# Microplastics transport in soils: A critical review

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## Abstract

Microplastics (MPs) in terrestrial environments are an emerging contaminant of huge concern to ecosystems and human health. However, our understanding of the MPs fate, particularly their transport mechanisms, remains elusive. This knowledge gap arises from the multiplicity of coupled physical, chemical and biological processes and parameters affecting MPs transport, together with scarcity of systematic studies that aim to isolate their individual effects. In this paper, we provide a critical review of the state-of-the-art in our understanding of MPs transport, highlight knowledge gaps, and suggest future research to bridge them. We classify the governing factors into four main categories: (i) MPs properties; (ii) soil properties; (iii) hydrological conditions; and (iv) biological activity. Our analysis highlights the intricacy of MPs transport, showing that seemingly non-monotonic trends and even complete lack of correlation between some parameters and MPs transport could be explained by the interference (co-effects) with other parameters and processes.

**Keywords**

Microplastic mobility; Emerging contaminants; Soil physics; Critical review; Hydrology

**Highlights**

- Microplastic mobility in soils is affected by multiple, often coupled, factors
- Including microplastic & soil properties, hydrological conditions, and living organisms
- Multiplicity of control parameters and mobility metrics complicates comparison across studies
- Non-monotonic trends in MP mobility are due to coupling and co-effect among factors

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## 1. Introduction

Plastics are widely used globally due to their low manufacturing costs, ease and versatility of use, durability and stability (Tábi et al., 2021). Annual production of plastics increased dramatically, from ~2 Mt in 1950 to ~390 Mt in 2021 (PEMRG, 2022). Plastics degrade into smaller particles through oxidation, hydrolysis, biodegradation, photodegradation, and mechanical processes (Sarkar et al., 2020). Microplastics (MPs), particles larger than 1 μm (Weber et al., 2022; >0.1 μm according to Koelmans et al., 2015) and smaller than 5 mm, can easily migrate by wind and water, making them extremely abundant in atmosphere, soil, and water (Avio et al., 2017; Bullard et al., 2021), including in very remote areas (Ali, 2021). MPs are believed to pose a serious risk to living organisms including humans, animals, and plants (Leslie and Depledge, 2020; Rochman et al., 2013; X. Zhang et al., 2022a; Djouina et al., 2023). Moreover, MPs can act as vectors to transport other contaminants adsorbed on their surface, such as heavy metals, pathogens (bacteria, fungi, protozoa, worms, viruses), and antibiotics (González-Pleiter et al., 2021; S. Liu et al., 2022; Lu et al., 2022; Wang et al, 2021), posing additional risks to the environment and human health.

To date, most research on the environmental impacts of MPs has focused on the aquatic environment, with only a limited number of studies on terrestrial environments (Dioses-Salinas et al., 2020; Wong et al., 2020). MPs can infiltrate with water through the soil matrix (Helmberger et al., 2020), reaching surface and groundwater. MPs can also concentrate in the topsoil (H. Liu et al., 2022), and negatively impact microorganisms (Qiu et al., 2022) and plants (Zhu et al., 2022). A formidable challenge in understanding the fate of MPs in soils is that, unlike in oceans, MPs can strongly affect the host (soil) properties—specifically the properties controlling their transport (de Souza Machado et al., 2018; Guo et al., 2022; F. Wang et al., 2022), which in turn affects the MPs fate.

Being an open scientific question with crucial environmental impacts, there is a surge of research on MPs in soils. Recent studies reviewed the interaction of MPs with contaminants in soils (Chang et al. ,2022; Yang et al, .2022); the sources, distribution, behavior, and detection techniques of microplastics in soils (Yan and Yang, 2023); transport and transformation of microplastics and nanoplastics in soils (Liu et al, 2021); the migration of microplastics in the soil-groundwater environment (Ren et al., 2021); the effects of MP on soil properties (F. Wang et al., 2022); the occurrence, fate, and transport of MPs in soils (Zhou et al., 2020); and their deleterious environmental effects (Sajjad et al., 2022). While we now have a better understanding of multiple aspects affecting MPs in soils, their *transport mechanisms*—the focus of this review—remain elusive. This gap is mainly due to the intricate coupling between the physical and chemical properties of MPs and soils (solid matrix and solution), and the interference with the environmental conditions and the living organisms. This coupling results in a dependence of the properties of both MPs and soils on a wide range of parameters, that also affect each other. The size, shape, and type of MPs (Zhou et al., 2020), as well as soil properties such as porosity, texture, and composition, all affect the migration of MPs (Liu et al., 2021). MP transport in the soil is further affected by the bioturbation of plant roots and soil living organisms (H. Li, et al., 2021; Luo et al., 2023), and by secondary/tertiary plastic decomposition by bacteria into smaller particulates (Lwanga et al., 2018). An added challenge is the lack of univocal set of definitions and characteristics for the MPs properties, including shapes, sizes (Hartmann et al., 2019; Weber et al., 2022) and MPs transport metrics (X. Zhang et al., 2022a).

