



The impact of microplastics on small organism dispersal: mechanisms, risks, and research gaps

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Abstract

Microplastics (MPs), small plastic particles under 5 mm, are increasingly recognized for their environmental persistence and ubiquity across ecosystems. While research has long focused on MPs' toxicity, their influence on the dispersal of small organisms, including fungal, bacterial, and viral pathogens and their vector species such as insects, is gaining attention. This perspective examines how MPs could act as carriers for microorganism dispersal via the formation of unique biofilms, termed as 'plastisphere,' which hosts diverse microbial communities and facilitates horizontal gene exchange, including antibiotic-resistant genes. We also explore indirect impacts, as MPs influence the physiology and life history traits of organisms, which can alter dispersal dynamics. Despite increasing interest, significant research gaps remain, particularly concerning MPs in terrestrial ecosystems and the effects of biofouled versus pristine MPs in natural settings. Additionally, inconsistent methodologies, such as the use of unrealistically high MP concentrations and the lack of control materials or systematic experimental design challenge current research, limiting a comprehensive risk assessment. Addressing these limitations is essential to accurately evaluate MPs' role in the dispersal of small organisms and to inform potential policy measures.

Keywords Microplastics (MPs) · Dispersal · Pathogen · Plastisphere

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Introduction

Since the 1930s, synthetic plastic production has dramatically increased, valued for its durability and versatility. However, this durability also means that plastic waste rarely decomposes, instead breaking down into persistent, small particles known as microplastics (MPs), defined as plastic fragments smaller than 5 mm in size (Koelmans et al. 2022). With plastic production continuing to rise, an estimated 3.1 gigatons of MPs are expected to accumulate in the environment by 2050 (Schwarz et al. 2023).

The small size and low density of microplastics allow them to be easily carried by wind and water currents over long distances (Fig. 1). They are now widespread across the globe, found in remote regions, including the deep sea, high mountains, polar areas (Peng et al. 2018; Bergmann et al. 2019), and within diverse organisms, including humans (Ragusa et al. 2021; Nihart et al. 2025). These particles originate from various human activities, including tire and brake wear, littering, wastewater discharge, and agricultural practices (Tian et al. 2022), making MPs an indicator of the Anthropocene era (Alves et al. 2023). Most research on MPs has traditionally focused on their toxicity, revealing various detrimental effects on organisms' health and life histories. Recently, however, MPs' roles in ecosystem interactions and feedbacks are starting to attract research attention (Rillig and Lehmann 2020). In particular, a critical aspect has come to light: MPs may act as vectors for

