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Review

Factors Influencing the Vertical Migration of Microplastics up and down the Soil Profile

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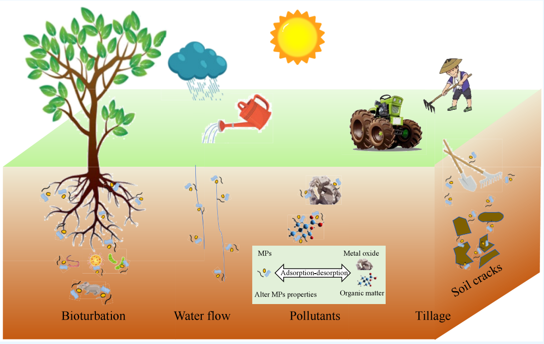
Cite This: *ACS Omega* 2024, 9, 50064−50077

ABSTRACT: Soil ecosystems are under serious threat from microplastics (MPs), and this is causing worldwide concern. The relationship between soil and MPs has become a popular research topic, and the vertical migration of soil MPs is of increasing interest. This Review summarizes the current status of research into the factors affecting the vertical migration of soil MPs. Published research shows that the characteristics of MPs and the physicochemical properties of the soil affect the infiltration process. Soil organisms play a key role in the vertical migration by acting as vectors or as a result of adsorption. Dissolved organic matter and metal oxides transfer MPs by adsorption−desorption. In addition, rainfall and dry−wet cycles alter the mobility of soil MPs, leading to changes in migration processes. Agricultural activities such as tillage and irrigation may distribute MPs throughout the topsoil. Vertical migration of soil MPs is a process influenced by a combination of factors, and the role of these factors in MP deposition needs to be explored further.



1. INTRODUCTION

Over the past few decades, plastics have revolutionized the way we live, and we are in an "Age of Plastics".[1] Plastics are widely used in everyday life, industrial manufacturing, medical devices, and other fields, in part because of their low cost, high stability, ease of production, and versatility.[2] Global plastic production has grown at a rate of 8.7% per year over the past 50 years, with cumulative production expected to reach 34,000 t by 2050.[3] Despite stringent constraints on the use and management of plastics, the recycling rate of plastics still falls short of requirements, and there is already a huge imbalance between the production and disposal of plastics.[4] Plastics are dispersed into ecosystems under the influence of natural transport and human activities,[5] and are gradually degraded to microplastics (MPs) or nanoplastics (NPs) by collision abrasion, ultraviolet radiation, long-term weathering, biotic and abiotic aging processes, as well as under the action of other physical, chemical and biological factors.[6] Microplastics (MPs) are defined as polymers smaller than 5 mm, and microplastics can be further broken down into smaller particles called nanoplastics (NPs), which have been widely characterized in different environmental matrices, raising serious environmental concerns.[7] Microplastics of different concentrations, shapes, sizes and species are found in a wide range of ecosystems: terrestrial, marine and riverine, and even in polar regions.[8] MPs in aquatic ecosystems have been extensively studied, with 80% of MPs recorded from terrestrial systems.[9] It is estimated that the annual load of MPs received in terrestrial ecosystems is 4−23 times higher than that in marine systems.[10] In soils heavily contaminated with MPs, the concentration of has been found to be as high as 6.7% by weight of the soil.[11] It can be seen that the problem of soil pollution caused by microplastics should receive wide attention.

Existing studies have shown that MPs aggregated in soil can directly or indirectly affect soil physicochemical properties, e.g., MPs change soil water content and water holding capacity,[12] and affect soil nutrient content through adsorption−desorption processes with soil organic matter and between soil minerals.[13] In addition, microorganisms, as major participants in soil nutrient cycling and material transport, are also affected by MPs to varying degrees.[14,15] Due to the adaptability of microorganisms to changes in substrate and soil properties, they are sensitive to microplastics, and soil MPs can alter the diversity of fungal communities.[15] While soil physicochemical properties, soil organisms and human activities are closely related to the horizontal and vertical migration of MPs in soil.[16,17] Currently, many studies have focused on the horizontal transport process of MPs, but there is still much room for exploration of their vertical migration in soil.[18] Different concentrations of MPs have been found in surface

Received: April 29, 2024
Revised: November 20, 2024
Accepted: November 29, 2024
Published: December 11, 2024

https://doi.org/10.1021/acsomega.4c04083

and deep soil after 32 years of mulching, suggesting that MPs are involved in a series of environmental behaviors (vertical migration, aging, and transformation) in soil, and that the process of vertical migration, in particular, may play an important role.[19] MPs that have accumulated in the surface layer of soil can infiltrate into the deep soil layer over time, causing harm to the groundwater environment and posing a threat to the ecosystem.[5,20] Currently, studies on the vertical migration of MPs in soil have been conducted mainly in the laboratory, and studies in the field are very limited.[21,22]

The vertical migration of MPs in soil is affected by a variety of factors, and differences in their own properties will lead to differences in the ability of MPs to migrate vertically.[23] Moreover, factors such as soil biological activities,[24] soil environmental factors,[25] leaching,[26] and agricultural activities[27] are also closely related to the vertical migration process. Vertical distribution of MPs in soil exhibits different characteristics under the combined effect of several factors. In one study, it was found that the abundance of MPs gradually decreased with increasing soil depth, and the polymer types also varied; for example, the percentage of polyvinyl chloride (PVC) and polyethylene (PE) gradually increased, and polystyrene (PS) gradually decreased.[28] However, another study found that the abundance of MPs decreased and then increased in the 0−90 cm soil layer, and the average particle size of MPs gradually decreased.[29] It can be seen that since MPs are affected by a combination of their own characteristics and soil environmental factors, the mechanism of their vertical migration in soil is not fully understood. In order to gain a better understanding, it is essential to have knowledge of the factors that may affect this process.[30]

The main objective of this paper is to summarize the factors influencing the vertical migration of MPs in soil. In contrast to previous studies that mainly focused on the horizontal migration of MPs in soil,[5] this study emphasizes its vertical migration process. By considering various physical, chemical, and biological factors (e.g., MPs physicochemical properties, soil organic matter, soil organisms, and dry−wet cycles), a comprehensive description of the vertical migration of MPs in soil is provided.

2. RESEARCH METHOD

2.1. Literature Search. The data in this paper were obtained from the Web of Science (WOS) core database, which was searched by the keywords “microplastics”, “soil”, “migration” or “transport”. The search period covered was from 1 January 2019 to 30 September 2024. To ensure the accuracy and scientific validity of the results, the search results were further screened, and after CiteSpace (6.2) to remove duplicate data, 713 publications were finally obtained.

CiteSpace software is a bibliometrics-based visualization and analysis software. It can analyze relevant information from a large volume of literature (e.g., publication and cooperation of authors and institutions, co-occurrence and clustering of keywords, national cooperation, etc.) and display it in a visual form, presenting relevant information about a research field selectively on a map according to need, so that researchers can find effective information from it, and intuitively analyze the research development pulse and hotspots of the research field trends.[31] This review analyzes the results of the retrieved literature using the CiteSpace (6.2) software.