In this review, we focus on the *vertical* migration of MPs, due to its immediate relevance to the contamination of plants and groundwater. Yet, we note the coupling between *vertical* and *horizontal* transport: due to heterogeneity in vertical permeability, horizontal migration could mobilize MPs to locations where it is then easy to migrate vertically. There are several different metrics characterizing quantitatively the vertical migration of MPs. These metrics could be further categorized into (a) flux- and (b) depth-based, where in both one could use either mass or number of particles. Flux-based metrics include: (i) "transport rate" (Gui et al., 2022), also termed "mass recovery rate" (Xu et al., 2022a) or "mass balance" (Rong et al., 2022): the percentage of MPs traversing the sample, by weight; (ii) "loss ratio" (Rehm et al., 2021): same as (i), using number of MPs. A variant of (ii) is "MP concentration" (Qi et al., 2022), which is the number of MPs, however per mL of water measured at the outlet; (iii) "total mass recovery" (Y. Wang et al., 2022b): the ratio of MP concentration to that of a tracer (measured from the two breakthrough curves, BTC); (iv) "breakthrough concentration" (Dong et al., 2021): MP concentration relative to that in a injected suspension via which MPs were introduced (measured from the BTC). Depth-based metrics include (v) "maximum penetration depth" (Ranjan et al., 2023); (vi) "depth ratio" (Cohen and Radian, 2022): relative number of particles reaching the maximum depth in which any MPs were found; and (vii) "relative mobility" (X. Zhang et al.,2022b): number MPs in a certain location (depth) normalized to the total number of MPs (in the entire soil and effluent water). While these characteristics are *related*, i.e. larger value of a metric indicates a higher MP mobility, they do not describe the *same* phenomenon nor bear the same environmental impact, and hence could not be used interchangeably. For instance, a scenario where only very few MPs reach very deep would be characterized by a low transport rate and loss ratio, however by a large *maximum* penetration depth (X. Zhang et al., 2022b). This ambiguity in the *main characteristic* makes comparison between studies challenging.

To illustrate the complex dependence between basic properties and MPs mobility, we plot the MPs mobility against the most basic MP property—their size (Fig. 1). This comparison highlights the non-intuitive and non-monotonic nature of this dependence. As some of the mobility metrics cannot be compared quantitively, we present the flux-based metrics (Fig. 1a) separately from the depth-based ones (Fig. 1b). Furthermore, only "maximum penetration depth" is shown in Fig. 1b, as the most widely used depth-based metric, whereas “relative mobility” is a depth-specific property and thus could not be directly compared with any other metric. Differentiating the data in Fig. 1 into series based on other basic properties, including MP type, shape and soil texture, highlights the complexity of the relationships between MP transport and the system’s properties, namely that multiple properties co-affect different aspects of MP transport, resulting in a non-monotonic response. Furthermore, it shows that available data is limited, often by technical reasons; e.g. all studies concerning small MPs (<10 μm) have been done with a single MP type and shape: polystyrene (PS) spherical beads, probably because of their availability.

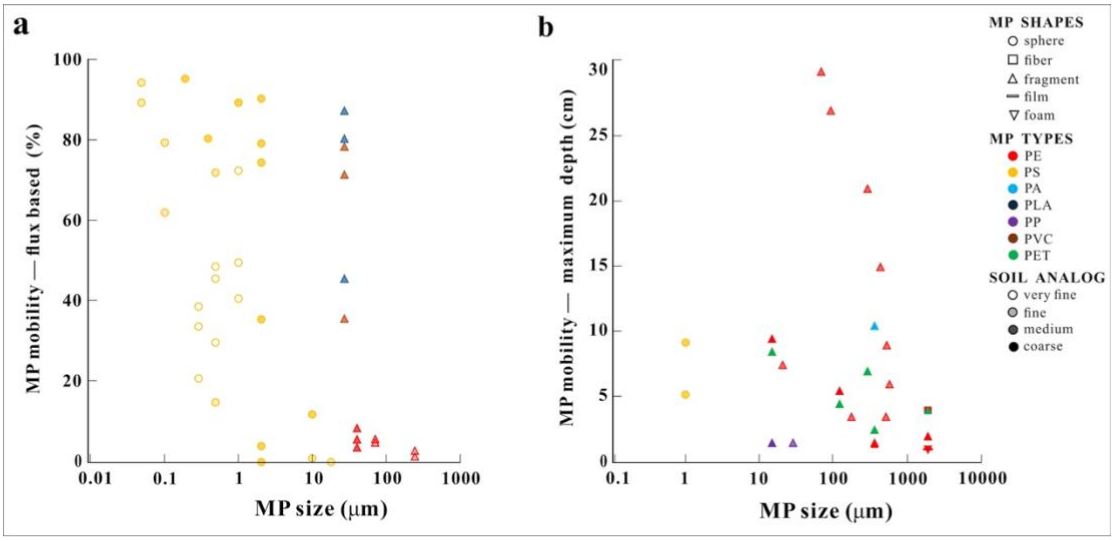


**Figure 1.** Complex, non-monotonic relationships between microplastic size and their mobility, indicating the intricate dependence of MP mobility on multiple properties.

Another fundamental challenge in understanding MP transport is the intricate coupling between various physical and chemical mechanisms. Notably, surface properties of small particles (both MPs and soil) are inherently both, i.e. they fall in the field of *physical chemistry*. Out of those, possibly the most intricate effect is the Zeta potential, related to the electrostatic forces near the surface of particles suspended in liquids. Its sign describes the nature of the forces (attraction or repulsion) and its magnitude how strong they are, and thus the stability of the suspended particulates (Bhattacharjee, 2016). Oppositely charged particles (having negative and positive Zeta potential) tend to flocculate, while having the same charge causes repellence. This means that Zeta potential is a property of the whole soil-MPs system, affected by the surface properties of both the soil particles and the MPs, as well as the geochemistry of the soil solution. Thus, Zeta potential has an overarching effect on multiple processes that in turn could either enhance or inhibit MP transport: adsorption of MPs onto the soil matrix can retard their transport, while flocculation of MPs (on their own or with other particulates) could enhance their transport with other particles.

This paper provides a critical review of the state-of-the-art understanding of how MPs are transported in soils. We point to several non-intuitive and often contradictory findings, and show these can be explained by the interference (co-effects) among factors and processes. That is, in many experiments the simultaneous changes in multiple parameters alter the competition between various factors and processes, leading to non-monotonic trends in MP mobility when plotted vs. a single factor. Finally, we outline the knowledge gaps and propose future research directions.

