Current understanding of subsurface transport of micro- and nanoplastics in soil

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Abstract
Environmental problems caused by plastic pollution in terrestrial systems have received increasing attention, especially the issues related to micro- and nanoplastics. Soils are a major receptacle and reservoir of plastics, and accumulated plastics can negatively affect soil health. In this short review, we discuss the current state of knowledge of subsurface transport of micro- and nanoplastics in soils. We discuss the fundamental transport mechanisms for micro- and nanoplastics and highlight the peculiarities of environmentally relevant micro- and nanoplastics. Plastic particles \(>10\ \mu\text{m}\) are generally filtered out in soil, but smaller plastic particles have the potential to move through soil. Larger plastics in soil will break down into micro- and nanoplastics over time due to environmental weathering reactions, making the plastics more prone to subsurface transport. Moreover, interactions with microorganisms and dissolved organic matter may render micro- and nanoplastics more hydrophilic, thereby facilitating subsurface transport. Further, soil organisms can move plastic particles by bioturbation, and plastics themselves can affect soil hydraulic properties. Although much of the past research has focused on transport of pristine plastic particles, focus should be given to environmentally relevant plastics, considering the complexities of irregular shape, polydisperse size, and heterogenous surface properties, as well as the temporal changes of these properties caused by continuous environmental modifications.

1 INTRODUCTION

Plastic pollution in oceans has been an environmental issue since the 1970s (Carpenter & Smith, 1972). It is estimated that about 8 million tonnes of plastic are deposited in oceans every year (Ocean Conservancy, 2020), and over 250 million tonnes of plastics will be accumulated in oceans by 2025 (Jambeck et al., 2015). In contrast to marine environments, plastic pollution in terrestrial environments has received less attention until recently. In fact, terrestrial environments are an even larger sink of plastics: 4–23 times more plastics are released to lands instead of oceans (Horton, Walton, Spurgeon, Lahive, & Svendsen, 2017). Terrestrial environments receive plastics from littering, atmospheric deposition, irrigation and flooding, agricultural mulching, and compost and sewage sludge application (Figure 1). These plastics can be classified into macro-, micro- and nanoplastics, often defined as particles \(>5\ \text{mm}\), 100–5 mm, and \(<100\ \text{nm}\), respectively (Galloway, Cole, & Lewis, 2017; Gangadoo et al., 2020). Micro- and nanoplastics are either breakdown products from weathering of macroplastics (secondary micro- and nanoplastics) or...
engineered to be in micro- and nanosize (primary micro- and nanoplastics).

Compost and sewage sludge are considered as a major contributor of plastics to terrestrial systems, as both compost and sewage sludge for the most part are directly applied to soils. It is estimated that the application of compost leads to an annual plastic input of 0.016–6.3 kg ha\(^{-1}\) to agricultural soils (Bläsing & Amelung, 2018), and sewage sludge introduces 63,000–430,000 tons of micro- and nanoplastics to farmlands in Europe every year (Nizzetto, Futter, & Langaas, 2016). In addition, residues from agricultural plastic mulch films can accumulate in soils, particularly if the plastic films cannot be completely removed after harvest. Soils in China have been reported to contain as much as 72–260 kg ha\(^{-1}\) of plastic film residues (Liu, He, & Yan, 2014). Soils are therefore a major receptacle and reservoir of disposed plastics.

The accumulation of macro-, micro-, and nanoplastics in soils affects soil physical, chemical, biological properties, and thereby soil functions (Awet et al., 2018; de Souza Machado et al., 2018; Wang et al., 2020; Yang et al., 2020). The changes in soil functions inevitably disturb soil biota (e.g., affecting plant performance and impeding animal fitness) (de Souza Machado et al., 2019; Huerta Lwangwa et al., 2016; Rillig, Lehmann, de Souza Machado, & Yang, 2019). Micro- and nanoplastics have been found to be taken up by plant roots (Li et al., 2020; Sun et al., 2020) and ingested by soil invertebrates (Huerta Lwangwa et al., 2017; Selonen et al., 2020). Moreover, the bioaccumulation of micro- and nanoplastics also introduces pollutants that are sorbed to plastics into the food chain (Wardrop et al., 2016).