2.3. Bibliometric Analysis. Figure 1 shows that there is a significant increase in soil MPs-related research from 2019 to 2023, and the increase in 2024 is not known because the retrieved data ends in September 2024.The research on soil MPs migration subsequently increases during 2019−2023, and the research on soil MPs migration occupies a significant portion of the field of soil MPs research. The keyword co-occurrence network of soil MPs migration in 2019−2024 (Figure 2) shows that the research on soil MPs migration mainly focuses on how soil microbiota, organic matter, ionic strength, metal oxides, chemicals, etc., affect the vertical migration process, as well as the ecological and environmental risks posed by soil MPs. The study of the factors affecting the vertical transport of soil MPs has gradually become a research frontier in this field.

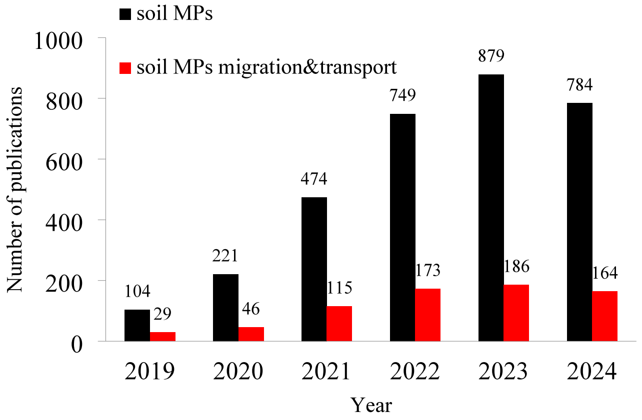


Figure 1. Number of papers published with the keywords “soil MPs” and “soil MPs and migration or transport,” 2019−2024.

3. INFLUENCE OF PHYSICOCHEMICAL PROPERTIES OF MPS ON THEIR VERTICAL MIGRATION

Differences in the physicochemical properties of MPs (e.g., shape, size, surface charge) have been shown to affect their vertical migration and distribution in soil.[32] Shape, size, and density are the main factors controlling the deposition process, and certain environmental factors can affect the migration behavior of MPs by changing their physical properties.[33]

3.1. The Physical Properties of MPs. After plastics enter the soil and undergo aging and crushing, they form different shapes: fragments, pellets, fibers, films, and foams. Differences in shape (Table 1) lead to differences in the rate of vertical migration, e.g., pellet MPs are more able to migrate vertically compared to other shapes, this is because pellet MPs are denser and migrate downward more easily, whereas fiber MPs are more likely to be trapped by soil particles and are less able to migrate.[34] However, it has also been demonstrated that fiber MPs are capable of vertical migration in soil, with the proportion of fibers increasing linearly with soil depth and the proportion of fragments and membranes decreasing linearly.[35−38] This may be due to them creating connections between soil pores, in addition, fiber MPs are more likely to flow into runoff water and migrate deeper into the soil by gravity.[23,35] From the available studies, it seems that a particular shape of MPs does not determine their vertical migration ability, and the influence of other factors, such as the particle size of MPs, should not be underestimated, Waldschläger and Schüttrumpf (2020) found that fiber size has an impact on vertical migration: the smaller the size, the greater the depth of infiltration.[39] It is noteworthy that the vertical migration behavior of irregularly shaped MPs has not

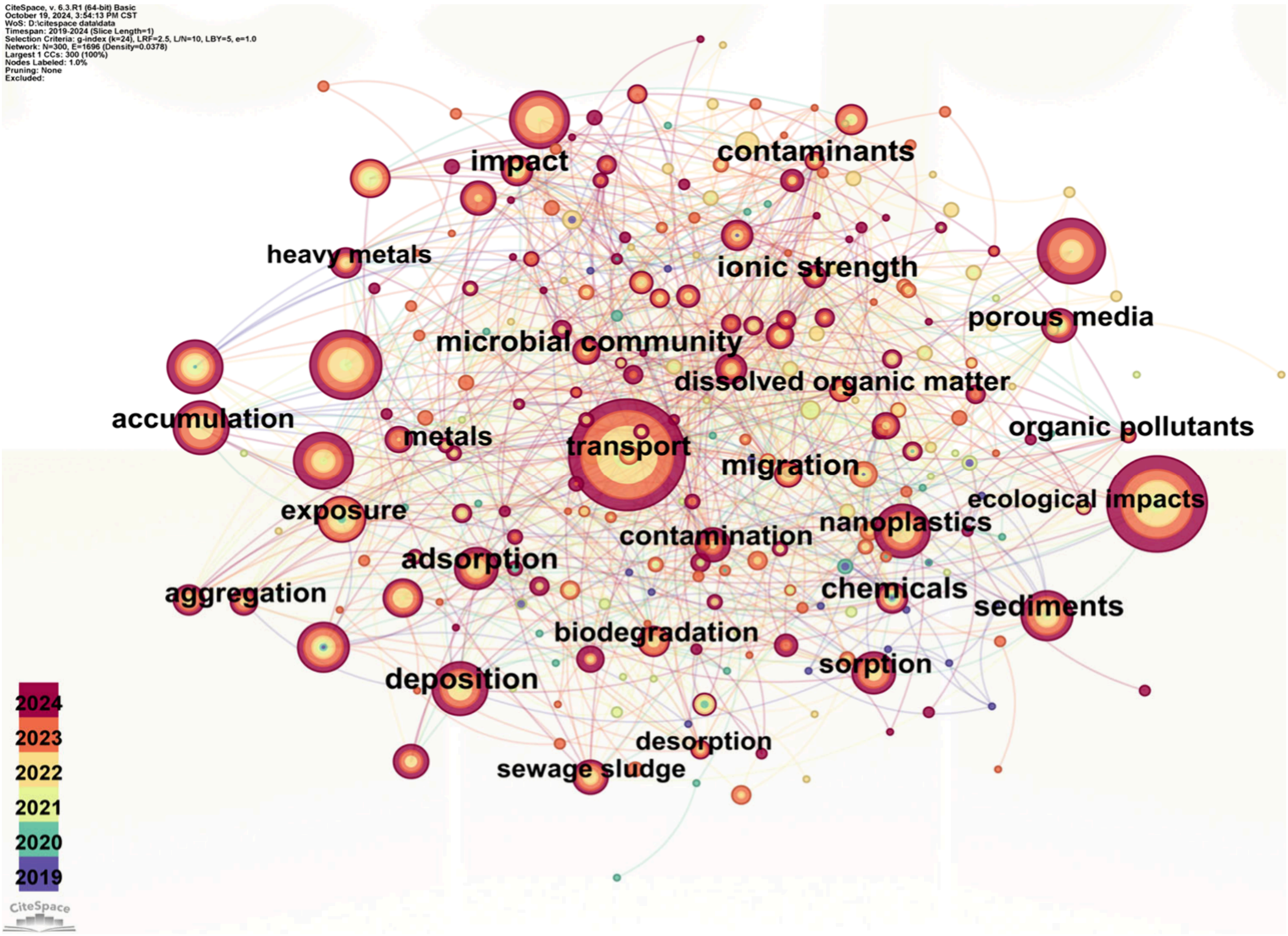


Figure 2. Co-occurrence network of keywords related to MP migration in the soil from 2019 to 2024.