## 2. Methodology for review and analysis, and structure of our paper

The reviewed papers were found in Google Scholar database using the keywords "microplastic" AND ("transport" OR "move" OR "mobile" OR "mobility") AND ("soil" OR "porous media" OR "sand"), resulting in a total of 81 papers. Out of those, we included only papers which focus on MP migration into the soil. We note that due to the ambiguity in the definition of MP size ranges (Hartmann et al., 2019), several papers analyzed here include MPs smaller than 1 μm, which, according to some definitions (e.g. Weber et al. 2022), could be classified as nanoplastics. We did not, however, consider papers which were strictly labeled as dealing with nanoplastics (i.e. where keywords included "nanoplastic" but not "microplastic"), even if *some* of the data in them could be considered as microplastic according to the size definition of Koelmans et al. (2015).

Many of the studies on MPs in soils were conducted using artificially constructed soil analogs such as quartz sand or glass beads. These experiments, by simplifying visualization and/or analysis, provide invaluable insights into the transport of MPs in natural soils and thus are included in this review and analysis. We also note important contributions from physicists using controlled systems with idealized media, for instance microfluidic channels, to enhance fundamental understanding of specific aspects, e.g. MP entrainment in liquid films (Wu et al., 2021); such works did not appear within our search and were not included in the review. For brevity, in the rest of the paper, when making general statements for which the distinction between natural soils and artificial analogs is not crucial, we use the terms *soil* and *porous matrix* interchangeably.

The paper is structured such that each section focuses on the impact of a group of properties on MP transport, while pointing to their coupling with others. Sections 3-5 overview the impact of MP properties, soil properties, and the hydrological conditions, respectively, with further division of each of them to subsections focusing on physical and chemical aspects. Section 6 overviews the effect of living organisms. Section 7 provides concluding remarks, summarizing the research gaps and suggesting future directions. For completeness, Tables S1 and S2 in the Supplementary Information (SI) list the experimental conditions classified in terms of the MPs and soil properties, respectively.

## 3. Microplastics properties

The main MP properties reviewed here for their effect on MP transport include their size, type, shape, and their derivatives such as density, hydrophobicity, surface roughness, hydrodynamic diameter, and Zeta potential.

### 3.1 Physical properties

*3.1.1 Microplastics particle size*

A basic property that has a substantial influence on MP mobility is microplastics size. Since MP size affects multiple mechanisms which control MP mobility, there is a complex, nonmonotonic trend: in general, MP mobility for larger MPs (≳1 μm) is inversely proportional to the MP size. This inverse proportionality was found in terms of different MP mobility metrics, including maximum depth (Ranjan et al., 2023; Gao et al., 2021; X. Zhang et al., 2022b; O'Connor et al., 2019), proportion of MPs reaching the maximum depth (Cohen and Radian, 2022), mass recovery rate (Rong et al., 2022), and breakthrough concentration (Y. Wang. et al., 2022a). This is rather intuitive: for a given size of soil pores, smaller MPs can traverse further (Gao et al., 2021; Ranjan et al., 2023; O'Connor et al., 2019). In contrast, for MPs ≲1μm, increasing MP size *increases* MP mobility (transport rate in Gui et al., 2022; mass recovery rate in Rong et al., 2022). The reason that the trend in MPs size vs. mobility reverses for very small MPs is linked to the fact that for very small particles, other forces and mechanisms start to become dominant. In particular, further decreasing MPs size below ~1μm decreases their Zeta potential and hence the repulsive energy barrier between MPs and soil particles (Gui et al, 2022), enhancing their adsorption to the soil particles. Due to the complexity of these microscopic mechanisms, the critical size for which the mobility trend reverses can depend on other factors and hence is not univocal (e.g., 1 μm in Rong et al. (2022) vs. 2 μm in Wang, Y. et al. (2022a) vs. 10 μm in Qi et al. (2022)). At even smaller MPs sizes, yet other mechanisms can become dominant, again reversing the trend: For MPs smaller than 0.1 μm and low Zeta potential, Y. Wang et al. (2022b) and Li et al. (2019) showed that MPs transport once again becomes inversely proportional to their size (smaller particles exhibited higher total mass recovery and mass recovery rate). The authors attributed this to hydrodynamic diameter, which is the diameter of the MP particles including their electronic layers (Maguire et al., 2018), implying this mechanism can become dominant for very small MPs. It was also found that MP size and concentration co-affect MP transport, such that the trend of transport vs. concentration changes beyond a certain MP size (0.1μm in Y. Wang et al. (2022b)).

Considering the variations in pore sizes, the control parameter becomes the ratio of MP size to pore sizes (e.g. in terms of ratio of average diameters, $D_{MP}/D_S$), where a smaller ratio promotes MP transport (Waldschläger and Schüttrumpf, 2020). The critical ratio allowing a particle to fit through a constriction between particles forming a porous matrix can be evaluated by considering a sphere pack; e.g. for an ordered hexagonal packing of equal-sized spheres, the narrowest aperture (between each triplet of particles) is about 10% of the particle diameter. Indeed, MPs were found to be highly mobile for $D_{MP}/D_S < 0.1$, and nearly immobile for $D_{MP}/D_S > 0.3$ (Gao et al., 2021; Ranjan et al., 2023).

### *3.1.2 Microplastics shape*

Microplastics can be found in natural soils in a variety of shapes, with the most common being beads (spheres), fragments (*irregular*-shaped), foams, films and fibers (Sajjad et al., 2022). There has been limited research on the impact of MP shapes on transport. Moreover, other properties and conditions were often varied among these studies, making it difficult to compare results and establish a general effect of shape (Tables S1-S2).

In general, fiber, fragments, and beads migrate deeper than films and foams. Beads were found to reach deeper than films, because films were trapped more easily by plant roots (H. Li et al., 2021). Fragments were found to move deeper than fibers (Gao et al., 2021; Cohen and Radian, 2022; Waldschläger and Schüttrumpf, 2020), possibly due to the tendency of fibers to become entangled with soil grains (de Souza Machado et al., 2018; Waldschläger and Schüttrumpf, 2020). X. Zhang et al. (2022b) showed that for similarly-sized MPs, fibers reached deeper than fragments, which in turn were more mobile than foams and films. However, It is hard to draw conclusive evidence regarding MP fiber mobility from X. Zhang et al. (2022b), as the authors did not specify the diameter—the dominant characteristic length in fibers (Waldschläger and Schüttrumpf, 2020).