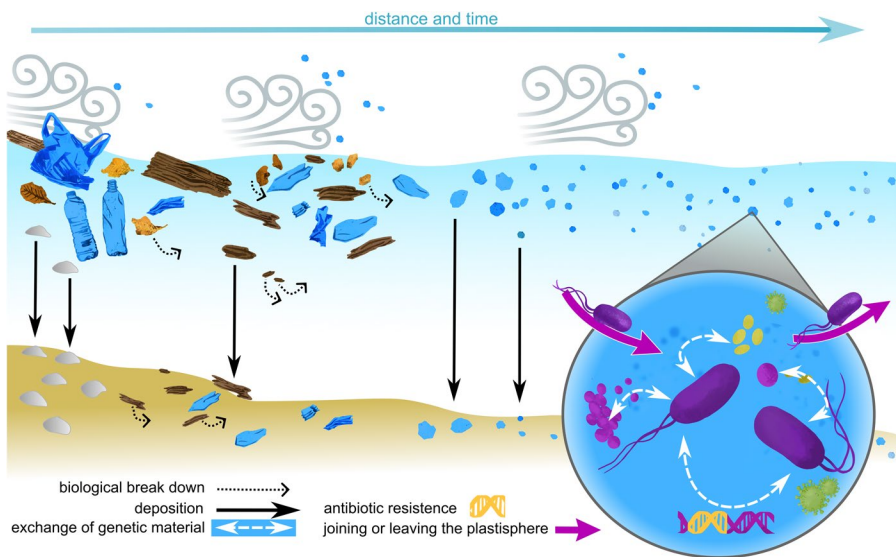


Fig. 1 Comparison of the dispersal capacity of plastic (blue particles) vs. organic matter or sediment. Over time plastic splits into smaller particles that are transported easily by wind and water currents. Their small weight per surface area and durability amplify microplastic spread through the environment. In contrast, organic substrates with similar density (e.g., leaves or wood) will fully break down over time and sediment with similar longevity (e.g., rock or sand) can deposit quickly. Microplastics form a unique microhabitat, termed the ‘plastisphere’ (zoom-in circle), where various species of bacteria, fungi, algae and metazoans assemble. The microbial community composition on MPs has been found to be distinct from the environment, with heightened presence of pathogens and antibiotic resistance genes, the later possibly driven by an increased rate of horizontal gene transfer. As microplastics spread over vast distances, microbial ecosystems may experience higher rates of invasion and disturbance from microorganisms transported by the plastisphere

small organisms, including pathogens, potentially facilitating their dispersal across diverse ecosystems.

This paper explores current research regarding MPs' role in organism dispersal and highlights research gaps, emphasizing two main pathways: MPs as vectors transporting small organisms and genetic materials that can lead to gene flow due to horizontal gene transfer, and MPs' indirect impacts on the dispersal abilities of organisms by affecting their physiological traits. Despite having a potentially significant effect, the roles of MPs in the dispersal of small organisms and the underlying mechanisms remain poorly understood, requiring further research. We highlight important limitations of current research and point to interesting questions for elucidating the roles of MPs for future investigation.

Microplastics as dispersal vectors for small organisms

Plastisphere: a unique microenvironment

Once in the environment, MPs develop an eco-corona of organic materials and biomolecules, attracting colonizing microorganisms, including bacteria, fungi, algae, and metazoan, such as nematodes (Delacuvellerie et al. 2022). This biofilm creates a distinct microenvironment known as the 'plastisphere' (Zettler et al. 2013), which is compositionally different from the surrounding soil or water. Several studies found that the plastisphere had a distinct microbial community and recruited unique species, which can potentially cause microbial invasion in diverse ecosystems and disturb microbial community composition (Li et al. 2021; Ogonowski et al. 2018). In addition, autotrophic organisms and species whose metabolic traits allow them to use plastic as a carbon source may be predisposed to colonize the plastisphere. The chemical properties of MPs can also influence the associated microbial communities. For instance, the chemical inertness and absence of bioavailable nitrogen in the polymer backbone of these microplastics can cause converging effects on the microbial community composition, especially in the long term (Zhang et al. 2023). However, the majority of microorganisms growing on microplastics seem to belong to opportunistic colonists (Oberbeckmann and Labrenz 2020). For example, both parasitic and saprophytic (i.e., consuming dead or decaying organic matter) fungi species have been found to thrive in the plastisphere (Kettner et al. 2017). Despite the variability in species composition depending on environmental conditions, the plastisphere represents a potential vehicle for the dispersal of small organisms and genetic materials that can be horizontally transferred between them.

Potential for pathogen enrichment in the plastisphere

Research on the enrichment of small organisms in the plastisphere has largely focused on pathogens because of their direct and immediate socioeconomic and public health implications. Studies indicate that MPs may selectively enrich pathogenic organisms and antibiotic resistance genes, providing a habitat conducive to gene exchange. For example, a study of biofilm formation on MPs in the river water identified two opportunistic human pathogens (*Pseudomonas monteilii*, *P. mendocina*) and one plant pathogen (*P. syringae*) only in the microplastic biofilm, but not in biofilms formed on natural substrates, such as rocks and leaves (Wu et al. 2019). Antibiotic resistance genes had higher abundance on MPs than the

surrounding sediment and water in a river estuary (Guo et al. 2020). Diverse fungal, protozoan, and helminth pathogens were also found to associate with the plastisphere, including some major disease-causing agents worldwide (reviewed in Ormsby et al. (2023)). The risk and potential impact of pathogen enrichment in the plastisphere can be particularly high in economically disadvantaged societies (Gkoutselis et al. 2021) and in farmland with abundant plastic film residues from agriculture practice (Li et al. 2024).