Table 1. Vertical Distribution of MPs by Shape

reference	studied area	depths	abundance	shape
41	Shanghai, China	0−3 cm	78.00 ± 12.91 items·g^{-1}	fiber: 53.33% fragment: 37.58% film: 6.67% pellet: 2.12%
		3−6 cm	62.50 ± 12.97 items·g^{-1}	fiber: 37.62% film: 33.76% fragment: 28.30% pellet: 0.32%
42	Sheshui River basin, China	0−10 cm	2693 ± 1470 n·kg^{-1}	fiber and fragment: 65.1%
		10−20 cm	2351 ± 1064 n·kg^{-1}	fiber and fragment: 65.6%

been extensively studied, and the shape of MPs is an important factor controlling their vertical migration in the soil environment. Therefore, future studies could explore more about the differences and mechanisms of vertical migration behavior of MPs under regular and irregular shapes.[40]

The ability of MPs to migrate vertically to deeper soil layers does depend on their size (Table 2) and whether they are small enough to pass through soil crevices; if not, they accumulate in the soil.[43] Smaller MPs are more likely to infiltrate deep soil or groundwater, and smaller sized MPs may pose a greater ecological risk because they are more readily consumed and taken up by plants and animals.[37,44] Zhang et al. (2022) found that small MPs could migrate up to 7 cm vertically, while large MPs migrated only 4 cm, and the migratory capacity gradually decreased with increasing particle size.[37] Previous studies have suggested that large-sized MPs may be more likely to accumulate in topsoil, while small-sized MPs are more likely to accumulate in deeper soils.[45] With the increase of infiltration depth, the maximum size of MPs retained at different depths and their concentrations has been found to exhibit a decreasing trend.[46] However, Xu et al. (2022) showed that in artificial ecosystems the size of MPs in the top soil layer (0−10 cm) was in the dominant particle size range of 200−500 μm, whereas in the deeper soil layer (10−20 cm) it was in the dominant particle size range of 500−1,000 μm, which is significantly different from the results of other studies.[47] This may be due to (1) the continuous input of plastics by farmers in artificial ecosystems. (2) Stronger UV radiation and higher temperatures in artificial ecosystems compared to natural ecosystems lead to the fragmentation of imported plastics in the topsoil into small-sized MPs. Alternatively, studies examining different sampling depths may also explain this inconsistency. Overall, MPs with smaller particle sizes have a greater ability to migrate vertically through the soil than larger MPs, and larger MPs will inevitably increase clogging in soil pores.[48] It is worth noting that it may not be

Table 2. Vertical Distribution of MPs According to Size

reference	studied area	depths	abundance	size
47	Xishuangbanna, China	0−10 cm	4487.5 ± 6440.2 particles·kg^{-1}	994.2 ± 398.3 μm
		10−20 cm	2281.3 ± 2461.5 particles·kg^{-1}	1222.9 ± 365.8 μm
41	Shanghai, China	0−3 cm	78.00 ± 12.91 items·g^{-1}	1.91 ± 0.13 mm
		3−6 cm	62.50 ± 12.97 items·g^{-1}	1.48 ± 0.11 mm
42	Sheshui River basin, China	0−10 cm	2693 ± 1470 n·kg^{-1}	<1 mm: 69.8−97.4%
		10−20 cm	2351 ± 1064 n·kg^{-1}	<1 mm: 62.5−98.5%
52	Beijing, China	0−10 cm	1107−3680 items/kg (average: 2451 ± 93 items/kg)	1.29 ± 0.94 mm
		10−20 cm	840−2867 items/kg (average: 1813 ± 47 items/kg)	1.15 ± 0.88 mm
		20−30 cm	680−2480 items/kg (average: 1461 ± 162 items/kg)	1.02 ± 0.78 mm
29	Hesse, Germany	0−30 cm	14.91 particles·kg^{-1}	1.77 mm
		30−60 cm	4.52 particles·kg^{-1}	1.45 mm
		60−90 cm	8.23 particles·kg^{-1}	0.93 mm

Table 3. Vertical Distribution of MPs by Polymer Type

reference	studied area	depths	abundance concentration	polymer type
28	Cléry-Saint-André, France	0−5 cm	2.9 g·kg^{-1}	PVC: 60.31%; PP: 17.86%; PS:14.64%; PE: 3.52%
		15−20 cm	2.544 g·kg^{-1}	PVC: 73.43%; PP: 7.94%; PS: 7.82%; PE: 8.37%
		30−35 cm	0.9 g·kg^{-1}	PVC: 51.84%; PP: 21.92%; PS: 4.85%; PE: 11.17%
59	Amu Darya−Aral Sea basin, Republic of Uzbekistan	0−5 cm	2064 ± 288 items·kg^{-1}	PU: 49.6%; SR: 17.6%; PMMA: 6.1%
		5−20 cm	3567 ± 533 items·kg^{-1}	PU: 36.7%; SR: 17%; PLA: 15.8%
		20−50 cm	6419 ± 1362 items·kg^{-1}	PU: 31.5%; SR: 16.6%; CPE: 9.2%

the case that smaller particle sizes of MPs are more susceptible to downward migration, and that MPs particle size plays the strongest role in their ability to migrate in a range of effective.[49] In the study of the vertical migration behavior of PEMPs with 3 clock particle sizes in soil, it was found that the migratory capacity was ranked as 25−147 μm > 0−25 μm > 147−250 μm.[49] Wei et al. (2024) also found that the threshold of the effect of MPs' particle size on their migration was found, and the migration rate of the MPs changed more rapidly when their particle sizes were less than 20 μm, and when the particle sizes were larger than 20 μm, although the migration rate still decreased with increasing particle size, it changed to a lesser extent.[50] There are two possible reasons for the "effective particle size" effect: (1) At the same concentration, larger MPs are more stable and have less tendency to aggregate than smaller MPs due to the reduced surface area, and the heterogeneous aggregation of MPs with the soil medium is reduced, making it easier for them to be transported in the soil.[36] (2) The maximum energy barrier between MPs and soil increases with increasing particle size, which in turn reduces the adsorption capacity of soil particles for large-size MPs, resulting in enhanced vertical mobility in the soil.[51]