### *3.1.3 Microplastic concentration*

In general, MPs migration is proportional to MP concentration. Xu et al. (2022a, 2022b) showed that higher concentration of MPs (for two sizes, 0.1 μm and 2 μm) resulted in higher mass recovery rate, suggesting that this is due to adsorption of some MPs on soil pores which then depleted the amount of further available sites for adsorption, allowing the remaining MPs to traverse the soil. Contradictory findings for very small MPs (≤0.1 μm) are probably due to increasing dominance of mechanisms co-interacting with MP concentration for smaller MPs, that inhibit MPs transport, including (i) aggregation and deposition (Y. Wang et al., 2022b); (ii) adsorption on soil particles due to the increase in MP specific surface area (Shen et al., 2019); as well as clogging of pores by small MPs. Another possible explanation for these differences is variations of MP and soil properties among these experiments (see Tables S1-S2). Flow rates can also interplay with MP concentration to co-affect MP transport. Hou et al. (2020) showed an increase in adsorption of MPs on sands with water flow rate, that leads to a rate-dependent critical MP concentration. The authors explained this by an increase in the number of potential adsorption sites with rate, allowing MPs to explore more of the soil pores at faster flows, overcoming the competing effect of larger drag on MPs recovery rate. Therefore, at a given flow rate, above a critical (flow-dependent) MPs concentration, MP recovery increased with MP concentration, while decreasing with concentration if the initial concentration was below that critical value (Hou et al., 2020).

### 3.2 Chemical properties

*3.2.1 Microplastics type*

Different MP types (i.e. polymer material they are made of) have different properties including density as well as surface properties including hydrophobicity (contact angle), surface roughness, and Zeta potential (O'Connor et al., 2019; Fei et al., 2022; Ranjan et al., 2023; Gao et al., 2021; Cohen and Radian, 2022). Each of these properties can affect various aspects of MP transport, and therefore MP type does not exhibit a univocal effect on transport.

In general, denser MP has higher mobility. For example, polyethene (PE) reached deeper than polypropylene (PP), which was explained by the lower density and increased buoyancy of PP hindering infiltration (O'Connor et al., 2019). However, surface properties often dominate over density: lower hydrophobicity, higher Zeta potential, and lower roughness were found to have a stronger positive effect on MPs transport than higher density (Fei et al., 2022; Ranjan et al., 2023; Gao et al.,2021; Cohen and Radian, 2022). Despite its lower density, the mass recovery rate of polylactic acid (PLA) was higher than polyvinyl chloride (PVC) because PLA has higher Zeta potential and lower hydrophobicity (Fei et al., 2022). Comparing PE, polyethylene terephthalate (PET), and PP, showed the following order of PE>PET>PP in terms of depth reached (Ranjan et al., 2023; Gao et al., 2021), again explained by the lower hydrophobicity and higher Zeta potential of PE vs. PET, despite its lower density (all other conditions uniform). The lower mobility of PP was explained by its low density and Zeta potential, and its higher hydrophobicity and surface roughness (Ranjan et al., 2023; Gao et al., 2021). Lower hydrophobicity was used to explain deeper penetration of polyamide (PA) (vs. PE, PET, and PP in Gao et al., 2021; and vs. PET in terms of depth ratio in Cohen and Radian, 2022). Inconsistencies between studies, e.g. deeper penetration of PET vs. PE in Gao et al. (2021), opposite than the trend found by X. Zhang et al. (2022b), could be due to differences in other parameters including the soil properties, hydraulic conditions, and MP size and shape. Notably, the differences could also be due to the different mobility metrics used, e.g. relative mobility in X. Zhang et al (2022b) vs. penetration depth in Gao et al. (2021).

### 3.3 Microplastics aging

Aging of MPs changes a variety of physical and chemical properties. The mobility of aged MPs was found to be greater than that of pristine MPs, in terms of both MP concentration (Qi et al., 2022) and maximum depth (X. Wang et al., 2022a). One reason is that aging alters MP surface properties, including roughness of the surface and the presence of oxygen-containing groups (Ali et al., 2023), where the latter can reduce MP adsorption (Qi et al., 2022; Yan et al., 2020). Furthermore, aging alters polymer structure, reducing MP size and changing their shape (Ren et al., 2021; Yan et al. 2020), and reducing their hydrodynamic diameter (X. Wang et al. 2022a). Aging also increases MP Zeta potential, and hence the interaction energy between MPs and other particles including the soil particles (X. Wang et al. 2022a), and can reduce MP hydrophobicity, promoting MP transport (H. Li et al., 2021).

## 4. Soil properties

### 4.1 Physical properties

#### *4.1.1 Soil texture, grain and pore size*

Overall, coarser texture promotes MP transport; this was found in terms of mass recovery rate (Dong et al., 2022; Wu et al., 2020), transport rate (Gui et al., 2022), number of MPs traversing the sample (Xing et al., 2021), and loss ratio (Rehm et al., 2021). For a given MP size, larger soil particles, which in turn imply larger pore sizes, enhance the MPs mobility, in terms of mass recovery rate (Dong et al., 2022; Hou et al., 2020), maximum depth (Gao et al., 2021; Ranjan et al., 2023), and MP outlet concentration (Qi et al., 2022). When the soil particle size is much larger than MP size, their ratio $D_{MP}/D_S$ might dominate MPs transport (Waldschläger and Schüttrumpf, 2020; Hou et al., 2020). For sands, a critical $D_{MP}/D_S$ value of ~0.1 was found (Gao et al., 2021; Ranjan et al., 2023). Notably, as most soils are composed of a wide range of particle (and pore) sizes, the average grain diameter $D_S$ is insufficient to describe how soil texture affects MPs mobility, and one may need to use more comprehensive parameters such as particle size distribution.