Some plastics in soils can also be transported offsite by wind, water, and organisms and thereby pollute air, surface water, and groundwater (Figure 1). This not only contaminates other environmental compartments with plastics but also spreads pollutants that are sorbed onto plastic particles. Soils thus may be a transient storage compartment for plastics, particularly for micro- and nanoplastics, which are susceptible to offsite transport. Therefore, it is critical to understand the fate and transport of micro- and nanoplastics in soils. Here, we provide an update of the current understanding of subsurface transport of micro- and nanoplastics in soils. We particularly focus on: (a) colloidal and surface properties of micro- and nanoplastics, (b) transport of micro- and nanoplastics by water flow, (c) transport by bioturbation, and (d) effects of micro- and nanoplastics on soil hydraulic properties.

**Core Ideas**

- Soils are a major reservoir for micro- and nanoplastics.
- Environmental weathering modifies surface and colloid properties of micro- and nanoplastics.
- Environmentally weathered micro- and nanoplastics are more mobile.
- Large portion of microplastics likely will accumulate in soils.
- Studies on the transport of environmentally relevant plastics in soils are needed.

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**FIGURE 1** Sources and pathways of plastics in terrestrial environments. Red arrows indicate input of plastics to soil, yellow arrows indicate interaction mechanisms and exports from soil.
properties. We discuss the transport of environmentally relevant micro- and nanoplastics in soils in terms of fundamental mechanisms of colloid transport and highlight complexities associated with environmentally relevant micro- and nanoplastics.

2 | COLLOIDAL AND SURFACE PROPERTIES OF MICRO- AND NANOPLASTICS

Colloidal and surface properties of micro- and nanoplastics affect their fate in the environment, including their transport in soils. These colloidal and surface properties largely depend on the origin of the plastic particles (i.e., whether the micro- and nanoplastics are primary or secondary). Below, we discuss the differences in the properties of primary and secondary plastics.

2.1 | Primary micro- and nanoplastics

Primary micro- and nanoplastics are particles that are intentionally engineered to be in the micrometer and nanometer size. They are extensively used in the life science and pharmaceutical industry, the electronics industry, as well as in cosmetic and personal care products (Hernandez, Yousefi, & Tufenkji, 2017; Landfester et al., 2002; Ragan et al., 2018). These micro- and nanoparticles are generally composed of polystyrene or polyethylene, with polystyrene making up the majority of the market share (Research and Market, 2020; Trends Market Research, 2019). Polystyrene micro- and nanoparticles are being extensively used in pharmaceuticals, rinse-off cosmetics, and personal care and cleaning products (Research and Market, 2020) but are being phased out more and more as their environmental impact is being recognized (Microbead-Free Waters Act, 2015; Rochman et al., 2015). Polystyrene micro- and nanoparticles are also being used as model particles in colloid and surface science, to assess toxicity of nanoparticles (Loos et al., 2014), as well as to study the fate and transport of colloids in porous media (Bradford, Yates, Bettahar, & Simunek, 2002; Elimelech & O’Melia, 1990a, 1990b; Wan & Wilson, 1994).

The model polystyrene particles are mostly spheres having a smooth surface, with diameter ranging from 10 nm to <25 μm, and they are either nonmodified or modified with surface functional groups, such as carboxyl, sulfate, and amino groups (Figure 2; Cho et al., 2014; Dong et al., 2019). These surface modifications affect the surface charge and the hydrophobicity of the particles (Aramarak, Flury, Harsh, & Zollars, 2014; Dong et al., 2019). When these particles are released to the environment, further surface modifications will occur as the particles interact with other constituents, such as inorganic ions, dissolved organic matter, or extracellular polymeric substances (Cho et al., 2014; Wu, Jiang, Lin, & Ouyang, 2019). Their fate and transport in porous media, such as soils or sediments, will then be affected by their modified surface properties (Li, He, et al., 2019; Tong, He, Rong, Li, & Kim, 2020).

