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Review

Recent advances on the transport of microplastics/nanoplastics in abiotic and biotic compartments

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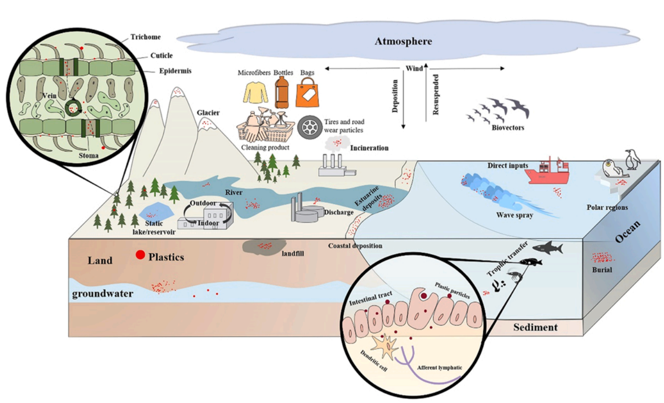
HIGHLIGHTS

- The transport of MPs in macroscopic compartments are discussed.
- Uptake pathways of MPs/NPs in different biota are summarized.
- Different mechanisms of cellular internalization of NPs in organisms are analyzed.
- Bioaccumulation potential and biomagnification effects of MPs/NPs are assessed.
- Evidence for trophic transfer of MPs/NPs along the food chain is highlighted.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastics enter the environment and break up into microplastics (MPs) and even nanoplastics (NPs) by biotic and abiotic weathering. These small particles are widely distributed in the environmental media and extremely mobile and reactive, easily suspending in the air, infiltrating into the soil, and interacting with biota. Current research on MPs/NPs is either in the abiotic or biotic compartments, with little attention paid to the fact that the biosphere as a whole. To better understand the complex and continuous movement of plastics from biological to planetary scales, this review firstly discusses the transport processes and drivers of microplastics in the macroscopic compartment. We then summarize insightfully the uptake pathways of MPs/NPs by different species in the ecological compartment and analyze the internalization mechanisms of NPs in the organism. Finally, we highlight the bioaccumulation potential, biomagnification effects and trophic transfer of MPs/NPs in the food chain. This work is expected to provide a meaningful theoretical body of knowledge for understanding the biogeochemical cycles of plastics.

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1. Introduction

Plastics, the new era of industrial polymers, have contributed to the development of society and the convenience of people's lives for their excellent properties (low cost, durability, versatility) (Zhang et al., 2020b). However, the dramatic increase in the production and consumption of plastics, as well as the lack of effective waste management and disposal measures, good and sustainable recycling methods and efficient elimination technologies for plastics have led to its significant accumulation in the environment (Borrelle et al., 2020; Velis and Cook, 2021). As of 2015, the production of plastic waste had reached 6500 million tons (Mt), and by 2060, the stock of plastic waste in the environment is expected to reach 12,000 Mt, the explosive growth of plastics predicts that it will expand at a rate of 2–10 times to reach scale of the next decade (Borrelle et al., 2020; Geyer et al., 2017; Jambeck et al., 2015).

To date, more than a decade since marine ecologist Richard Thompson's seminal study introduced the concept of microplastics (MPs) (Thompson et al., 2004). MPs in the environment are categorized as primary MPs and secondary MPs. Primary MPs are generated by human activities and released directly into the environment (Hernandez et al., 2017). Secondary MPs are inadvertent products of macroscopic plastics that are fragmented and degraded by biotic and abiotic weathering processes, secondary MPs undergo changes in shape and chemical structure compared to primary MPs under synergistic weathering (Arp et al., 2021; Duan et al., 2021). Nanoplastics (NPs) are considered heavily as an extension of microplastics, but essentially differ from microplastics and other nanoparticles, especially in that their high specific surface area and volume ratio enable them to be highly reactive and prone to heteroaggregation with natural solids and organic matter, interaction with light and greater toxicity with biological interactions (Brewer et al., 2020; Gigault et al., 2021). However, there is no definitive scientific definition of nanoplastics, even in terms of size, the scientific community remains inconsistent, with controversy mainly resting on size cut-off values of 100 and 1000 nm (Alimi et al., 2018; Gigault et al., 2018). Differences in particle size along a unified continuum from macroplastics to microplastics to nanoplastics commonly result in different biological interactions, physicochemical behaviors and fates (Fig. 1).