In addition to the obvious effect of larger soil pores in coarse-textured soils (Dong et al., 2022; Xing et al., 2021), larger soil particles have lower specific surface area, and hence adsorb and retain MPs less than finer soils. Soil texture also affects soil Zeta potential. In most cases, both soil and MPs surfaces are negatively charged; in such cases, coarser soils have higher Zeta potential (Dong et al., 2022; Rong et al., 2022; Gui et al., 2022; Li et al., 2023), and thus stronger repulsion which retains fewer MPs, promoting their mobility (in terms of mass recovery rate in Wu et al., 2020). MP surface roughness was found to reduce MP penetration depth, due to increased friction with the soil pores (Ranjan et al., 2023), however this effect is subject to interference with other mechanisms and properties, including water flow rate and MP concentration (Hou et al., 2020). Higher porosity was also found to promote MP mass recovery rate (Li et al., 2023; Dong et al., 2022). We stress however that porosity, being a scalar representing a sample-averaged property (similarly to average diameter), may not suffice to provide a clear trend of MP mobility. For instance, a soil can have larger porosity but with reduced connectivity, where many large pores connected to smaller pores (which act as bottlenecks) or to dead-ends. This can be used to explain the seemingly non-intuitive result of Wu et al. (2020), showing a higher MP mass recovery rate in low-porosity desert soil vs. high-porosity red soil.

### 4.1 Geochemical properties

#### *4.2.1 Mineralogy of soil grains*

Soil mineralogy affects MP transport in two ways. One is by forming MP-minerals aggregates which have higher *density* than MPs alone, and thus can enhance depth of MPs penetration (Yan et al., 2020). The other is by affecting the *chemical* properties that affect MP migration, including MP Zeta potential, the hydrodynamic diameter, and the interaction of MPs and minerals (Yan et al., 2020; Li et al., 2019, 2020; M. Li et al., 2021; Wu et al., 2020; Gui et al., 2022). Yan et al. (2020) found enhanced penetration depth due to increase in Zeta potential when natural soil minerals were added. In contrast, Wu et al. (2020) and Gui et al. (2022) found that the presence of iron or aluminum oxide minerals (Fe/Al oxides) decreases MP mobility (both mass recovery rate and transport rate) because MP adsorbed on the surface of Fe/Al oxides. The surface charge of Fe/Al oxides is pH-dependent: it is positive for acidic and neutral pH, reducing with increasing pH up to 8.5; above 8.5, it reverses sign to negative (for example in hematite, due to the deprotonation of Fe-OH; Nie et al., 2023). At pH of 6, Fe/Al oxides with positive charge were found to adsorb the negatively charged MPs, decreasing MP mobility (in terms of both mass recovery rate and transport rate; Li et al., 2019; Wu et al., 2020; Gui et al., 2022). Another inhibiting effect on MP transport is that the diameter of the MP-Fe/Al oxide aggregates is larger than individual MP particles; this was shown to decrease MP mass recovery rate and transport rate (Li et al., 2019, 2020; Gui et al., 2022). The kaolinite and bentonites with negative charge were found to promote the migration of negatively charged MPs when the pH of the solution was 6, because of the repulsion force between MP and sand (Li et al., 2020; M. Li et al., 2021).

#### *4.2.2 Organic components*

Soil organic matter enhances MP transport (Ivanic et al., 2023; Gao et al., 2021; Dong et al., 2021; Hou et al., 2020; Y. Wang et al., 2022b; Xu et al., 2022a; 2022b; W. Zhao et al., 2022). For instance, dissolved organic matter was found to increase breakthrough concentration by increasing the MP surface wettability, thereby increasing the dispersion of MPs particles on the soil pore surfaces (Ivanic et al., 2023). Humic acid (HA) was found to enhance the maximal MP penetration depth by increasing repulsion between the MPs and soil particles, and possibly decreasing MP hydrophobicity (Fig. 2; Gao et al.,2021). Further studies showed that HA decreased the roughness of MP surface, promoting MPs mass recovery rate (W. Zhao et al., 2022; Dong et al., 2021, 2022). Similarly, fulvic acid (FA) was found to increase MP breakthrough concentration by increasing the Zeta potential of both MPs and sand particles and thus their repulsive force (Fig. 2; Y. Wang et al., 2022b). However, Hou et al. (2020) demonstrated that MP mass recovery rate does not always increase with FA concentration, because for high values of FA (>5 mg/L) other factors such as hydrophobicity and buoyancy can dominate MP transport over electrostatic forces (Hou et al., 2020). Soil colloids were shown to promote MP mass recovery rate by filling the concave area of the soil's pores (in the contact between the grains), thereby reducing the soil's surface roughness and increasing the repulsive force between MPs and pore walls (Xu et al., 2022a; 2022b).

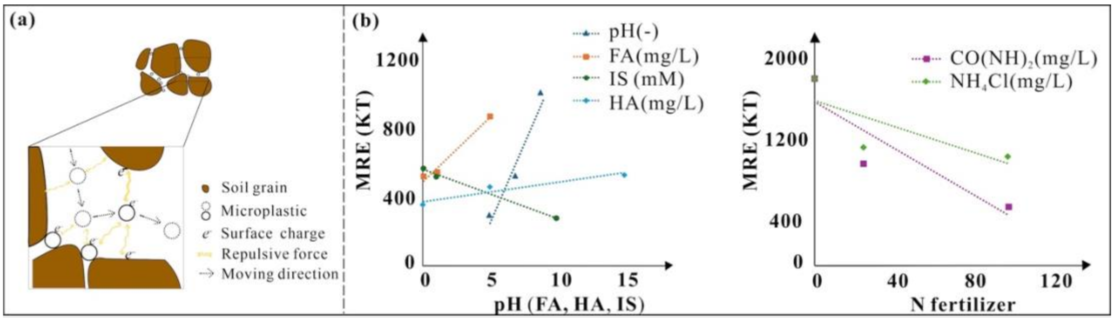


**Figure 2.** Schematic diagram of the interaction force between MPs and soil particles (a) and the relationship between maximum repulsive energy (MRE) of Derjaguin-Landau-Verwey-Overbeek (DLVO) theory, pH, fulvic acid (FA), humic acid (HA), ionic strength (IS), CO(NH)2, and NH4Cl(b). Data in (b) is from Y. Wang, et al. (2022b), Wang X. et al. (2022c), and Rong et al, (2022).