2.2 | Secondary micro- and nanoplastics

Secondary micro- and nanoplastics are generated when larger plastic pieces are broken down by weathering processes,
such as photooxidation, hydrolysis, biodegradation, and abrasion. They are inevitably released into the environment during the life cycle of plastic products, and typical examples include microfibers from textiles, abrasion particles from car tires, plastics in land-applied compost and sewage sludge, as well as tiny plastic debris from agricultural mulches and improperly disposed plastic trash. Secondary micro- and nanoplastics are mostly composed of polyethylene, polyester, polyethylene terephthalate, and polyvinyl chloride (Vilakati, Sivasankar, Mamba, Omine, & Msagati, 2020; Wang et al., 2019; Yu et al., 2018). In contrast to primary particles, the secondary micro- and nanoplastics are more irregular in shape and have more variable and heterogeneous surface properties.

The surface properties of secondary micro- and nanoplastics change due to weathering, especially the exposure to light, water, and oxygen (Figure 2). Weathering introduces oxygen-containing functional groups (e.g., hydroxyl, carbonyl, and carboxyl groups) to the surface of the particles, making them more hydrophilic and often negatively charged (Kalogerakis et al., 2017; Liu et al., 2019; Liu, Zhan, et al., 2020). Interaction with soil minerals and organic matter further alters the surface charge of micro- and nanoplastics (O’Connor et al., 2019). Association with microorganisms and microbial exudates can form an eco-corona (i.e., a covering of the plastic surface with biomolecules such as exoproteome and extracellular polymeric substances) (Galloway et al., 2017). All these modifications will render the secondary micro- and nanoplastics more mobile in porous media as compared with the unmodified plastic particles (Yan et al., 2020).

### 3 | TRANSPORT OF MICRO- AND NANOPLASTICS BY WATER FLOW

#### 3.1 | Model micro- and nanoplastics

There is abundant information about the transport of micro- and nanoplastics in porous media, as such particles are frequently used as model colloids to evaluate basic mechanisms of filtration and transport (Table 1). In most studies, researchers have used pristine spherical polystyrene particles (i.e., primary micro- and nanoplastics) of various sizes and surface properties and sand or glass beads as porous media. These well-controlled studies have provided the basis for developing theories of particle–collector interactions, and these theories were further verified with microscopic visualization and tested in soil columns as well as in situ field experiments. More recent experiments have included well-designed nonspherical polystyrene particles to determine the effect of particle shape on transport (Table 1). Micro- and nanoplastics have also been used as tracers to determine transport pathways and distances in soils and sediments.

Studies on colloid transport have revealed several mechanisms controlling the transport of plastic particles (Figure 3a). In porous media, colloid-sized plastic particles can attach to the solid–water interface under physicochemically favorable and unfavorable attachment conditions. Under favorable conditions (i.e., attractive interface interaction), the attachment occurs in the primary energy minimum, whereas under unfavorable conditions (i.e., repulsive interface interaction), the attachment occurs primarily in the secondary energy minimum. Surface heterogeneity (charge or roughness) of particles and collectors enhances the attachment of particles on the solid–water interface and can lead to attachment in the primary energy minimum even under unfavorable attachment conditions (Redman, Grant, Olson, & Estes, 2001; Shen, Li, Wang, Huang, & Jin, 2011). Accumulation of particles on solid–water interfaces can either increase attachment through ripening (Darby & Lawler, 1990; Tobaison, 1989) or decrease attachment through blocking (Johnson & Elimelech, 1995; Ko & Elimelech, 2000).

Physical factors also affect the transport of plastic particles. Flow rate affects the hydrodynamic shear exerted on particles, which can lift and drag particles, resulting in less retention under higher flow rate (Sasidharan, Torkzaban, Bradford, Dillon, & Cook, 2014; Shen, Jin, Li, Zheng, & Huang, 2014). Pore straining and wedging trap colloid-sized and larger particles in small pores of porous media (Bradford et al., 2002; Johnson, Li, & Yal, 2007). For colloid-sized particles, their pore straining and wedging are enhanced by decreased repulsive interface interactions. Size exclusion (i.e., where particles only flow in pores with diameters larger than their diameter as well as in the center, faster flowing streamlines of pores) is responsible for the earlier arrival of particles in the effluents compared with conservative tracers (Keller, Sirivithayapakorn, & Chrysikopoulos, 2004; You, Badalyan, & Bedrikovetsky, 2013). In structurally heterogeneous porous media, high-permeability pathways (e.g., preferential flow) promote the transport of plastic particles (Bradford et al., 2005; Bradford, Bettahar, Simunek, & van Genuchten, 2004).

