPs and MPs. MNPs induced a negative impact on the microalgal growth up to 47%. Similarly, to remediate MNPs, few chemical substances can also be used. Ramirez Arenas et al. (2020) assessed the capability of nanoparticles (TiO_2/CeO_2) collectively with chemical coagulants, polyaluminum chloride, or iron chloride to remove PS NPs through water treatment method. The findings suggest that polyaluminum chloride became greater green in comparison with iron chloride seeing that all nanoparticles are coagulated at low dosage at the turn aspect, NPs coagulation was found much less efficient compared with TiO_2 and CeO_2 NPs, indicating that NPs was more solid and harder to dispose of. Additionally, the usage of bioplastics (biodegradable materials) can assist to reduce the MNP effect in the soil environment; these biopolymers biodegrade completely into carbon dioxide without producing any other hazardous products. Biodegradable bioplastics (PLA, polyhydroxyalkanoates) that made from distinctive biomass feed stocks, for instance, microalgae, could help resolve the problem of plastic pollution within the environment (Chia et al., 2020; Mofijur et al., 2021; Zhang et al., 2019). The legislation or policies have to be focused to reduce the plastic waste (MNPs) in the environment, for instance, reusable and recyclable plastic manufacturing products, with restriction of MPs in personal care products and cosmetics in some European countries (Boyle & Ormeci, 2020). Under REACH regulation in 2019, ECHA reported that the limitation of MPs to products and look forward to reduce and release of 500,000 tonnes of MPs. Besides, for the products containing MPs, there may be a necessity for labeling to reduce MPs release and enhance their right disposal as well as pre considered necessary for monitoring and reporting in order to increase data collection and discover feasible future risks.

Some countries, for example, Malaysian authorities, have implemented “No Plastic Bag” campaign in any state imposing the minimal fee of RM0.20 per plastic bag to customers in all commercial enterprise premises. This has recommended the citizens to carry their own buying bags and decrease the plastic utilization, adapting the “green” lifestyle. The implementation of government law can help to reduce and control using plastic, especially MNPs in numerous industries. Lastly, public schooling is likewise critical in dealing with and decreasing MNPs within the environment.

Public training also aids in increasing consciousness to the public about the terrible effects of MNPs to the environment. The public community wants to be educated to practice 3 “R” in their life, for instance, reusing plastic baggage; reducing using single-use disposable plastics, plastic bottles, or plastic straws; and adopting recycling habits. While grocery buying, it’s really helpful to use personal buying bags, use recycle bag, and buy bins for bottles to lessen using plastic. When buying foods for take-out at the café or restaurants, use personal food boxes to reduce the usage of Styrofoam.

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