## 5. Hydrological conditions

Since transport of MPs in soils is driven by water infiltration, the hydrological conditions that control how water is introduced to the soil play a decisive role. The interaction of MPs with water is complex: in addition to the amount of water and its velocity, the transport of small MPs also depends on the motion of air-water interfaces in the vadose zone. The fact that MPs are hydrophobic further complicates their migration, as explained below.

### 5.1 Physical conditions

*5.1.1 Water flux*

Higher water flux in general promotes MP transport (Fei et al.,2022; Qi et al.,2022; Y. Wang et al., 2022a; Dong et al., 2022). This is mainly due to the increase in the shear force which sweeps MPs with the water flow; however, slower water infiltration allows more transverse (horizontal) flow, which could enhance MP transport by allowing the water to traverse larger MPs-contaminated areas in the soil (shown in terms of mass recovery rate in Hou et al. (2020) and Fei et al. (2022)). Higher water velocity was shown to increase the detachment of MPs from the soil matrix (Y. Wang et al.,2022a; Qi et al.,2022; Dong et al., 2022).

Further intricacies arise due to co-effects of flow with ionic strength, MP concentration and pore size (Dong et al., 2022; Hou et al., 2020). Dong et al. (2022) showed a positive correlation of water velocity and MP mass recovery rate under high ionic strength (10 Mm NaCl), however with negligible influence of velocity on MP transport at lower ionic strength (0.1 Mm NaCl). Similar non-monotonic relationship between MPs transport and water velocity was observed when varying MP concentration and sand particle size (Hou et al., 2020). Hou et al. (2020) showed a non-monotonic behavior—an initial increase in MP mass recovery rate with velocity followed by decrease at even higher velocities, for MP concentrations of 0.3 and 0.5 mg/L. The authors attributed this to increasing frequency of collisions between MP particles with flow rate, which can then sample a larger portion of the pore space, causing MP aggregates to break; all these increase the probability of MPs to adsorb on the soil particles. We note most studies on the effect of flow rate were conducted in coarser soils, where rates would be higher than in finer soils.

#### *5.1.2 Saturation*

Soil water saturation (the relative pore volume occupied by water) also affects MP transport (Dong et al., 2022). Due to the hydrophobic nature of MPs, contact with water is minimized, and MPs can remain trapped within the air-water interface (Al Harraq and Bharti, 2022). As decrease in water saturation results in more air-water interfaces, which in turn limits MP migration in soils (Dong et al., 2022). Another reason for this trend is the increase in trapped air bubbles, that act to decrease the available pore space for migration of water and MPs (Dong et al., 2022). For low density MPs (which buoyant in water), however, increasing water saturation was shown to decrease MP mass recovery rate because of buoyancy effects (O'Connor et al., 2019; H. Li et al., 2021).

#### *5.1.3 Wetting-drying cycle*s

Since MP transport is strongly linked to water saturation (Dong et al., 2022) and to the air-water interfaces (Al Harraq and Bharti, 2022), cycles of wetting and drying (which cause the interfaces to advance and recede) play a crucial role. A positive correlation between the number of cycles and the maximum MP depth was reported for various settings (Gao et al., 2021; O'Connor et al., 2019; Ranjan et al., 2023, Z. Zhao et al., 2022b). In addition to interface motion, wetting-drying cycles are associated with soil surface damage, in particular crack formed by repeated shrinkage and expansion (Tang et al., 2021; Wan et al., 2019), serving as preferential pathways for MPs. Freeze-thaw cycles, a different mechanism that also induces preferential flow paths by shrinkage and expansion, was also found to increase MP breakthrough concentration (Li et al., 2023). Another mechanism associated with wetting-drying cycles which affects MP transport is mechanical abrasion and weathering of MPs resulting in fragmentation into smaller particles; this was used to explain increased MPs penetration depth with wet/dry cycles (Ranjan et al., 2023).

### 5.2 Geochemistry: Soil solution

#### *5.2.1 pH*

The MP mass recovery rate and breakthrough concentration were found to increase with pH (Fei et al., 2022; Wu et al., 2020; Y. Wang et al., 2022b). The authors concluded that this is due to the increase in the Zeta potential of both MP and soil particles with pH, indicating a stronger repulsive force between them (Fig. 2). The repulsion (associated with electrostatic forces) was suggested as the dominant factor promoting MP mass recovery rate with pH (Wu et al. 2020). Decreasing pH increases the concentration of $H^+$ in the solution, neutralizing the negative charge on the MP surface such that the MP hydrodynamic diameter increased (Fei et al., 2022). Elsewhere, increasing pH was shown to demote MP-minerals aggregation, promoting MP mobility: increasing pH from 3 to 8.5 reversed the interaction force (from repulsive to attractive), decreasing MP-Fe/Al oxides aggregation (Nie et al., 2023).