In unsaturated porous media, the air–water interface provides additional attachment sites for colloid-sized microand nanoplastics (Knappenberger, Flury, Mattson, & Harsh, 2014; Sang et al., 2013). The particles can directly attach to air–water interfaces through hydrophobic forces and even penetrate the air–water interface, after which capillary forces keep the particle pinned to the interface (Aramrak et al., 2014). Moreover, straining and wedging are enhanced, and film straining by thin water films becomes effective (Torkzaban, Bradford, van Genuchten, & Walker, 2008).

Transient water flow (i.e., the changes in saturation and flow rate) affect both physicochemical and physical retention mechanisms. Wetting of porous media can induce expansion of thin water films, remobilizing particles that are retained by
| Plastic type                                                                 | Evaluated mechanisms                        | Flow condition | Porous medium                    | Plastic size $^a$ (μm) | References $^b$ |
|-----------------------------------------------------------------------------|---------------------------------------------|----------------|----------------------------------|------------------------|-----------------|
| Polystyrene (nonmodified, carboxylate-, amine-, and sulfate-modified)       | Primary minimum deposition                  | Saturated      | Sand/glass-bead column           | 0.02–5.7               | (1–5, 5–15)     |
|                                                                             |                                             |                | Soil column                      |                        | (16–21)         |
|                                                                             |                                             |                | Micromodel                       |                        | (22, 23)        |
| Secondary minimum deposition                                                | Saturated                                  |                | Sand/glass-bead column           | 0.02–5.7               | (1, 3, 4, 6, 7, 12, 14, 15, 24–43) |
|                                                                             |                                             |                | Soil column                      |                        | (17–21, 44)     |
|                                                                             |                                             |                | Micromodel                       |                        | (22, 23, 45–47) |
| Surface heterogeneity (chemical and physical)                               | Saturated                                  |                | Sand/glass-bead column           | 0.02–10                | (1, 10, 13, 24–26, 29, 32, 37, 48–53) |
|                                                                             |                                             |                | Soil column                      |                        | (18–21, 44, 54) |
|                                                                             |                                             |                | Micromodel                       |                        | (55–57)         |
| Blocking, ripening                                                         | Saturated                                  |                | Sand/glass-bead column           | 0.239–21               | (4, 43, 58–62)  |
|                                                                             |                                             |                | Soil column                      |                        | (21)            |
|                                                                             |                                             |                | Micromodel                       |                        | (60)            |
| Straining, wedging                                                         | Saturated                                  |                | Sand/glass-bead column           | 0.45–4.25              | (27, 59, 60, 63–66) |
|                                                                             |                                             |                | Soil column                      |                        | (18, 20, 44, 54, 67) |
|                                                                             |                                             |                | Micromodel                       |                        | (60)            |
| Size exclusion                                                              | Saturated                                  |                | Sand/glass-bead column           | 0.05–3                 | (60, 68, 69)    |
|                                                                             |                                             |                | Micromodel                       |                        | (60, 70)        |
| Flow rate                                                                   | Saturated                                  |                | Sand/glass-bead column           | 0.03–40                | (1, 2, 4, 6, 7, 13, 25, 27, 32, 35, 38, 52, 71–74) |
|                                                                             |                                             |                | Micromodel                       |                        | (22, 74–76)     |