Plastics as a creation of the Anthropocene are increasingly acknowledged as a global problem due to their ubiquitous distribution. Thousands of studies have documented the existence of microplastics in diverse media including aquatic ecosystems, terrestrial ecosystems, atmospheric ecosystems and biota (Kane et al., 2020; Koutnik et al., 2021; Ribeiro et al., 2019; Rillig Matthias and Lehmann, 2020; Rochman, 2018; Savoca et al., 2021; Yin et al., 2022; Zhang et al., 2020c). Much of the early knowledge of plastic pollution came from the oceans, these small particles of plastic were reported by scientists more than half a century ago. Currently, MPs have spread throughout the world's oceans, from offshore to pelagic, from surface microlayer to submarine plain, even in trenches as deep as 10,890 m, the ocean appears to be considered a huge sink (Galgani and Loiselle, 2019; Katija et al., 2017; Peng et al., 2020) (Table S1). Freshwater is closer to the sources of plastics than the ocean, taking on a function on land as the source of MPs (wastewater treatment plants), transport medium (rivers) and sink (static reservoirs or lakes). Of all the freshwater surveys currently available on seven continents, Lake Geneva in Switzerland has an abundance of 48,146unit km^{-2}, with concentrations that are likely to be many orders of magnitude higher than the microplastic concentrations in marine ecosystems (Alimi et al., 2018; Li et al., 2020a, 2018). Although research on terrestrial ecosystems is limited, soils may hold more MPs than ocean basins, as the sum of MPs released to agricultural land through wastewater and biosolids alone may far exceed the total load of MPs in the ocean surface microlayer (Koutnik et al., 2021; Zhou et al., 2020). Thousands of tons of MPs circulate in the atmosphere enabling them to reach incredible places such as remote mountainous areas, plateaus, polar regions and even the troposphere (Allen et al., 2021, 2019; Dong et al., 2021; Mishra et al., 2021). The bulk distribution of plastics in the environment and the foraging strategies of organisms make it inevitable to be uptake and accumulate by biota. Until now, over 1,500 species from marine creatures to terrestrial animals have been reported to ingest plastics (Santos et al., 2021). Increased reports of plastic ingestion by wildlife are inextricably linked to the distribution and accumulation of plastics in the environment. Small particles of plastic can attach to the surface of algae or be captured by plant roots and enter the base of food webs (Larue et al., 2021; Wang et al., 2021b; Yin et al., 2021). Consumers in the food web ingest MPs/NPs directly or indirectly which are usually retained in the digestive tract and eventually excreted with feces (Li et al., 2021a; Ory et al., 2018; Zantis et al., 2022). When plastics are small enough to approach the size of natural