The main polymer types (Table 3) of MPs in the soil environment are PE, PP, PS, PVC, PUR, PET, PA, HDPE, EVA, and CA, with a range of densities from 0.028 to 1.58 g/cm^3.[30] Density affects the migration of MPs in porous media, transport of MPs is sensitive to changes in particle density.[39,53,54] O'Connor et al. (2019) investigated the vertical migration behavior of MPs and found that the maximum penetration depth of PP was only 1.5 cm compared to 7.5 cm for PE; this was attributed to the lower density of the former.[54] In addition, in a comparison of the vertical migration velocity of two MPs, both with a diameter of 5 mm but with different densities (EPS: 22 kg/m^3; PE: 826 kg/m^3), expandable polystyrene (EPS) exhibited a higher velocity.[55] However, Waldschläger and Schüttrumpf (2020) also investigated the vertical migration behavior of MPs with different densities and found that MPs of the same size but with different densities (PET: 1.368 g/m^3; PP: 0.870 g/m^3) differed only by a few centimeters in infiltration depth, and the effect of particle density appeared to be small,[39] suggesting that density is not the only factor affecting the migration of MPs, and future studies should focus on the factors affecting MPs migration and their relative importance.[35]

The effect of MPs' surface roughness on the vertical migration process should not be ignored. During vertical migration, biofilm increased the deposition of NPs and MPs in soil due to increased size and surface roughness.[56] Ranjan et al. (2023) investigated the effect of surface roughness on the vertical migration of PP, PE and PET, and their results showed that the higher the value of roughness, the less vertical migration occurred, while the lower the value of roughness, the greater the degree of infiltration.[46] This is because the interlocking of MP particles with sand grains with high surface roughness is stronger than that of MP particles with low surface roughness, and the strength of interlocking determines the ability of MPs to be transported in the soil.[46] In addition, as the surface roughness of the MPs increases, the contact angle of the hydrophobic material increases, thereby increasing hydrophobicity,[57] and the hydrophobicity of the plastic particles significantly affects the mobility of the MPs.[58]

3.2. MP Chemical Properties. Surface hydrophobicity is another factor that affects the mobility of MPs. The hydrophobicity of plastics generally depends on the hydrophobicity of the base polymer and additives such as plasticizers; the higher the hydrophobicity, the less migration by MPs.[58,60] There are differences in the behavior of hydrophilic and hydrophobic microplastics. For example, hydrophilic polystyrene particles exhibit greater mobility in soil compared to hydrophobic polystyrene particles.[60,61] Liu et al. (2019) found that the relative mobility of the four NPs was strongly correlated with their degree of hydrophobicity.[62] Gao et al. (2021) investigated the surface hydrophobicity of three MPs (PP, PE, PET), and PP exhibited the highest hydrophobicity, followed by PET and PE, and this order closely matched the depth of vertical migration of the three MPs.[58] Also, since PE (density 0.893 g/cm^3) infiltrated deeper than PET of the same size but with a higher density (1.430 g/cm^3), this suggests that the surface hydrophobicity of the MPs has a greater effect on infiltration or vertical migration than density.

In the environment, the physicochemical properties of MPs are altered by exposure to chemical, physical and photodegradation.[63] During environmental weathering, the appearance of carbonyl functional groups leads to an overall negative charge on their surface.[64] Surface charge induces MPs to interact with cations and anions carried by pollutants in the environment. Due to the negative surface charge of MPs, they can bind ions such as organic substances or metal hydroxides.[65] Yan et al. (2020) confirmed that surface charge is the main factor influencing the mobility of MPs.[66] Wang et al. (2022) found that MP^+ adhered to the soil faster than MP^-.[67] Positively and negatively charged MPs have different adsorption capacities on soil, and these are related to the zeta potential of the soil and are affected by the pH and ionic strength of the suspension.[60] In addition, positively and negatively charged MPs have different pathways of uptake and migration by the plant root system, with positively charged MPs having lower levels of aggregation in the apical region, while negatively charged MPs are more readily taken up by the plant root system.[68]

Commercial NPs have well-defined size and active surface functional groups, including carboxyl groups,[69] sulfonic acid groups,[70] and amino groups.[71] Dong et al. (2019) investigated the migration and retention of NPs with surface carboxyl (NPC), sulfonate (NPA), low-density amino (negatively charged, NPA^-), and high-density amino (positively charged, NPA^+) functional groups, and showed that the translocation of different NPs depended on their surface functional groups.[60] Surface functional groups affect the deposition process because they alter the physicochemical properties of MPs, including hydrophilicity and surface charge, which in turn affect their migration in the soil environment.[72] For example, the presence of oxygen-containing functional groups creates a negative charge on the surface of MPs, which enhances hydrophilicity,[73] and also makes them more susceptible to interacting with soil minerals, leading to a greater mobility.[74]

4. INFLUENCE OF SOIL ABIOTIC FACTORS ON THE VERTICAL MIGRATION OF MPS

Soil environmental factors (e.g., soil pH, ionic strength) also significantly affect the deposition process of MPs (Figure 3). Not only that, MPs can be moved vertically as a result of agricultural activities, such as plowing and harvesting. In addition, leaching and dry-wet cycles are closely related to the infiltration depth of MPs in soil.[54,66]

4.1. Soil Environmental Factors. The abundance, size and shape of MPs in soil profiles are significantly affected by soil pH.[34] Li et al. (2023) observed a positive effect of soil pH on the abundance of MPs, and the migration of MPs to the plant root system may have been controlled by pH.[75] pH can jointly affect the surface charge of MPs and the soil media, altering the electrostatic repulsion between the two and affecting migration.[76] At elevated pH levels, hydroxide ions on the sediment surface displaced hydrogen ions, resulting in a net negative surface charge. Concurrently, a higher pH corresponded to an increased density of negative charges on the MPs' surface.[75] Therefore, high pH will cause stronger electrostatic repulsion and promote the migration of MPs through the pore space to the deep soil.[72] Not only that, under high pH conditions, PSNPs are usually less capable of agglomerating, and the average particle size of the agglomerates is smaller and thus more capable of passing through the soil media.[77] In summary, soil pH affects the vertical migration of MPs mainly through two mechanisms: (1) Elevated pH changes the functional groups on the surface of MPs and alters their surface charge. (2) High pH reduces the agglomeration ability of MPs and MPs become more dispersed.[33] However, Ren et al. (2021) found that although the migration of MPs at pH 6 was higher than that of MPs at pH 4, the difference in MP migration between the two pH values was limited.[72] Thus, pH can control the migration of MPs in soil, but more research is needed to determine whether soil pH constitutes a key factor in their vertical migration.

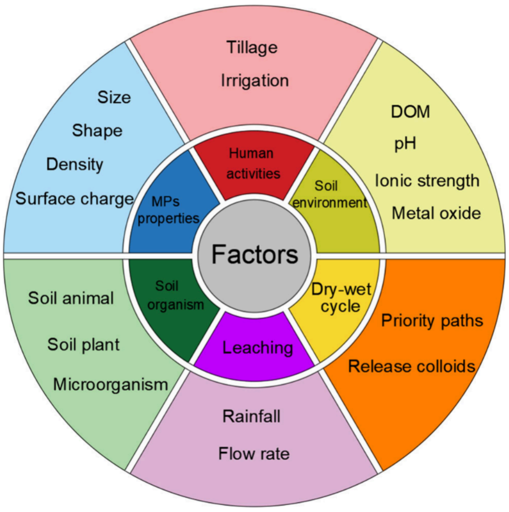


Figure 3. Factors influencing the vertical migration of soil MPs.