The selective enrichment of pathogenic organisms in the plastisphere could be due to the organisms' unique pre-adaptation. For example, several pathogenic 'plastiphilic' fungi exhibit a life stage that allows them to survive independently of a host and form resilient communities on exposed plastic surfaces. Many are melanized, which protects them from UV radiation and heat, enhancing their survival. Additionally, members of the genera *Leptosphaerulina* and *Phoma* possess enzymes that can break down complex substances, including plastics. These traits allow them to establish durable, nutrient-exploiting biofilms on microplastic surfaces (Gkoutselis et al. 2021). The enrichment of antibiotic resistance genes in the plastisphere has been proposed to arise from increased horizontal gene exchange in the biofilm matrix of the plastisphere (Yu et al. 2022). The combined effects of MPs providing a durable surface allowing close cell-cell contact for plasmid conjugation and the selection of more conjugation permissive bacteria in the plastisphere have been estimated to lead to a potential 100,000-fold increase in the transfer of antibiotic resistance genes in aquatic environments (Arias-Andres et al. 2018), which may result in the emergence and spread of multidrug-resistant pathogens.

However, evidence for selective enrichment of pathogens and antibiotic-resistant genes on MPs versus natural surfaces remains inconclusive. While Oberbeckmann and Labrenz (2020) found no evidence of pathogen enrichment on MPs than the surfaces of surrounding natural substrates across diverse aquatic ecosystems, a later meta-analysis of Yu et al. (2022) found the enrichment of antibiotic-resistant genes to be higher on MPs than on inorganic substrates, but lower than on natural organic substrates such as wood and leaves. The latter study also showed a strong influence of the environment, with the degree of enrichment being higher in freshwater than in saline water and sewage. The potential for microplastics to enrich pathogens and antibiotic resistance genes remains hypothetical, but MP particles should be regarded as a persistent reservoir and potential vectors that deserve further investigation, especially given the role of plastisphere biofilms in promoting horizontal gene transfer (Fig. 1).

Likelihood of MPs dispersing small organisms as vectors

Given the potential public health and food safety concerns, research about MPs dispersing small organisms as vectors largely focuses on evaluating their likelihood of spreading pathogens and antibiotic resistance genes. Due to their low density and high durability, MPs can be carried by wind and water currents over vast distances. MPs' large surface-to-mass ratio, especially in fiber forms (e.g., synthetic microfibers used for making clothing), enhances their transportability in the atmosphere. Studies show that MPs smaller than 2 mm can be easily suspended in water, remaining mobile and often fragmenting further (Harris 2020), increasing their potential for transporting attached microorganisms over long distances. Although organic natural particles (e.g., from leaves or wood) can have similar densities, due to their longevity, MPs will reach and persist in various environments (Fig. 1).