(Continues)
| Plastic type | Evaluated mechanisms | Flow condition | Porous medium | Plastic size<sup>a</sup> | References<sup>b</sup> |
|--------------|----------------------|----------------|---------------|--------------------------|------------------------|
| Structure heterogeneity of porous media | Saturated | Sand/glass-bead column | 1–90 | (60, 65, 77) |
| | Unsaturated | Soil column | (18, 67) | |
| | | Micromodel | (78–80) | |
| | | | | |
| Interaction with air–water interface | Unsaturated | Sand/glass-bead column | 0.02–6 | (81–98) |
| | | Soil column | (99–101) | |
| | | Micromodel | (102–126) | |
| | | In situ soil | (127, 128) | |
| Film straining | Unsaturated | Sand/glass-bead column | 0.014–0.97 | (81) |
| | Transient flow | Saturated/unsaturated | Sand/glass-bead column | 0.1–2 | (129–132) |
| | | Soil column | (100) | |
| | | Micromodel | (105, 106, 113, 114, 117, 120, 122, 126) | |
| Nonspherical particles | Saturated/unsaturated | Sand/glass-bead column | 0.2–6.1 | (133–137) |
| | | Micromodel | (138, 139) | |
| Cotransport | Saturated/unsaturated | Sand/glass-bead column | 0.05–2.6 | (15, 123, 140–142) |
| Tracer | Saturated/unsaturated | Aquifer/soils | 0.23–1.35 | (143–145) |
| Polyethylene, polypropylene, polyethylene terephthalate, polylactic acid, polyamide, styrene-butadiene-rubber | Infiltration, travel distance | Unsaturated | Sand/glass-bead column | 21–5,000 | (146–148) |
| Secondary micro- and nanoplastics | Transport | Saturated | Soil column | 0.422–0.487 | (149, 150) |

<sup>a</sup>For spherical particles, particle size refers to diameter; for nonspherical particles, particle size refers to equivalent diameter, calculated as \((abc)^{1/3}\), where \(a\), \(b\), and \(c\) are the longest, medium, and shortest side lengths, respectively.

<sup>b</sup>References are not meant to be exhaustive, but rather show a selection of articles. References are listed separately in the supplemental material.
FIGURE 3 Retention mechanisms of (a) conventional colloids and (b) micro- and nanoparticles

Air–water interfaces, pore straining, wedging, and film straining (Aramrak et al., 2014). Moreover, the wetting front (moving air–water interface) can scour off particles deposited on collector surfaces (Aramrak, Flury, & Harsh, 2011). Increasing flow rate intensifies hydrodynamic shears, promoting particle remobilization. Transients in hydrochemical properties (i.e., ionic strength, pH, and electrolyte type) alter the electrostatic forces between particles and attachment interfaces and thus lead to mobilization or immobilization of plastic particles (Torkzaban, Kim, Simunek, & Bradford, 2010; Tosco, Tiraferri, & Sethi, 2009).

The transport of plastic particles is also affected by the coexistence of other substances, such as dissolved organic matter and metal oxides. For example, organic matter can adsorb onto the surfaces of polystyrene microspheres and collectors, contributing to the repulsive interaction energy, and thus can reduce the deposition of microspheres (Franchi & O’Melia, 2003). On the other hand, iron oxides can lead to decreased transport of plastic particles (2 μm) through modification in surface properties of plastic particles and creation of additional deposition sites on collector surfaces (Li, He, et al., 2019). The cotransport of plastic particles with other substances induces alterations in the abovementioned mechanisms by providing or blocking retention sites, as well as by increasing or decreasing particle mobility.

For nonspherical plastic particles, their transport and retention depend on aspect ratio, orientation, and flow hydrodynamic. Increase in aspect ratio promotes retention by increasing the frequency of particle–collector collisions and the probability of attachment on collectors (Salerno, Flamm, Logan, & Velegol, 2006). Side-on orientation of nonspherical plastic particles on collector surfaces substantially increases the depth of the secondary energy minimum, leading to more attachment under unfavorable conditions (Knappenberger, Aramrak, & Flury, 2015). In pore spaces, nonspherical plastic particles tend to be orientated with the major axis aligned to flow direction, which decreases their retention by straining as compared with equivalently sized spherical particles (Xu, Liao, & Saiers, 2008). Moreover, nonspherical plastic particles tend to experience more hydrodynamic forces and torques, which can counterbalance the attractive interaction energies, leading to less deposition under favorable conditions (Seymour, Chen, Su, & Li, 2013).