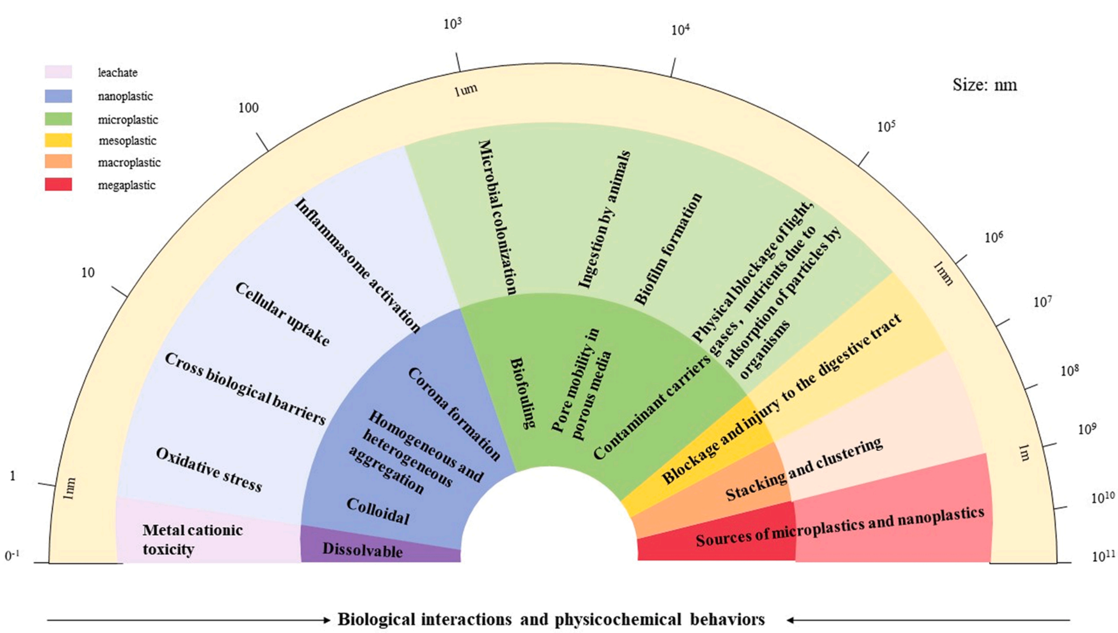

Fig. 1. Size distribution of plastics and their physicochemical behaviors and biological interactions in the environment.

proteins to enter cells across biological membranes by active endocytosis and passive diffusion, they can cross the epithelial cells of digestive tract and translocate to other tissues via blood circulation. (Ramsperger et al., 2020; Liu et al., 2021a). Simple trophic transfer of MPs/NPs in the food chain has been demonstrated, with these small particles moving up the food chain in prey-predator interactions (Chae et al., 2018; Elizalde-Velazquez et al., 2020; Zhu et al., 2018). Growing evidence shows that plastics are constantly in motion in biotic and abiotic compartments. However, current literature is lacking on the multidimensional nature of plastic transport in the Earth system.

This review provides a comprehensive overview of recent advances in the transport of MPs/NPs between abiotic and biotic compartments. In general, we (1) summarize in detail processes and drivers of MPs transport in macroscopic compartments (aquatic ecosystems, terrestrial ecosystems, atmospheric ecosystems); (2) discuss emphatically the uptake pathways of MPs/NPs by different biota within ecological compartments; (3) analyze potential internalization mechanisms of NPs in organisms; (4) assess the potential for MPs/NPs bioaccumulation in food chains and whether biomagnification can occur; (5) highlight the trophic transfer of MPs/NPs in the food chain from prey to predator; (6) suggest prospects for future work priorities.

2. Transport dynamics of microplastics in macroscopic compartments

Over the past decade, scientists have used advanced and efficient methods to discover the presence of microplastics in the oceans, freshwater, soils, atmosphere, groundwater and biota (Liu et al., 2021b). Deep-sea circulation, ocean currents, turbidity currents and biofouling have expanded understanding of the long-range transport of microplastics within and between oceans (Kane et al., 2020; Kooi et al., 2017; Pohl et al., 2020). Microplastics in the soil broken down into smaller pieces by the physicochemical action of microorganisms, which may make it easier for them to penetrate into the deeper layers of the soil (Li et al., 2022; Luo et al., 2022). In rivers, microorganisms colonized the surface of microplastics to form heterogeneous aggregates that change their density and weight, resulting in deposition, while settled microplastics can be resuspended and transported to downstream ecosystems by water flow (He et al., 2021; Luo et al., 2022). MPs suspended in air can be deposited to terrestrial and aquatic environments by wet and dry deposition, as well as transported over long distances under the influence of wind (Allen et al., 2019; Brahney et al., 2020). These ecological compartments are not independent, they are intertwined to form a whole ecosphere. Therefore, understanding the transport of microplastics within macroscopic compartments is necessary to comprehend the complex and continuous movement of plastics in the ecosphere.

2.1. Transport of microplastics in aquatic ecosystems

2.1.1. Ocean

It is speculated that there are 4.85 trillion microplastics in the global ocean to date, of this, the plastic accumulated on the ocean surface accounts for about 1% of the global marine plastic budget, with most of the rest changing plasticity under physicochemical and biological action eventually sinking to the sea floor. (Eriksen et al., 2014; Kane et al., 2020; Law and Thompson, 2014). Marine plastics have long-lasting half-lives, hardly degrade in the environment in a short time and their relatively high buoyancy facilitates their transport over long distances. Some physical and biological processes can explain the transport dynamics of marine plastics and thus contribute to our understanding of the transport pathways and fate of microplastics in the ocean (Lavers and Bond, 2017) (Fig. 2).