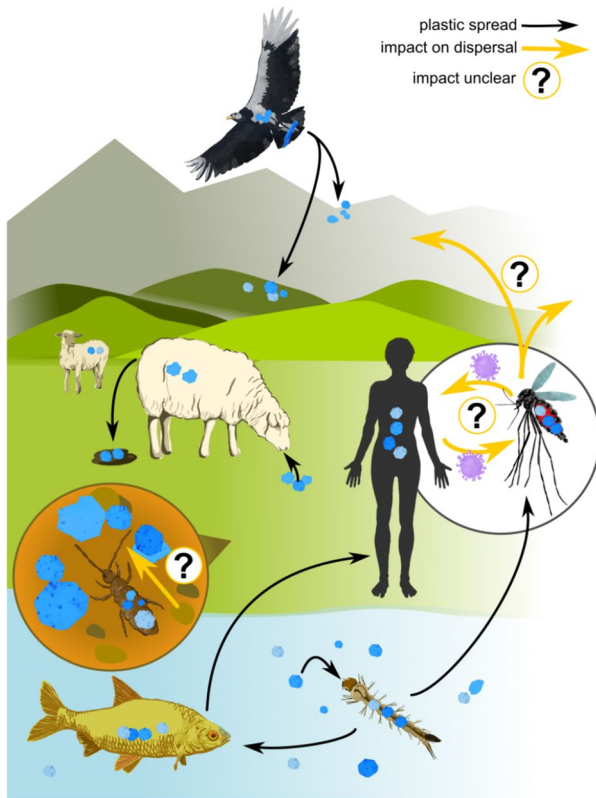


Fig. 2 Plastics can be transported by various organisms and potentially interfere with their dispersal. In addition to abiotic factors (such as wind and water), plastics (blue particles) can spread across environments and trophic levels (black arrows) via ingestion (fish, sheep, human, mosquito larvae) and excretion (sheep). Alternatively, plastic can attach to small organisms (springtail) or be actively carried to remote, otherwise protected areas (vulture). In turn, MPs are hypothesized to change the dispersal propensity of organisms (yellow arrows and question marks). The movement of small organisms may be hindered by MP attachments or by changing the composition of the soil habitat (springtail). Further, ingested plastics may modify an organism's vectorial capacity by interfering with its microbiome, which can hinder or amplify disease replication (mosquito). Alternatively, there may be a direct influence on the dispersal propensity of vector species (mosquito). In general, it is still largely unknown how MP ingestion affects the condition of an organism and consequently impacts its dispersal

It has been estimated that more than 1000 metric tons of plastic particles fall within south and central western U.S. protected areas per year due to atmospheric deposition (Brahney et al. 2020). Even though the density of small organisms is generally lower on MPs than on natural organic particles, considering MPs' vast quantity and that many small organisms can survive in the plastsphere for a long time, e.g., the pathogenic bacterium *Staphylococcus aureus* has been shown to survive on dry plastic for up to three years (Chaibenjawong and Foster 2011), it is highly plausible that they can disperse using MPs as a vector.

Additionally, MPs can be transported biotically—by organisms that either ingest or carry MPs externally (Fig. 2). For instance, mosquitoes have been shown to carry MPs through various life stages, transferring them from aquatic to terrestrial habitats (Al-Jaibachi et al. 2018). Birds and grazing animals like sheep (Beriot et al. 2021) can ingest MPs and

release them through defecation, spreading them across ecosystems. In another example, scavengers like vultures are found to transport large quantities of plastic debris including MPs from foraging areas to distant communal roosts, creating ‘plastic islands’ in natural parks protected from human activities (Ballejo et al. 2021). Flying insects like bees may also transport MPs externally due to the static charge on their bodies, potentially bringing MPs (and small organisms attached to them) into hives, honey, and wax (Alma et al. 2023). In the soil ecosystem, earthworms contribute significantly to MPs’ vertical movement (Rillig et al. 2017), and microarthropods such as springtails can transport MPs over distances of centimeters within days (Maaß et al. 2017). These findings suggest that MPs can serve as durable and versatile vectors that move small organisms (and are themselves moved by some organisms), between diverse environments, often in ways that natural particles cannot, due to the shorter lifespan of organic matters.

That MPs can disperse small organisms or antibiotic-resistant genes is highly plausible, although there is limited direct evidence beyond laboratory settings. However, some studies demonstrate that organisms on MPs can survive environmental transitions, another indication that MPs could facilitate the dispersal of small organisms across different ecosystems. For example, *Escherichia coli*, *Enterococcus faecalis* and *P. aeruginosa* have been shown to colonize polyethylene microparticles and survive environmental changes along a simulated river-estuary-marine-beach continuum for 25 days, with their densities decreasing over time (Metcalf et al. 2023). Such studies support that small organisms attached to MPs can resist environmental change and successfully disperse despite succession of community compositions in the plastisphere, further suggesting potential risks of biological invasion and pathogen spread, which remain to be investigated in future research.

Indirect effects of MPs on the dispersal of small organisms

Besides directly transporting microbes as vectors, MPs can indirectly influence the dispersal of other small organisms by altering their physiology and habitat features. Furthermore, MPs can interfere with the vectorial capacity of organisms (i.e., the ability of an organism, typically a vector species such as mosquitoes, to carry and transmit other small organisms from one environment to another), possibly leading to cascading effects on dispersal patterns within and between ecosystems.