In addition, it has been proposed that as ionic strength increases, the translocation of MPs decreases and the mobility decreases.[40,78] The increase in ionic strength leads to increased contact between particles, resulting in a greater likelihood of MPs accumulating and precipitate in the pores, thus enhancing the effect of strain.[79] Indeed, strain and van der Waals forces affect the entire migration process, which in turn reduces the migratory capacity of MPs. The energy barrier disappears when the ionic strength is higher, and the attraction between the MPs and quartz sand is dominant. When the ionic strength is relatively low, the primary energy barrier results in repulsion becoming dominant, thereby promoting the deposition of MPs.[80] Zhang et al. (2024) found that the migratory ability of PSNPs declined as ionic strength increased and pH decreased, primarily due to the compression of the double layer and protonation reactions.[81] Zhang et al. (2023) found that as the ionic strength increased, the zeta potential of PSNPs and quartz sand gradually increased, the electrostatic repulsion decreased,[82] and the electrostatic attraction gradually increased, and the PSNPs were adsorbed in the media with a reduced migratory ability.[74] In summary, the ionic strength affects the migration of MPs mainly by altering the interaction force between the MPs and the soil medium; when the ionic strength is high, the two are attracted to each other and the MPs are trapped in the soil medium, whereas when the ionic strength is high, the two repel each other, which is conducive to the vertical migration of the MPs.

Dissolved organic matter (DOM) is the most active and mobile component of soil organic matter (SOM) and is highly sensitive to environmental changes.[83] Ubiquitous DOM in the terrestrial environment plays an important role in the migration and fate of MPs. Humic acid (HA) can increase the steric hindrance and electrostatic repulsion between MP particles, so the addition of HA to media can promote the vertical migration of MPs.[58] Hou et al. (2020) found that the addition of fulvic acid (FA) increased the negative charge on the surface of MPs and that FA made MPs more stable and dispersed, which promoted their vertical migration.[80] Moreover, since the surface hydrophobicity of MPs plays an important role in their migratory ability, the presence of a large number of functional groups in HA can cover the surface of MPs, leading to changes in their hydrophobicity and indirectly affecting the vertical migration process.[21] The interaction between MPs and HA was revealed by Chen et al.(2023), who found that HA adsorbed on the surface of MPs made it easier for water molecules to bind to MPs, which indirectly increased their hydrophilicity.[84] In addition, the presence of HA creates a spatial site resistance that competes with MPs for deposition sites on the environmental medium, thus facilitating the migration of MPs.[85] However, Liu et al. (2023) investigated the combined effects of PS-MNPs and PFOS (perfluorooctanesulfonate) on a crop (*Glycine max*) and found that PFOS adsorbed on PSMPs resulted in enhanced surface hydrophobicity.[86] The effect of different DOMs on the surface hydrophobicity of MPs varies. Not only that, the interaction between DOM and MPs will somewhat change the surface roughness and functional groups of MPs.[87] It is worth noting that DOM in the terrestrial environment is complex and diverse, and the current experiments focusing only on one type of DOM may lead to biased results. Moreover, NPs form complexes with DOM and metal oxides, which together affect their migration processes.[88]

Metal oxides (e.g., manganese oxides, iron oxides, aluminum oxides) have been found to be present in natural soil porous media as complex oxides.[89] The presence of complex metal oxides in the soil environment leads to chemical inhomogeneity on the surface of the soil media, which in turn severely affects the adsorption−desorption process and migration behavior of MPs.[82] Tan et al. (2021) investigated the migration behavior of PSMPs in bare sand and manganese oxide-coated sand (MOCS) and found that the migration process of PSMPs in MOCS was limited due to electrostatic effects and increased media roughness.[82] Due to its own positive charge, goethite (GT) enhances the adsorption of MPs in soil media, causing heteroaggregation of MPs and limiting their vertical infiltration.[56,76] Yasir et al. (2022) found that higher GT content increases the roughness of the soil media, which promotes the deposition of NPs,[90] and iron plaques can change the physicochemical properties of MPs to enhance their adsorption capacity.[91] In addition, in real soil environments, iron minerals may adsorb and immobilize MPs on the surface of crop roots.[92] Overall, metal oxides affect the vertical migration of MPs in soil through three main mechanisms: (1) Metal oxides enhance the surface roughness of the soil medium so that the migration of MPs is limited. (2) Positively charged metal oxides adsorb and aggregate MPs into the soil. (3) The physicochemical properties of MPs are affected by metal oxides, which in turn affects the deposition process. Current studies tend to focus on the effect of a particular metal oxide on the vertical migration of MPs,[93] whereas metal oxides in real soil environments are often present in the form of complex metal oxides.[94] Therefore, we need to investigate further the role of metal oxides, especially complex metal oxides, on the deposition of MNPs in soil.[74]

Pore space is a necessary conduit for MPs to migrate deeper into the soil.[95] Soil porosity and continuity of soil pore distribution are critical for vertical migration.[96] Soil porosity meeting the requirements for the passage of MPs is a sufficient condition for their downward migration, i.e., MP particle size being smaller than the soil pores.[97] Liu et al. (2023) found that the greater the soil porosity, the easier MPs could migrate vertically in the soil surface layer.[38] At the same time, the retention of MPs in the soil will further reduce the effective pore size, resulting in it being more difficult for subsequent MPs to pass through.[98] Therefore, soils with less porosity are more favorable for microplastic retention; whereas soils with greater porosity or a higher proportion of cracks are favorable for vertical migration of microplastics.[32] Gao et al. (2021) used dMP/dsand as a parameter and proposed three different infiltration scenarios: unimpeded static percolation (dMP/dsand <0.11), finite depth infiltration (0.11 < dMP/dsand <0.32), and fine surface sealing (dMP/dsand >0.32). Thus, dMP/dsand can be used as a basis for studying downward infiltration of MPs in soil.[58] Using dMP/dsand as a reference, the vertical infiltration behavior of MPs of different sizes in soil media with different porosities can be determined. However, few studies have been conducted to investigate the vertical migration of MPs in real soil environments using dMP/dsand as a reference; further studies that consider both MP particle size and soil porosity are needed. In addition, McCarthy and McKay (2004) found that continuous turbulence may form under conditions of strong brine erosion and large porosity, which may greatly facilitate the downward migration of MPs.[99]