Horizontal large-scale flow is the most significant way in which floating microplastics can be transported over long distances in the global ocean, usually is caused by a steady wind blowing over a long period of time at the surface of the sea, which generates the so-called Ekman drift under the effect of the Earth's rotation, resulting in the massive accumulation of floating microplastics in the subtropical circulation known as the "garbage patches" (Onink et al., 2019; van Sebille et al., 2020). Large-scale circulation appears to explain the phenomenon of floating debris accumulating in the ocean to form "garbage patches", but these theories have difficulty in explaining the sources and transport pathways of plastics in the accumulation areas and even the time scale of the formation of the accumulation areas. In addition, the mesoscale eddies are another circulation pattern, with two types of cyclonic and anticyclonic eddies. Its diameter can reach hundreds to thousands of kilometers and remain for weeks to years (Chelton et al., 2011). This circulation pattern may play an important role in the transport of floating plastics that are retained in it. Mesoscale eddies have been shown to transport plankton, heat, salt and particles over thousands of kilometers (Berline et al., 2013; Braun et al., 2019; Dong et al., 2014). Mesoscale vortices form submesoscale when their fronts and filaments became unstable, this submesoscale process has a strong influence on the accumulation of floating plastic particles. D'Asaro et al. studied that the floating materials similar to plastic particles accumulate in the cyclonic vortex (D'Asaro et al., 2018). Moreover, the kinetic energy generated by the vertical shear stress of Stokes drift may have a

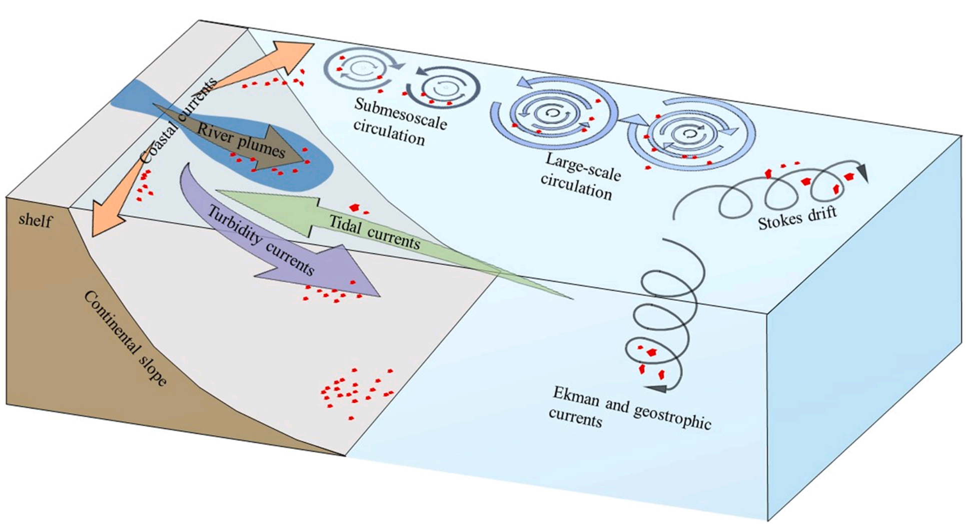

Fig. 2. Schematic diagram of the physical processes affecting the transport of plastics (red items) in the ocean.

profound effect on the fate of oceanic buoyant particles including oil droplets, plankton and microplastics. (Drivdal et al., 2014) Onink's study suggested that Stokes drift would leads to increased transport of microplastics to the polar regions, but is less relevant to the large-scale accumulation of microplastics in the subtropics (Onink et al., 2019). Although the complex relationship between Stokes drift and microplastic transport is not clear from current research, Stokes drift plays an indispensable role in the transport of marine microplastics.

The hydrodynamic conditions controlling the transport of microplastics in coastal waters are obviously different from those in the open sea, which are mainly influenced by tidal current, coastal current and stranding. Sterl et al. analyzed the contribution of barotropic tidal currents to the transport and accumulation of microplastics through numerical modelling. It was found that strong barotropic tidal currents had a large impact on the transport and distribution of microplastics in coastal and semi-enclosed seas, but not much on transport and accumulation in the open sea (Sterl et al., 2020). Microplastics are pushed offshore by surf and wind-induced nearshore currents and may become stranded in the sediment when they are washed ashore by waves (van Sebille et al., 2020). The tectonic morphology of continental margins may also control the transfer pathways of microplastics from riverine to deep-sea pathway systems such as submarine canyons and deep-sea trenches (Kane and Clare, 2019). Some studies have investigated the abundance of microplastics in submarine canyons, which are approximately twice as abundant as those reported on open slope, deep-sea plain and continental shelf (Kane and Clare, 2019; Pham et al., 2014). Since the impact of currents and complex topographic relief lead to spatial variations in the shear stress exerted on the seafloor, higher shear stress regions are observed at shelf breaks, upper continental slopes and especially in contourite moats, where bottom currents are most potent. Therefore, this contour currents are considered as an effective medium for microplastic transport (Drivdal et al., 2014; Kane et al., 2020). Besides, microplastics can be transported by the ingestion of zooplankton and large predatory fish, as well as by biological colonization of microbial communities such as bacteria, unicellular algae and fungi (Katija et al., 2017; Wright et al., 2020).