Physiological and behavioral changes affecting dispersal ability

MPs can influence small organisms by affecting their physiology, behavior, and life history traits, which in turn can alter their capacity and propensity to disperse. While physiology is crucial in predicting the exploration activity and dispersal of organisms (Malishev and Kramer-Schadt 2021; Wu and Seebacher 2022), studies have shown that MPs can disrupt feeding behaviors, reduce body condition, impair locomotion, and cause physiological stress in various small organisms, including invertebrates and fish (Franzellitti et al. 2019; Espinosa et al. 2016). The ingestion of MPs by small organisms may cause blockages in the digestive tract or dilute available nutrients, leading to weight loss or reduced energy levels. For dispersal, this can be critical because it may limit the ability of organisms to migrate, forage, or reproduce effectively.

Moreover, changes in behavior—such as reduced activity or altered predator-avoidance responses—can affect an organism’s natural movement patterns, hindering their dispersal and potentially confining them to smaller areas. For example, MPs have been shown to affect foraging behavior in honeybees, causing them to spend more time feeding, which could reduce population growth and the production of new queens, thus limiting their dispersal potential (Al Nagggar et al. 2023). Similarly, changes in growth, reproduction rates or offspring viability (Ju et al. 2019; Wang et al. 2024) could limit the spread of small organisms to new areas, indirectly affecting ecosystem dynamics and biodiversity in the long run.

It is also worth noting that the presence of MPs in the environment or ingesting some MPs through feeding do not necessarily cause harm to small organisms. For example, *Daphnia* selectively avoid ingesting MPs of the same size as their natural food particles (i.e., algae cells), and where ample food is present, MPs seem to have little effect on their physiology or reproductive fitness (Aljaibachi and Callaghan 2018). However, the majority of studies about the influences of MPs on the dispersal-related physiology and behaviors of small organisms focused on the short-term effect, making it impossible to draw strong conclusions regarding MPs’ effect on long-term dispersal. For example, honeybees fed on sugar solutions with MPs did not experience increased mortality (Buteler et al. 2022) but reduced feeding rate and body weight (Al Nagggar et al. 2023), which can potentially harm the health, productivity, and possibly the dispersal capacity of the hive over longer time scales. Furthermore, plastic pollutions can influence the dispersal of organisms in many different ways, making it a non-trivial task to predict the net result. The spread of the globally invasive snail *Physa acuta* provides an example to illustrate the multi-faceted influences. Although ingesting MPs reduces the snail’s locomotion speed and reproductive rate, the species also use plastic debris as an oviposition substrate, which facilitates its dispersal (Kumari et al. 2023).

Habitat and environmental alteration

Microplastics can further affect the dispersal of small organisms by altering the physical, chemical, and microbial properties of their habitats, especially in soil and aquatic environments. In soil ecosystems, MPs can change the soil’s structure, water-holding capacity, bulk density, and nutrient availability, which can impact soil-dwelling organisms like earthworms, springtails, and microbes (Fig. 2) (De Souza Machado et al. 2018; Qiu et al. 2022). Altered soil properties may hinder the movement or modify the distribution of these organisms, especially those that rely on specific soil conditions for survival and dispersal. For example, MPs of 0.5 μm sizes can fill the bio-pores generated by springtails within seconds, trapping and immobilizing them at a low concentration of 8 mg/kg, which likely occurs in natural soil environments (Kim and An 2019). Additionally, changes in soil structure may influence the vertical movement of organisms within the soil profile, affecting their access to resources and interactions with other species (Cui et al. 2022; Daghighi et al. 2023). In the aquatic ecosystem, MPs are shown to impact the movement of copepods by reducing their speed up to 40% and altering the turning angle distributions at moderate concentrations (Suwaki et al. 2020). Given the crucial role of copepods and other zooplankton as primary consumers in the food web, transferring energy and various pollutants up to larger predators like fish (Sodré and Bozelli 2019), MPs’ impact on these organisms may cause cascading effects in the ecosystem in ways difficult to predict, calling for modelling investigations.