#### *5.2.2 Ionic strength*

Multiple studies have shown that the MP mobility decreases with ionic strength (IS) (Dong et al.,2022; Hou et al.,2020; Wu et al.,2020; Y. Wang et al., 2022b; M. Li et al.,2021; shown in terms of both MP mass recovery rate and breakthrough concentration). Increasing IS decreases the Zeta potential of both soil particles and MPs, as well as the repulsion force between them (Y. Wang et al., 2022b; Hou et al.,2020). It was found that $Ca^{2+}$ has a greater effect on MP retention than $K^+$, $Na^+$, and $Mg^{2+}$ (Dong et al., 2021), and that $Al^{3+}$ has a greater effect on MP retention than $Na^+$ and $Mg^{2+}$ (Fei et al.,2022), because cations with higher ionic radii lead to stronger charge screening, which increases particle retention (Dong et al., 2021; Wu et al., 2020). In soil contaminated by MPs, different IS have different effects on the MP migration because the degree of aggregation of soil mineral particles with MPs can be different under different IS. For example, ~77% and ~97% of bentonites were adsorbed onto MPs forming MP-bentonite hetero-aggregates when IS was 5 mM and 25 mM NaCl, respectively; the diameter of the MP-bentonite hetero-aggregates increased with IS, which in turn decreased the MP mass recovery rate (M. Li et al.,2021).

#### *5.2.3 Chemical additives*

Additives such as nitrogen fertilizers, nonylphenol, surfactants, and biochar have different effects on MP transport. Nitrogen fertilizers were found to decrease MP mass recovery rate because they decrease the Zeta potential of both MPs and soil particles and increase the hydrodynamic diameter of MPs (Rong et al., 2022). Chlortetracycline hydrochloride (widely used antibiotic in agriculture) was shown to decrease MP mass recovery rate, due to a decline in the electrostatic repulsion between MP and sand grains (Xu et al., 2022b). The large specific surface area of biochar was shown to provide more adsorption sites for MPs, hindering their transport (X.Wang et al., 2022b), with stronger impact of $Fe_3O_4$ biochar (X. Wang et al., 2022c). Unlike biochar and nitrogen fertilizers, nonylphenol increases MP mass recovery rate, as it increases the MPs Zeta potential, and also possibly because of the hydrogen bonds forming between MPs and nonylphenol (Xu et al., 2022a). Perfluorooctanoic Acid (PFOA; a surfactant, considered an emerging pollutant) decreased the breakthrough concentration of negatively-charged MPs decreasing their Zeta potential hence promoting their adsorption in the soil; an opposite effect—increasing breakthrough concentration—was observed for positively-charged MPs, due to the reversal of their surface charge, limiting their adsorption in the soil (Rong et al., 2023).

The addition of surfactants was found to promote MPs mass recovery rate, as long as the surfactants concentration remained lower than the critical micelle concentration; this was explained by the increase in the Zeta potential of MPs and sand particle and the decrease of MP hydrophobicity by the surfactants (Jiang et al., 2021). Cationic surfactants were found to have a greater effect on MP transport than anionic surfactants, because the former provide more osmotic and elastic repulsion forces between MPs and sand particles (Jiang et al., 2022). Surfactants has a nontrivial co-effect with MP type on MP mobility: while the mobility of PE was higher than of PP without surfactants (in terms of maximum depth; Gao et al., 2021, O'Connor et al., 2019, Ranjan et al., 2023), addition of surfactants (both cationic and anionic) reversed that trend (in terms of MP mass recovery rate; Jiang et al., 2021, 2022). The authors explained this by the increase in Zeta potential, as well as the larger surface area and roughness of PP MPs, promoting surfactant retention (Jiang et al., 2021). However, we note the use of two different MP mobility metrics across these studies does not allow a decisive conclusion regarding the main reason for the reversal in mobility of PP and PE.

## 6. Living organisms

Living organisms affect MP transport (Lwanga et al., 2017; Riling et al., 2017; H. Li et al., 2021; He et al., 2020, 2021), with larger effect exhibited by larger living species (Ren et al., 2021). It has been shown that soil living organisms can promote MP migration by (1) creating macro-pores that serve as preferential MP pathways; and (2) digesting MPs, transporting them further to where MPs are either excreted as defecate, or released once the organism dies (Lwanga et al., 2017; Rillig et al., 2017). Plant roots enhance penetration depth of MP because their decomposition leaves a macropore for MP transport. Plant roots can also carry MPs with them as they grow; however, MP transport will depend on the roots' orientation, i.e. horizontal vs. vertical (H. Li et al., 2021). Rhizosphere secretion can also induce MPs aging and decrease their hydrophobicity, increasing MP mobility (H. Li et al., 2021).

Microscopic organisms interact with MPs in a more complex manner, by forming MPs-bacteria aggregates (He et al., 2021). Bacteria reduce the zeta potential of negatively-charged MPs (the Zeta potential of MPs-bacteria aggregates is lower than that of MPs), and increases the hydrodynamic diameter (aggregates has larger than individual MPs); both effects were shown to decrease the MP mass recovery rate. For positively-charged MPs, bacteria will reverse the MP charge (as the overall charge of the aggregates is negative), increasing the MP mass recovery rate in soils with negatively-charged grains (He et al., 2021). The gram-negative strain E. coli was shown to decrease MP mass recovery rate by creating a biofilm which narrows the soil pores as well as increases their surface roughness, as well as by decreasing the repulsive force between MPs and soil particles (He et al., 2020).

## 7. Conclusions and future perspectives

Microplastics transport is affected by a multitude of physical, chemical, and biological parameters, many of which are intimately coupled. These include properties of (i) the MPs—size, shape, concentration and type (density, surface roughness and wettability), and the zeta potential; (ii) the soil—texture, pore and particle sizes, mineralogy and organic matter content; (iii) hydrological conditions—flow rate, wetting-drying cycles, saturation, and soil solution geochemistry including pH, ionic strength, additives, and zeta potential; and (iv) living organisms—plants, animals and microorganisms (Fig. 3). Figure 3 presents only the co-effects that were evidenced in the literature, whereas intuitively we expect more to exist, for example between the Zeta potentials of the MP and the soil. Furthermore, many properties evolve with time, as MPs age and degrade or as the environmental conditions change.