2.1.2. Freshwater

It's estimated that as much as 1.15–2.41 Mt of plastic waste is transported from rivers to the ocean each year, a significant spatial heterogeneity exists between microplastic concentrations in freshwater and the ocean, which depends primarily on proximity to industrial and population areas(Alimi et al., 2018; Lebreton et al., 2017). Freshwater systems are closer to the sources of plastic compared to the ocean and can trap many particles during transport (Eerkes-Medrano et al., 2015). When microplastics enter the water column, they are deposited in the sediment or transported with the water flow because of particle density, shape, particle size or the interaction of microbial colonization and suspended clay particles that change the buoyancy of the MPs (Waldschlager and Schuttrumpf, 2019; Zhang et al., 2021c). MPs distribution and transport can be strongly affected by complex estuarine dynamics and river morphology. Density-driven turbidity currents, wind-driven and river discharge can accelerate the transport of microplastics from inland to estuaries and oceans (Lv et al., 2020; Pohl et al., 2020).

The macroscopic transport of microplastics in rivers is traditionally ascribed to four hydrometeorological processes: rainfall-driven surface runoff, wind and transport by river flow dynamics and tidal dynamics, which are thought to be important in explaining the spatial and temporal heterogeneity in the abundance of river MPs (Roebroek et al., 2021). Werbowski et al. quantified microplasticity in stormwater, which can reach concentrations of up to 24.6 particles /L, far in excess of wastewater treatment plants (WWTP) effluent concentrations, these particles are eventually carried into adjacent water bodies through runoff migration (Werbowski et al., 2021). However, it is difficult to assess the input of surface runoff to river water bodies because current studies of stormwater-driven runoff events are scarce and remain on a regional spatial scale. With wind as one of the mechanisms driving microplastic transport in rivers, downwelling-favorable winds sites have a more pronounced dense concentration of microplastics, and these low-density microplastics accumulate at the top of the water column which are more easily transported to the estuary by wind-generated currents, downwind changes the frontal surface of the river plume, and Ekman transport driven by the wind suppresses frontal density and leads to a downward circulation that promotes microplastic transport (Browne et al., 2010; Cohen et al., 2019; Lv et al., 2020).

The main physical variables of fluvial dynamics include river flow, flow velocity, and water depth, etc. High flow facilitates the transport of microplastics from the source to longer distances, moreover seasonal flow variations induced by flood events can intensify this transport. Higher flow velocities allow deposited particles to be resuspended and transported downstream, and MPs can be deposited and form hot spots as the channel width increases and flow velocity decreases as well as turbulence becomes less intense, as influenced by river geometry. Due to bed friction, the flow velocity of the upper water layer is much higher than that of the bottom water layer, so the concentration of MPs is usually higher in shallow water than in deep water (Gerolin et al., 2020; Han et al., 2020; He et al., 2021). Finally, the estuarine circulation generated by tidal and surface currents in the estuary under the action of wind and waves is highly important in contributing to the transport of MPs. The concentration of MPs may vary 1000-fold during a tidal change cycle, and the tidal velocity significantly increases the abundance of MPs, while the concentration of MPs from the land boundary to the ocean decreases as the tide weakens (Cohen et al., 2019; Zhang et al., 2020a). In addition, population density areas, land utilization, contribution of wastewater discharge, and extreme events such as typhoons also affect the distribution and transport of MPs to some extent.

2.2. Transport of microplastics in terrestrial ecosystems

MPs in the lithosphere are difficult to visualize and most MPs are hidden over time in deeper soils. The concentration of MPs in inland soils is an order of magnitude higher than in coastal and estuarine soils due to the loss of microplastics by sedimentation during transport (Koutnik et al., 2021). It is generally believed that MPs enter the soil mainly through sewage sludge application, agricultural film mulching, wastewater irrigation, plastic particles from road traffic, garbage and surface runoff and atmospheric deposition (Blasing and Amelung, 2018; Campos and Pestana, 2020; Evangeliou et al., 2020).