MPs can also alter microbial communities by introducing new microbes and other small organisms from the plastisphere. This can create competitive pressures within local microbial populations, potentially leading to shifts in community structure (Li et al. 2021; Dey et al. 2022; Ran et al. 2024). When small organisms, such as microbes or invertebrates, interact with MPs, they may inadvertently come into contact with new, potentially invasive microbes carried by the MPs. Such changes can influence dispersal dynamics, either by suppressing certain species or by promoting the spread of organisms that can thrive under these altered conditions.

Effects on vector organisms of pathogens

Another indirect effect of MPs on dispersal emerges through their impact on vector organisms, particularly those that transmit pathogens or other organisms. MPs have been shown to disrupt the gut microbiome in some vector species, such as mosquitoes (Edwards et al. 2023) and bees (Wang et al. 2022; Zhu et al. 2024), which can influence their vectorial capacity – the ability of these organisms to carry and spread pathogens. Specific strains of the endosymbiotic bacteria *Wolbachia*, for example, decrease the establishment and replication of viral diseases such as dengue or malaria in their mosquito hosts (Bian et al. 2010; Hughes et al. 2011). This effect has been used successfully to reduce human infection rates with Dengue virus by releasing *Wolbachia* carrying mosquitoes into natural mosquito populations (Hoffmann et al. 2024). MP potentially has the capacity to interfere with insect microbiomes (Edwards et al. 2023) possibly including *Wolbachia* and may therefore inadvertently hinder ongoing efforts to control vector-borne disease (Loiseau and Sorci 2022).

In addition, MPs can alter immune responses (Wang et al. 2022; Edwards et al. 2023; Ferrante et al. 2024) or energy levels (Wang et al. 2021) of vector species, making them more susceptible to infection or reducing their ability to resist colonization by pathogens. This can increase the spread of certain diseases as vector species move between environments. There are many pathways through which MPs can affect disease transmission via the pathogens' vector species, but evidence remains patchy and contradictory, preventing us from drawing concrete conclusions (Jones et al. 2024). Conflicting predictions on the effects of MPs on vector organisms can be expected as MPs interfere with host-pathogen interactions in diverse ways. While a diminished immune response and low energy levels can facilitate pathogen infection of the intermediate hosts (i.e., vector organisms), these intermediate hosts in low condition may, in turn, hinder the replication of the pathogens or are less likely to spread them to subsequent hosts, including humans. In general, it is likely that MPs can indirectly impact the dispersal of vector organisms and the pathogens they transmit (Figure 2), although the extent to which this can pose additional ecological and public health risks is unknown.

Outstanding limitation of current research and the way forward

Research on the impact of MPs on the dispersal of small organisms is an emerging field, but it remains in its infancy. This area faces several limitations, including general challenges in MPs-related research, such as the lack of standardized sampling protocols, measurement methods, and units for quantification, which complicate the comparison and synthesis

of results across studies (Sharma et al. 2024). Additionally, specific challenges pertain to studying the dispersal of small organisms, with most research concentrated in aquatic environments, leaving terrestrial ecosystems underexplored, although studies on the soil plastisphere have started to garner research attention recently (Rillig et al. 2024; Su and Yang 2024; Pahlavan 2024). The current literature also disproportionately focuses on a narrow range of organisms, primarily those relevant as food sources, pathogens, or economically significant species, such as crabs (De Barros et al. 2020), shrimps (Welden and Cowie 2016) and honeybees (Buteler et al. 2022). Here, we aim to highlight three, in our opinion, most pressing issues and advocate for their consideration to design more robust studies, fostering better comparability and advancing the field.