4.2. Leaching.

Leaching is a soil process in which soluble or suspended compounds (clay particles, organic matter, soluble salts, carbonates, and iron and aluminum oxides, etc.) migrate from the upper to the lower portion of the soil under the action of percolating water, or undergo lateral migration.[100] Leaching, as a prevalent physical process in soils, is a typical activity experienced by MPs and can significantly affect their vertical migration.[101] An increase in water flow rate due to rainfall clearly enhances leaching from the soil environment, and Yan et al. (2020) demonstrated the vertical migration capacity of soil MPs (even at lower densities than water) under the effect of rainfall.[66] Rainfall-induced leaching may transport MPs deposited in the soil surface layer to deeper layers of the soil, causing ecological risks in the groundwater environment.[51] Thus, the relatively similar concentrations of MPs in the surface and subsoil layers in some areas can be attributed to the extensive mountainous topography of these areas and the fact that heavy rainfall will induce hydrological effects that will result in the translocation of some MPs out of the surface soil.[33] Park et al. (2023) found that both heavy and moderate rainfall intensities promoted vertical infiltration of MPs, and that MPs were widely distributed throughout the soil layer under heavy rainfall intensity conditions, whereas most MPs were transported only to the surface layer under moderate intensity.[36] This may be due to the fact that, under high flow rate conditions, MPs have a greater shear force, which is more favorable to their vertical migration.[102] However, Zhang et al. (2022) found that the vertical mobility of MPs showed an increasing and then decreasing trend with increasing rainfall intensity.[37] A similar conclusion was reached by Hou et al.

(2020), who found that the movement of MPs in porous media first increased and then decreased with increasing flow rates.[80] This is mainly due to the fact that as the flow rate increases, the flow of pore water becomes more and more disordered, which causes the MPs to collide with each other or the soil media, increasing the probability that they will be captured by porous media; this effect gradually exceeds the positive effect of the increase in flow rate on migration. Therefore, the effects of flow rate and rainfall on the vertical migration of MPs are not fixed, and different intensities of rainfall and flow rate exert different forces.

4.3. Dry−Wet Cycle. In real soil environments, dry weather that occurs after weather events such as rainfall may affect the deposition of MPs. MPs are carried by rainfall deeper into the soil and remain in the subsurface for long periods of time, where they are subjected to dry-wet cycles that accelerate vertical dispersion. O'Connor et al. (2019) found that the greater the number of dry-wet cycles, the greater the depth of penetration of MPs, and that the depth of infiltration showed a significant linear relationship with the number of dry-wet cycles.[54] Gao et al. (2021) also found that after increasing the number of dry-wet cycles from 4 to 16, the infiltration depth of PEMPs increased from 7.5 to 9.5 cm, and PETMPs increased from 7.5 to 8.5 cm.[58] Koutnik et al. (2022) compared the vertical mobility of MPs under the action of freeze−thaw and dry-wet cycles and found that the concentration of MPs infiltrating up to 5 cm was more than 25% higher that of dry-wet cycles after 40 freeze−thaw cycles, and that freeze−thaw cycles were more effective in promoting the transport of MPs than dry-wet cycles.[103] This may be due to two reasons, first, freeze−thaw cycles have been shown to release colloids from soil[104] and biofilter amendments.[105] Since MPs could attach to these colloids or pore walls containing these colloids, the released colloids could enhance the downward movement of MPs. Second, freezing of ice could also exert positive pressure on pore walls and create additional preferential flow paths,[106] thereby easing the passage of MPs through the media. The mechanisms by which freeze−thaw and dry-wet cycles affect the vertical migration of MPs are not yet fully understood due to experimental design limitations; more research is needed. Changes in dry−wet cycles due to weather factors should be taken into account when assessing pollution by MPs in natural environments.[107] In addition, it has been demonstrated that different physicochemical properties of MPs control their migration processes.[39] There may also be differences in the effects of dry-wet cycles versus freeze−thaw cycles on MPs with different physicochemical properties. In addition, irrigation also triggers soil dry-wet cycles.

4.4. Agricultural Activities. Medium-sized (0.2−1 mm) MPs are able to migrate to deeper soil layers due to agricultural practices such as tillage and irrigation.[34] Vertically, irrigation water may transfer MPs to deeper soils. Liu et al. (2023) investigated the effect of irrigation on the migration of MPs in agricultural soils, and the results showed that MPs < 100 μm in the surface soil decreased significantly after irrigation, and MPs < 100 μm in the deep soil increased significantly.[38] Zhao et al. (2022) found that the abundance of surface soil MPs decreased and deeper MPs increased significantly with increasing irrigation, that the total soil MP transport increased 1.5-fold after four irrigation events, and that soil structure disruption caused by irrigation may also lead to a higher risk of MP leaching.[108] O'Connor et al. (2019) observed that the depth of MP migration in sand is closely related to the irrigation cycle and fits well into a linear model.[54]

Tillage leads to mechanical fragmentation and degradation of MPs, stimulating them to move downward in the soil and reach deeper soil layers efficiently.[45] Under conventional tillage, the extent to which different techniques affect the infiltration of MPs into the deeper layers of the soil may vary, and differences in local tillage practices and depths may result in the abundance of MPs in tillage soils differing significantly from those in other areas, and thus may be due to the fact that agricultural tillage translocates and mixes the surface and deeper layers of the soil, resulting in abnormal concentrations of MPs.[109] Plowboard tillage results in inversion of the corresponding soil layer, causing most of the MPs in the top layer of the soil to be carried to another layer. In contrast, other tillage methods, such as shallow hollowing or harrowing, have a mixing effect that may result in the distribution of MPs particles throughout the tillage layer.[27] It was found that the migration of MPs in the soil increased with the amount of drip irrigation, and that MPs were carried deeper into the soil as a result of drip irrigation tillage practices, and the effect varied between soil textures.[49] Besides, modern agriculture requires the use of agricultural machinery and, combined with extreme weather such as heavy rainfall events, will cause vibrations on the soil surface, which can lead to the upwelling of large particles (e.g., gravel) and promote the migration of smaller MPs particles to the deeper layers.[28] Not only that, planting different crops on the same piece of land can also affect the migration of MPs, Liu et al. found (2022) that the stems and roots of taller crops can act as anchors for mulch, attenuating the migration of large plastic debris near the plants. The taller the residual stalks of the crop after harvesting, the stronger the anchoring effect on the mulch, and the more it can impede the infiltration of MPs into the soil.[110]

Insecticides used in agricultural cultivation activities may also have an effect on the migration of soil MPs, Zhou et al. (2023) investigated the adsorption of neonicotinoid insecticides on two MPs, and the results showed that the presence of such insecticides, especially at a low concentration (0.5 mmol·L^{-1}), could, by improving electrostatic interactions and hydrophilic repulsion among MPs particles, facilitate the translocation of PE and PP.[111] In addition, neonicotinoid molecules have a spatial site-blocking effect on MPs, which reduces the collision of transported particles with the quartz sand surface, thus increasing the transport of MPs.[112] Notably, the migration was slowed down by the excess neonicotinoid molecules attached to the MP surface, resulting in high concentrations of neonicotinoids inhibiting the migration of MPs instead of further promoting the process.[113]