MPs are transported in the soil in both horizontal and vertical directions, which includes biotic and abiotic transport (Fig. 3). Surface soils are subject to horizontal migration in response to surface runoff, agricultural activities such as tillage, and wind flow (Guo et al., 2020; Werbowski et al., 2021). Once MPs entered the surface soil, they could migrate to deeper soils through leaching, agricultural activities, bioturbation, and dry-wet cycles (Li et al., 2020b; O'Connor et al., 2019). Leaching is the migration of soluble or suspended compounds in soil material from the upper part of the soil to the lower part in the action of infiltrating water, which has a significant contribution to the vertical movement of MPs, fine particles can move along the soil pores under the action of leachate, and MPs/NPs smaller than the soil pores will be leached out and may reach the shallow groundwater (Zhou et al., 2020). Different tillage practices affect the distribution of MPs in different soil layers. Traditional tillage practices cause the MPs in the upper and lower soil layers to be inverted, and the MPs in the deep soil layer will return to the surface (Rillig et al., 2017a).

As the representative of soil cavity organisms, earthworm is an important medium for the transport of MPs, which greatly increases the depth of downward transport of MPs by digging, casting, excreting (digesting MPs into fragmented NPs), and adhering to their exterior (Rillig et al., 2017b). In addition, smaller soil arthropods (mites, elasmobranchs and roundworms) remobilize and disperse MPs through

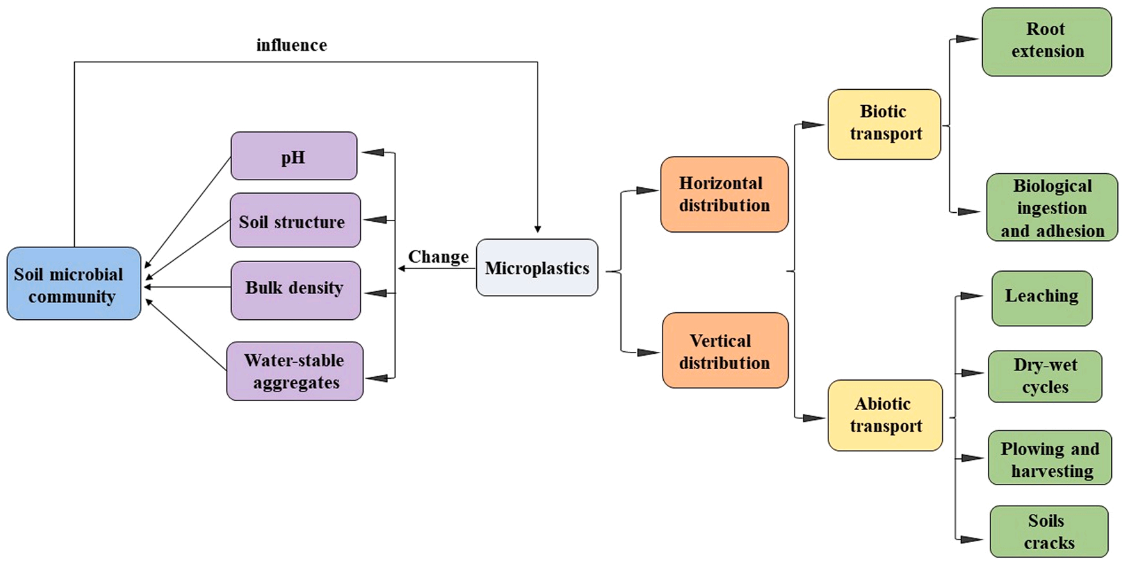

Fig. 3. Factors affecting the transport of microplastics in soil, including biotic and abiotic transport. Microplastics change the physicochemical properties of the soil and indirectly affect the activity of the soil microbial community. In turn, these microorganisms influence the transport of microplastics.