3.2 Environmentally relevant micro- and nanoparticles

In terrestrial ecosystems, such as soils and sediments, the fate and transport of micro- and nanoparticles are controlled by the abovementioned mechanisms. However, the primary and secondary plastic particles released to the terrestrial environment differ from model micro- and nanoparticles in terms of shape, polydispersity, and surface properties, making the quantification of retention mechanisms more challenging (Figure 3b). Only a few studies exist to date where transport of primary and secondary micro- and nanoparticles have been investigated (Table 1).

O’Connor et al. (2019) studied the vertical migration of primary microplastics in columns filled with construction sand. The plastics consisted of purchased pristine granular and pellet-shaped polyethylene and polypropylene, and polyethylene from face wash and body scrub, varying in diameter from 21 to 535 μm. The authors found that the transport during wetting–drying cycles was controlled by both particle size and polymer type, with the smallest polyethylene particles moving the farthest. Polyethylene showed enhanced
transport compared with polypropylene at similar particle size. Although no mechanisms were discussed in this study, we infer that plastic transport was mainly controlled by moving air–water interfaces during wetting–drying cycles. Although these plastics are more representative than the model polystyrene plastics, they were not exposed to environmental weathering, and thus still possessed pristine surface properties.

Liu et al. (2019) exposed pristine polystyrene microspheres to ultraviolet (UV) radiation and ozone, and observed that UV radiation and ozone caused the formation of epoxy/hydroxyl, carbonyl, and carboxyl groups on the surface of the microspheres (Figure 4, a–d). Consequently, the weathered microspheres were more mobile than the pristine microspheres during transport in a saturated loamy sand (Figure 4e). Yan et al. (2020) performed soil leaching tests to study the transport of naturally aged microplastics obtained from waste polypropylene seedling ropes. They found these microplastics were highly photooxidized (abundant carbonyl groups) and heteroaggregated with soil minerals. Heteroaggregation with soil minerals enhanced the transport of microplastics, and the presence of humic acid furthered the transport substantially. These results confirm that surface properties of microplastics are modified by weathering and association with soil minerals and humic acid, all of which tend to enhance the mobility of microplastics.

Another particularly challenging aspect of the transport of micro- and nanoplastics is if their shape deviates substantially from the spherical model that has been used to develop the basic principles of colloid transport and filtration. A large portion of secondary micro- and nanoplastics come in fiber shape, with thickness orders of magnitude smaller than their length (Li, Wu, Zhao, Gu, & Ji, 2019), which will greatly affect their motion in porous media. Engdahl (2018) developed a numerical model to simulate the transport of flexible fibers in porous media. In this model, fibers were represented as a chain of rigid rods connected by pivoting nodes, so the fibers that could deform according to the flow field and pore space. Model simulations showed that, in the absence of surface interactions, fibers with lengths smaller than the mean pore size can be transported like conservative solutes, whereas longer fibers tend to wrap around porous media grains (Engdahl, 2018). Given that most plastic fibers have a thickness of a few micrometers and a length of hundreds of micrometers (Li, Wu, et al., 2019), we do not expect fibers to migrate large distances in soil.

Although only few data are available on the transport of environmentally relevant plastic particles by water flow, it is reasonable to infer that plastic particles with sizes >10 μm will be mostly retained in the top of the soil, based on findings for other colloids with similar size (e.g., Phytophthora zoospores and Cryptosporidium parvum oocysts; Darnault et al., 2017; Jeon et al., 2016; Yu, Elliott, Chowdhury, & Flury, 2021), whereas macro pores in soils can provide potential pathways for plastic particles >10 μm (Cumbie & McKay, 1999; Darnault et al., 2004).
4 | TRANSPORT OF MICRO- AND NANOPLASTICS BY BIOTURBATION

The activity of soil fauna inevitably affects the downward migration of micro- and nanoplastics in soil. It has been reported that soil invertebrates (e.g., earthworms [Lumbricus terrestris], collembolans [Folsomia candida], and mites [Hypoaspis aculeifer, Damaeus exspinosus]) can facilitate the transport of microplastics from the soil surface to deeper soil layers (Table 2).