5. INFLUENCE OF SOIL BIOLOGICAL FACTORS ON THE VERTICAL TRANSPORT OF MPS

In the soil environment, animals, plants and microorganisms affect the vertical migration of MPs in different ways (Figure 4). Soil animals such as earthworms can move soil MPs by ingesting and then carrying them;[114] plant cells are able to take up MP particles, allowing them to accumulate in the root zone;[115] microorganisms affect the aggregation and deposition of MPs by altering soil physicochemical properties.[116]

5.1. Soil Animals. In soil, microinvertebrates (e.g., earthworms, mites, ants) are key mediators of vertical migration of MPs.[117] Heinze et al. (2021) observed in the field that earthworms can vertically transport MPs in soil to a

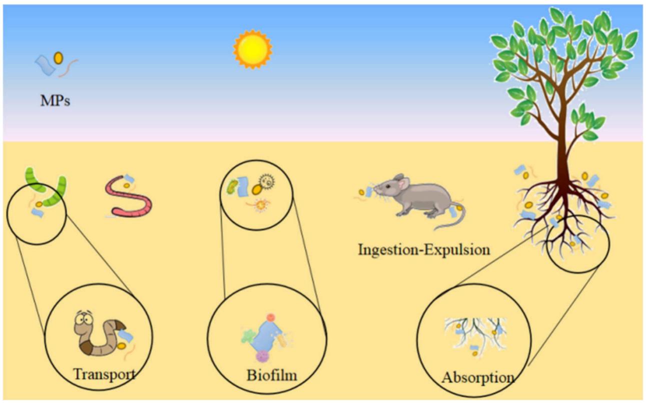


Figure 4. Effects on MPs of soil organisms.

depth of 100 cm.[35] Earthworms promote microplastic migration through burrowing, defecation and surface adhesion, leading to increased levels of MPs deep in the soil.[118] The presence of earthworms had a significant positive effect on the migration of MP particles from the soil surface to the deeper layers, with MPs particles penetrating into the lower and middle layers of the soil in the presence of earthworms, whereas in the absence of earthworms the MPs stayed in the surface layer of the soil only, and the magnitude of this effect was significantly influenced by the size of the MPs.[119] Soil animals will inevitably ingest MPs into the body and excrete them out of the body after intestinal motility, and the ingestion-excretion process will change the distribution of MPs in the soil. Huerta Lwanga et al. (2017) found MP particles (<150 μm) in earthworm embryos, and *Culex larvae*, which also feeds on MPs, persists in the gut of mosquitoes through larval to adult metamorphosis,[120] demonstrating an uptake-excretion mechanism.[24] In addition, ants, as ubiquitous organisms in soil ecosystems, are often overlooked in studies of the role of soil organisms in the carriage of MPs. Rillig and Bonkowski (2018) found that an ant species (*Rhytidoponera metallica*) could bury synthetic plastics (>1 mm) up to 40 cm deep.[121] Liu et al. (2023) found that two species of ants (*Pheidole* sp. and *Paratrechina* sp.) can actively carry MPs in the field, and the proportion of MPs in their original location (not carried by the ants) was only 18.4%, and that ants play an important but neglected role in the transportation and distribution of MPs in soil ecosystems.[122] Unlike earthworms, elasmobranchs and mites that transport MPs accidentally, ants may actively carry MPs in the field and in the laboratory. Moreover, ants transport MPs over greater distances than other soil fauna taxa, and ants may transport MPs over greater distances and at greater depths than other soil fauna, possibly due to their long foraging distances and deep nests, and their activities clearly influence the vertical distribution pattern of MPs in the local environment.[122] It is conceivable that similarly to earthworms and ants, other soil organisms such as elasmobranchs, leaf miners, or nematodes could also move MP particles, although the spatial scales may be smaller than those of earthworms or ants. Laboratory studies have demonstrated the transfer of MPs by small soil organisms, but ethics have prevented the study of larger organisms.[17] On a larger scale, animals like gophers, moles or voles may play an important role in the migration of MPs.[119] In addition, the results of laboratory studies on the effects of single biological species on the transport of MPs may be much smaller than in actual soil environments. Zhu et al. (2018) tested the role of predator−prey relationships in the transport of MPs by constructing a simulated food chain (prey-collembolan and predator-mite), and showed that predator−prey relationships did, indeed, facilitate the transport of MPs, with a 40% increase in transport compared to adding a single species.[123] Movement of MPs by soil microarthropods may affect the exposure of other soil biota to microplastics and alter the physical properties of the soil, and MPs may be further transferred through the food chain, posing a potential threat to terrestrial predators and humans. Therefore, future experiments should be based more on the construction of food chains to study the role of soil organisms in carrying MPs.

5.2. Crop Root System.

Plants need to absorb water and nutrients from the surrounding soil environment in order to sustain their growth and reproductive cycles,[124] resulting in localized suction at the root-soil interface.[125] During water uptake by plants, various substances (e.g., nanoparticles, humic acids, colloids, etc.) can also be carried to the root system by diffusion or mass transport and subsequently accumulate in the root zone.[126] A crop root system can act as a net to block the plastic film in the soil and affect its migration process.[28] Li et al. (2020) found that cracks produced at the site of lateral root sprouting in wheat and lettuce could serve as an entry point for the uptake of submicrometer and micrometer-sized MPs.[127] Liu et al. (2022) found that both 80 nm and 1 μm PS were aggregated in the vascular system of plant tissues, especially root columns, stem vascular bundles, and leaf veins, and mainly in the cell wall and intercellular regions, suggesting that MPs can be taken up by the root system and subsequently transferred to other parts.[128] Although primary and secondary roots of plant matter create more pores and cracks in the soil, the crop root system can tend to adsorb and retain MPs in the soil, in contrast to the effects of irrigation, rainwater infiltration, and soil fauna on the vertical transport of MPs.[129] The crop root system can act on the vertical migration of soil MPs through two mechanisms: (1) During the growth and expansion of the crop root system, the root system will inevitably come into contact with soil MPs, and thus MPs will directly contact the root system, especially the root tip, to undergo movement. (2) The pores and cracks created by crop root growth are conducive to the transport of MPs, and also increase the space for the root system to come into contact with MPs, thus making them more likely to be adsorbed by the root system. In addition, adsorption of MPs by crop roots may vary with changes in MP characteristics (e.g., particle size, polymer type, and surface charge) and root characteristics (e.g., surface morphology),[130] for example, because diffusion through cell wall pores can be limited, larger sized MPs cannot penetrate root tissues and tend to accumulate at the surface;[131] in addition, adsorption of MPs on root hairs is influenced by surface charge.[68] Compared to the important role of soil fauna on the vertical migration of MPs, the effect of crop roots is smaller and slower, Li et al. (2021) found that crop roots partially altered the migration of MPs in the 0−12 cm soil layer over a period of 2 months,[129] whereas Rillig et al. (2017) found that soil fauna, such as earthworms, significantly moved MPs from 0.71 to 2.80 mm sized MPs to a depth of 10 cm.[119] This may be due to the fact that soil animals such as earthworms and ants are more subjectively mobile and have more access to MPs, whereas plant roots grow more slowly and have a smaller area of influence.