- **Use of pristine vs biofouled MPs in experiments:** Studies investigating MPs' impact on the dispersal-related physiology of small organisms often use pristine MPs—those that are non-aged and lack biofilms. However, these pristine MPs have physiochemical properties that differ significantly from MPs found in natural environments (Zidar et al. 2024). Aged MPs, which are covered with biofilms and likely interact differently with organisms, are rarely included in such studies, limiting their ecological relevance (Phuong et al. 2016; Connors et al. 2017). For instance, experiments on *Daphnia magna* have shown that under certain concentrations of biofouled MPs, the positive effects of biofilm as a food source may offset the negative effects of food dilution caused by the MPs (Amariei et al. 2022). Such studies highlight the complex ecological impact of microplastics at different stages and are useful for environmental evaluation and monitoring.
- **Implement environmentally relevant concentration and size distributions:** Laboratory exposure experiments investigating the effects of MPs often employ environmentally unrealistic concentrations and size distribution of MPs, which can limit the ecological relevance of the findings. While some studies consciously use concentrations representative of heavily polluted industrial areas to simulate worst-case scenarios or predict tipping points, others rely on excessively high concentrations that fail to reflect environmental realities, rendering the results inapplicable (Cunningham and Sigwart 2019). Additionally, the size distribution of MPs strongly influences organismal responses such as growth, development, and movement (Selonen et al. 2020). For instance, exposure to $10 - 27 \mu\text{m}$ microplastics caused the greatest adverse effects on the freshwater midge *Chironomus tepperi* compared to larger or smaller particles (Ziajahromi et al. 2018). Despite the importance of both concentration and size distribution, studies that systematically examine these variables remain rare. Advancements in analytical technologies can help address this gap. For example, a recent technique combining hyperspectral stimulated Raman scattering (SRS) imaging with an automated plastic identification algorithm enables the rapid and sensitive analysis of microplastic distributions, revealing environmentally relevant concentrations, such as $2.4 \pm 1.3 \times 10^5$ particles per liter of bottled water, 90% of which are nanoplastics (Qian et al. 2024). Incorporating such realistic concentrations and size distributions into experimental designs is essential to improve the accuracy of projections on how microplastics affect the dispersal of small organisms.
- **Implement suitable control materials:** The selection of proper control materials is crucial for studying the role of microplastics in the dispersal of small organisms. Control

materials are essential to help isolate the specific effect of MPs (i.e., how they differ from natural organic or inorganic particles). Furthermore, no single substrate can control for all relevant variables. Glass is commonly used as a control in plastisphere studies due to its environmental persistence and nutrient-neutral nature (Metcalf et al. 2022). However, glass is not an ideal control in the context of dispersing small organisms because of its smooth surface, higher density, and sinking behavior, which limit its ability to mimic the transport dynamics of MPs. In aquatic ecosystems, microbial community composition often depends more on the availability of surfaces to colonize than on the specific material type, due to the different lifestyles between free-living and sessile organisms (Oberbeckmann and Labrenz 2020). Furthermore, the weathering of plastics introduces additional complexities for choosing appropriate controls for studying the role of MPs on the dispersal of small organisms. For example, weathered plastics change size and surface roughness while releasing compounds such as phthalates and Bisphenol A (Luo et al. 2020; Wu et al. 2021), which can affect diverse dispersal-relevant physiological traits but are difficult to replicate in control experiments. Thus, it is essential to implement a combination of control materials that account for physiochemical and ecological factors that are relevant to the environment under study for gaining comprehensive insights.

Conclusion

Microplastics, through their unique durability, buoyancy, and ability to host diverse microbial communities, have the potential to directly act as vectors for dispersing small organisms and providing opportunities for horizontal gene transfer. They can also indirectly impact the dispersal of small organisms by altering their physiology, the environment, or through ecological interactions. While the risks of spreading pathogens or promoting their genetic exchange via MPs are largely hypothetical, the findings thus far highlight the need for further research, especially in terrestrial ecosystems where studies remain scarce. Experimental inconsistencies, such as the use of pristine MPs, unrealistic exposure concentrations, and the lack of proper control limit the ability for us to draw broad conclusions from current findings. Research standardization and experiments with systematic combinations of control conditions are crucial for evaluating the role of MPs on the dispersal of small organisms, including pathogens and other species of socio-economic interest, thereby informing future policy decisions and helping address potential public health and ecological threats. Ultimately, understanding how microplastics alter the movement of organisms and genes is key not only to assessing pollution risks, but also to predicting how human-made materials reshape fundamental ecological and evolutionary processes.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflict of interest.

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