Soil invertebrates can transport micro- and nanoplastics through pushing, ingestion and egestion, as well as adherence to their exterior. Earthworms (Lumbricus terrestris) incorporated 35–73% of microplastics (<50 μm and 63–150 μm in diameter) from surface litter into their burrows, and more of the smaller particles (<50 μm) were transported (Huerta Lwangaa et al., 2017). Rillig, Ziersch, and Hempel (2017) found that polyethylene microplastics were transported from soil surface up to a depth of 10 cm, with the smallest fraction (710–850 μm) found the most in the deepest layer. These results suggest that earthworms transport microplastics in a size-selective manner, with smaller particles transported deeper than larger particles.

Earthworms also can actively drag larger, macroscopic plastic pieces down into their burrows, without ingesting the plastic pieces (Zhang et al., 2018). Further, the interaction between soil invertebrates, such as trophic predator–prey relationships, can promote the transport of micro- and nanoplastics due to the increased exposure of micro- and nanoplastics to soil invertebrates (Zhu et al., 2018).

The vertical movement of soil invertebrates creates macro-pores in soil, which serve as conduits for the transport of micro- and nanoplastics by leaching. Yu et al. (2019) found that microplastics were transported downward for up to 50 cm in a sandy soil due to the bioturbation of earthworms, and further leaching induced the remobilization of microplastics with even the largest fraction (250–1,000 μm) detected in the leachate of a 60-cm-high column.

5 | EFFECTS OF MICRO- AND NANOPLASTICS ON SOIL HYDRAULIC PROPERTIES

Micro- and nanoplastics have also been found to affect soil hydraulic properties, such as hydraulic conductivity and water retention characteristics. de Souza Machado et al. (2018) manually mixed different types of microplastics into a loamy sand (soil particles smaller than 630 μm), and they found that polyester fibers (8 μm × 5,000 μm, 0.4% [w/w]) considerably increased the porosity, water holding capacity, and evapotranspiration; however, polyethylene fragments (643 μm, 2% [w/w]) only had a small effect. To the contrary, incorporation of polyester fibers (5 μm × 2,650 μm, 0.3% [w/w]) was reported to reduce water holding capacity of a clayey soil (Zhang, Zhang, & Li, 2019). Interestingly, despite these changes, no significant changes in saturated hydraulic conductivity were detected for neither the loamy sand nor the clayey soil (de Souza Machado et al., 2018; Zhang et al., 2019).

Instead of artificially incorporating microplastics into soil, Yu, van der Ploeg, Ma, Ritsema, and Geissen (2020) placed polyethylene pieces (~4 g) on the surface of a sandy soil (7 kg air-dried soil in a 11.6-cm × 50-cm column) in the absence and presence of earthworms, and they found that although polyethylene pieces were transported by earthworms into soil, polyethylene did not affect the saturated hydraulic conductivity of the soil. These results indicate that the effect of micro- and nanoplastics on soil hydraulic properties depends on plastic characteristics as well as soil texture. The limited amount of experimental data available is insufficient to make definitive conclusions about the effects of micro- and nanoplastics on hydraulic properties of soils.

6 | RESEARCH NEEDS

In this update, we summarized the colloidal and surface properties of micro- and nanoplastics, their subsurface transport by water flow and bioturbation, as well as their effects on soil hydraulic properties, with special emphasis on environmentally relevant plastics.

Micro- and nanoplastics can enter soil as either primary or secondary plastic particles, and their transport is affected by their colloidal and surface properties, which highly depend on their intrinsic characteristics and subsequent environmental modifications. Fiber-shaped microplastics are prone to entangle in the soil matrix due to their elongated shape and thus are unlikely to migrate for a long distance in soils. Generally, plastic particles with size of >10 μm likely will be filtered out in the soil by virtue of their size and therefore are not expected to move far through soil. Although the well-developed colloid transport theory can be used to estimate transport of micro- and nanoplastics in soils, the following aspects need special consideration for primary and secondary micro- and nanoplastics:

1. Micro- and nanoplastics entering soils are often polydisperse, and their surface properties are highly heterogeneous. Pristine model plastic particles are mainly spherical and homogeneous, and using them to study the fate and transport of micro- and nanoplastics in soils may limit the practical value of the results. Thus, it is important to study the fate and transport of environmentally relevant micro- and nanoplastics of different shape and sources, such as plastic particles in personal care products,
## TABLE 2  Transport of micro- and nanoplastics by soil fauna

| Microplastic or nanoplastic Type | Shape | Size (μm) | Experimental Setup | Organisms | Major results | References |
|---------------------------------|-------|-----------|--------------------|-----------|---------------|------------|
| Polyethylene                    | na    | <150      | Mesocosm packed with sandy soil | Earthworm (*Lumbricus terrestris*) | Earthworms deposited microplastics on the walls of their burrows | Huerta Lwanga et al. (2016) |
| Polyethylene                    | na    | <50 to <400 | Mesocosm packed with sandy soil | Earthworm (*Lumbricus terrestris*) | Earthworm induced size-selective downward transport of microplastics, with smaller particles transported farther than larger ones | Huerta Lwanga et al. (2017) |
| Polyvinyl chloride              | na    | 80–250    | Petri dishes filled with plaster of Paris and charcoal | Collembolan (*Folsomia candida*) and mite (*Hypoaspis aculeifer, Damaeus expinosus*) | *Folsomia candida, Hypoaspis aculeifer*, and *Damaeus expinosus* horizontally dispersed microplastics up to 9 cm | Zhu et al. (2018) |
| Polyethylene                    | na    | 150–1,000 | Column packed with sandy soil | Earthworm (*Lumbricus terrestris*) | Microplastics were vertically transported by earthworms and leached out from soil | Yu et al. (2019) |
| Polyethylene                    | Sphere | 700–2,800 | Plant pot packed with sandy loam soil | Earthworm (*Lumbricus terrestris*) | Smaller microplastics were transported downward to a greater extent than larger ones by earthworms | Rillig et al. (2017) |
| Polystyrene                     | Sphere | 0.256     | Column packed with sandy loam soil | Earthworm (*Lumbricus terrestris*) | Earthworm caused mixing of microplastics into lower soil depths | Heinze (2019) |

*na, not available.*
microfibers from textiles, and secondary plastics from discarded waste.

2. Environmental modifications alter surface properties of micro- and nanoplastics through weathering and interactions with environmental constituents and further affect the fate and transport of these plastic particles in the environment. These modifications highly depend on the environment where the plastic particles are released. Ultraviolet exposure often makes plastic more brittle, whereas hydrolysis reactions and association with dissolved organic matter can make plastics more hydrophilic. Therefore, it is necessary to evaluate the effect of different environments on the modifications and subsequent fate and transport of micro- and nanoplastics.

3. Water flow translocates micro- and nanoplastics through the soil matrix by combined physical and chemical effects, and bioturbation in soils creates pathways for the downward transport of micro- and nanoplastics. The actual transport of micro- and nanoplastics in soils is driven by water flow as well as bioturbation, although few data are available on their combined effects. For instance, earthworms can move micro- and nanoplastics, and even macroplastics, into the first few decimeters of a soil, but the incorporation of micro- and nanoplastics in earthworm cast may render the plastic particles less mobile afterwards.

4. The study of environmentally relevant micro- and nanoplastics in environmental media is challenging because we currently do not have an optimal and accepted analytical method to extract, quantify, and identify micro- and nanoplastics in terrestrial samples, particularly in those containing large amounts of organic matter. Several analytical methods have been described and proposed in the literature (Bläsing & Amelung, 2018; Corradini, Meza, Eguiluz, Huerta-Lwanga, & Geissen, 2019; Liu, Lu, et al., 2020), but these methods remain unsatisfactory for plastics in the nanometer size range (Wang, Taylor, Sharma, & Flury, 2018).

5. Laboratory-scale studies under well-controlled conditions provide good means to study the fate and transport of micro- and nanoplastics in soils. Such studies remain essential, particularly to evaluate the mechanisms on how micro- and nanoplastics interact with soil and soil organisms under environmentally relevant concentrations. In addition, field studies are required to evaluate long-term transport of micro- and nanoplastics in the terrestrial environment.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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