5.3. Microorganisms. MP particles, because of their small size, can easily be adsorbed on the surface of bacteria or be engulfed by them, and thus be transported through a small volume of the soil with the movement of the bacteria.[132] It has been proposed that MPs can be transported on a small scale by fungal hyphae.[133] Notably, MPs can attach to specific pathogenic bacteria, affecting their migration while also causing the pathogenic bacteria to migrate with MPs, expanding their transmission range.[134] Growth substrates and secretions of some bacteria alter the electronegativity of soil particles, thereby reducing the electrostatic repulsion between MPs and soil particles, and thus reducing the ability of microplastics to migrate.[135] Arbuscular mycorrhizal fungi (AMF) are common microorganisms in the soil-plant system, and it has been demonstrated that AMF can significantly affect the migration of MPs in the soil environment, and the effect has a "size effect", specifically, the presence of AMF promotes the migration of MPs of small particle size to plants, but exacerbates the fixation of MPs of large particle size at the soil interface, which also indicates the effect of particle size on the deposition of MPs. Specifically, the presence of AMF promoted the migration of small-sized MPs to plants, but exacerbated the immobilization of large-sized MPs at the soil interface, which also indicates the influence of particle size on MPs deposition.[136] There are two reasons for the "size effect" of AMF on the migration of MPs: (1) In the case of MPs of different particle sizes, the effect of AMF on soil charge is different. (2) AMF causes differences in plant root secretions, and different root secretions affect the degree of aging of MPs of different particle sizes in the inter-root soil.[136] Furthermore, MPs can adsorb a number of microorganisms onto their surfaces to form biofilms. MP biofilms include different functional protozoa, fungi, and bacteria, and are composed of one or more organisms that form a small unique ecological niche called the "plastic ring".[137] These extracellular polymeric substances provide additional surface area and functional groups that enhance the adsorption capacity of MPs. Thus, biofilms themselves can act as adsorbents and may alter the surface properties of MPs, affecting their mobility by influencing their interactions with contaminants such as antibiotics, hormones, pesticides and heavy metals.[138] Therefore, the presence of biofilms will alter the migration process of microplastics,[139] for example, biofilms can enhance the migration of MPs by altering their adsorption of tetracycline and Cu(II).[140] Once formed, biofilms on the surface of MPs can develop rapidly on any surface where water, nutrients, carbon, and energy are available.[141] The colonization of MPs by microorganisms affects the accumulation of MPs to varying degrees, but the formation of microbial biofilms on plastic surfaces can significantly accelerate the accumulation of MPs and other substances in the environment.[142] However, microbial contributions to the migration of MPs can be limited by size and range of activity, and their influence is not as pronounced as that of external forces and soil flora and fauna.[143] Thus, when microbial membranes on MPs are not sufficiently developed, they may not be sufficient to promote the deposition of MPs.[144]

6. CONCLUSIONS AND RECOMMENDATIONS

This review summarizes the factors influencing vertical migration of MPs through the soil profile. Soil provides the location for vertical migration of MPs, which jeopardizes the groundwater environment. Vertical migration of MPs in soil is affected by a variety of factors: physicochemical properties of MPs are the essential factors affecting deposition. Environmental factors can affect the migration behavior of MPs by changing their physical and chemical properties. Leaching will affect the mobility of MPs, and increases in flow rate and rainfall will obviously enhance leaching. Rainfall and flow of different intensities will have different effects on the migration of MPs in the soil. MPs are affected by dry—wet cycles and these affect vertical dispersal after deep penetration into the soil. MPs migrate to deeper soil layers due to agricultural practices such as tillage and irrigation. In addition, soil animals can move MPs from the soil surface to the deeper layers. Unlike animals, plants tend to transport MPs upward or retain them in the soil. The growth substrates and secretions of microorganisms will change the MPs' soil repulsion forces and affect their deposition.

Based on our comprehensive analysis of the literature, problems and challenges in the current study of vertical migration of soil MPs are as follows:

(1) So far, studies on the influence of the shape of MPs on their vertical migration in soil have mainly considered regular shapes (e.g., fibers, particles, etc.), but irregularly shaped MPs also occupy an important part of the natural soil environment, and more research is needed to reveal what kind of migratory behaviors are exhibited by irregularly shaped MPs, and whether there are any differences in the vertical migration of regularly shaped MPs versus irregularly shaped MPs, as well as the mechanisms of the influences.

(2) Most of the existing studies suggest that the vertical migration capacity of MPs increases with decreasing particle size, but the effect of particle size seems to have an "effective particle size" effect, and changes in particle size beyond the threshold of "effective particle size" may not have a significant effect on MPs migration. The deposition behavior of MPs needs to be investigated over a wider range of particle sizes to find out whether the "effective size" effect exists and, if so, what the range of "effective size" is.

(3) A wide variety of pollutants are present in soil, and studies on the cotransport of MPs with other environmental pollutants are still relatively scarce. Due to the carrier function of MPs, there is an adsorption—desorption process between MPs and pollutants, and the cotransport of pollutants with MPs poses a serious potential risk to the soil environment and ecological safety, and further studies are needed to assess the impact of cotransport of MPs with multiple pollutants.

(4) Soil animals, plants and microorganisms are all known to play important roles in the fate of MPs, and there are differences in the migration of MPs when multiple soil organisms are present compared to a single soil organism. It is necessary to consider multiple soil organisms and construct a simulated food chain to explore the role of soil organisms in the migration of MPs.

(5) Many studies have been conducted to investigate the influencing factors affecting the vertical migration of MPs in soil, and many important conclusions have been obtained; however, few studies have been able to compare the size and degree of contribution of different factors to the vertical migration of MPs in soil. For

example, it is known that the physicochemical properties of MPs such as particle size, shape, density, etc. have a key influence on their deposition process, but which specific physicochemical property plays a decisive role or plays a greater role than others will greatly improve our understanding of the migration behavior of MPs in the soil environment.

(6) Most of the current laboratory studies use artificial media to assess the vertical migration of MPs; using natural soil or sediment as a medium will greatly improve our ability to predict the fate of MPs in real soil environments.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Grant No. 42177447), the Science and Technology Development Plan Project of Jilin Province (Grant No. 20220508124RC), and the Natural Science Foundation of Jilin Province, China (Grant No. 20210101395JC).

ABBREVIATIONS

MPs, microplastics; NPs, nanoplastics; PE, polyethylene; PP, polypropylene; PS, polystyrene; PVC, polyvinyl chloride; PLA, polylactic acid; PU, polyurethane; SR, silicone resin; PMMA, poly(methyl methacrylate); CPE, chlorinated polyethylene; EPS, expandable polystyrene; PET, polyethylene terephthalate; DOM, dissolved organic matter; HA, humic acid; FA, fulvic acid; PFOS, perfluorooctanesulfonate; MOCS, manganese oxide-coated sand; GT, goethite

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