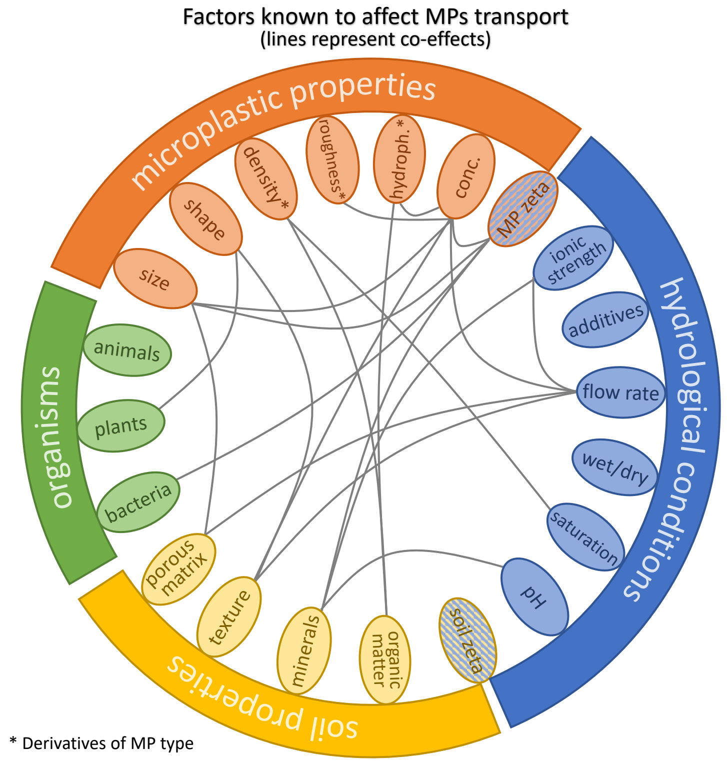


**Figure 3.** Factors shown to affect MP transport (ovals), including co-effects (marked by lines) where two factors exhibit a combined (one- or two-way) effect.

A formidable source of complexity challenging our understanding of MP transport in soils is the way the aforementioned factors interact to affect transport, leading to co-effects among two (and possibly more factors). A striking example is MP size, possibly the most fundamental and influential property. MP transport exhibits a complex, non-monotonic dependence on MP size (Fig. 1), which is moderated by co-effect of size with various factors including soil pore sizes, soil mineralogy and MP Zeta potential. While the first co-effect of MP sizes and soil pore size is intuitive (larger pore sizes allow larger MPs to pass through), others are not. For instance, as MP size decreases below a certain threshold (which in turn could depend on multiple factors such as soil solution chemistry), additional mechanisms which affect transport become more dominant. At an intermediate MP size range (below ~1μm, above ~0.1μm), a decrease in MPs size decreases their Zeta potential, which enhances MP adsorption on the soil particles, reducing their mobility (reversing the trend for MP larger than ~1μm). At yet smaller MP sizes (below ~0.1μm), aggregation of MPs with ionic compounds from the soil solution (a process which by itself is also moderated by the MP zeta potential), the larger hydrodynamic diameter of the aggregate reverses again the mobility trend to be inversely proportional (same as for large MPs, above ~1μm).

Exploring the interactions among multiple factors and the resulting co-effects (Fig. 3) requires further experimental studies where all parameters besides those investigated are controlled and known. In many cases, multiple parameters that are not the control parameters are unknown or vary together with other parameters, challenging conclusive evidence on the specific effect of the actual control parameter of interest. Another challenge causing a gap in our knowledge is the use of different mobility metrics. Some of these metrics, e.g. maximum depth reached and concentrations of MPs traversing a given sample length, refer to disparate aspects of MP mobility that cannot be compared quantitatively, and have quite different environmental implications. This ambiguity could be overcome by measuring mobility using multiple complementary metrics.

Further, more specific gaps include: (i) use of soil analogs such as glass beads or even micromodel; while providing fundamental insights into the physics, further studies needs to confirm their applicability to natural soils, in particular clay-rich where the complex geochemistry and pore size distribution may govern MP transport (Waldschläger and Schüttrumpf, 2020); (ii) transport of MPs when other particles adsorb on them, and the potential impact of changes in the surface properties of the aggregate (vs. the MP alone); this is of particular practical importance for MPs that act as vectors for other contaminants such as heavy metals, pathogens or antibiotics (González-Pleiter et al., 2021; S. Liu et al., 2022; Lu et al., 2022); (iii) preferential pathways—known to occur for hydrophobic soils, and are expected to occur even in non-hydrophobic soils with the addition of a relatively small amount of some of the more hydrophobic MPs (Cramer et al., 2022); addressing this requires more fundamental studies of the underlying physics, in particular for small MPs where colloidal forces may become important (Al Harraq and Bharti, 2022). Finally, we note there are some aspects which are less studied than others, potentially because of technical challenge rather than being less important, such as MP shape, which is expected to have a substantial impact on transport, and of MP composites as many plastics are not made of a single polymer.

In conclusion, several knowledge gaps hinder our ability to predict MP transport in soils, owing to the complex underlying physics, chemistry and biology. This scientific challenge makes MP transport a vibrant, exciting topic which is becoming intensely explored from various disciplines. In this review, we have highlighted several knowledge gaps, that require further fundamental understanding of the transport mechanisms; some of those could only be addressed by first studying idealized systems to understand how small, hydrophobic particles move in heterogenous porous materials. Ultimately, after addressing these gaps, more applied studies which incorporate complexity of natural soils and the various environmental conditions, will be required to enable prediction and mitigation of MP pollution in soils.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.


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## Author contributions

All authors: Conceptualization, Investigation, Visualization, Writing—original draft, review & editing; AB, MVDW, RH, PW: supervision; RH, QL: Funding acquisition; RH: project management.

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