chewing and scraping activities, but this movement is strongly size-dependent and their migration distance to MPs is limited, rodent mammals such as moles and gophers facilitate the transport of MPs in both horizontal and vertical directions(Maass et al., 2017; Rillig, 2012). As a producer at the bottom of the food chain, plants play a role in the transport of MPs. Traditionally, researchers have presumed that plant root extension, root movement and root water uptake would contribute to the transport of MPs to the deeper layers of the soil, but recently Li et al. experimentally found that plant roots promoted the upward migration of MPs in the soil profile, this may be related to the buoyancy effect from the cracks left by plant roots in the soil (Li et al., 2021b). Moreover, some studies have found that plant root tips can absorb NPs and transport them to the above-ground part from down to up through the xylem by hydroponic experiments (Lian et al., 2020; Liu et al., 2022). Of course, this is only under ideal conditions in the laboratory. Uptake of MPs by plant roots has a size-exclusion effect, how large the size of MPs can be uptake by plant roots still needs plenty of experimental verification. Besides, NPs may be more likely to interact with soil components to form heteroaggregates under actual conditions, which also greatly increases the difficulty of their entry into plant tissues.

High intensity and frequency of precipitation and irrigation can infiltrate MPs from the topsoil to deeper soils, while this is also influenced by the characteristics of MPs (Zhang et al., 2022). Furthermore, several studies have found a significant effect of the number of dry-wet cycles on the increase of the penetration depth of MPs in soil through column experiments, which may be instructive for the potential sources and risk assessment of MPs in groundwater (Gao et al., 2021; O'Connor et al., 2019). Soil agglomerates are the basis of soil structure, their structural changes affect the physicochemical and hydrological properties of the soil (Huang et al., 2022). MPs could alter the stability of soil agglomerates which negatively affect microbial activity and soil function. In addition, MPs alter the ratio between macro- and micro-agglomerates to influence their particle size distribution (de Souza Machado et al., 2019; Hou et al., 2021). Most studies have revealed the impact of MPs on soil aggregates, but whether this interaction also affects the migration of MPs in soil needs to be investigated in depth.

2.3. Transport of microplastics in atmospheric ecosystem

Over the past decades, there has been some understanding of the ultra-long distances transport of dust and even its global circulation, but only recently has it been discovered that dust is entrained with large amounts of MPs (Rochman and Hoellein, 2020; van der Does et al., 2018)(Table S2). Dris et al. found for the first time the presence of MPs in atmospheric particulate matter and also highlighted their importance as a component of airborne particulate matter (Dris et al., 2015). Allen et al. also collected wet and dry deposition samples of MPs in remote mountainous areas and demonstrated that their presence was reached by atmospheric transport over distances approaching 100 km (Allen et al., 2019). Liu et al. detected fragments of incompletely incinerated PP and ultrafine fibers from abrasion of textile materials in their pelagic suspended atmospheric samples, presumably originating from land and reaching the ocean through the atmospheric circulation (Liu et al., 2019). Until recently, the traces of MPs were also found in the free troposphere (Allen et al., 2021). This evidence of the potential for intercontinental and transoceanic transport of airborne MPs has far-reaching implications for understanding the biogeochemical cycles of plastics.

Lately, atmospheric transport of MPs is considered as an important transport vector, which may lead to their deposition to other compartments. At the same time, this transport strongly affects the dynamic balance of MPs in different ecosystems, including the exchange between the ocean and the land (Zhang et al., 2020c) (Fig. 4). MPs are continuously imported into marine ecosystems through the atmosphere, with finer particles reaching exceedingly remote polar regions through the atmospheric circulation. As a rule, the abundance of marine atmospheric MPs decreases with increasing distance from land because of high anthropogenic emissions from coastal activities and loss of MPs due to deposition during long-distance transport. Ding et al. found fibers are the most dominant shape in the marine atmosphere, probably due to their low settling velocity with longer residence time in the air, in addition to the fact that small and light plastic particles are more likely to be suspended in the atmosphere, facilitating their long-distance transport (Ding et al., 2021). Wang showed in his transoceanic investigations that MPs can travel long distances through the atmosphere to reach over the ocean 1000 km away. Wind speed, pressure, humidity and atmospheric temperature may affect the abundance and distribution of microplasticity during the long-distance transport of MPs across the sea (Wang et al., 2021d). Conversely, land is also fed by marine MPs, with 11% of the deposition flux of MPs in the western United States coming from marine emissions. The aerosols produced by these ocean sprays are driven by the wind and disperse to urban areas near the coast (Brahney et al., 2021; Liu et al., 2019). The East Asian summer monsoon

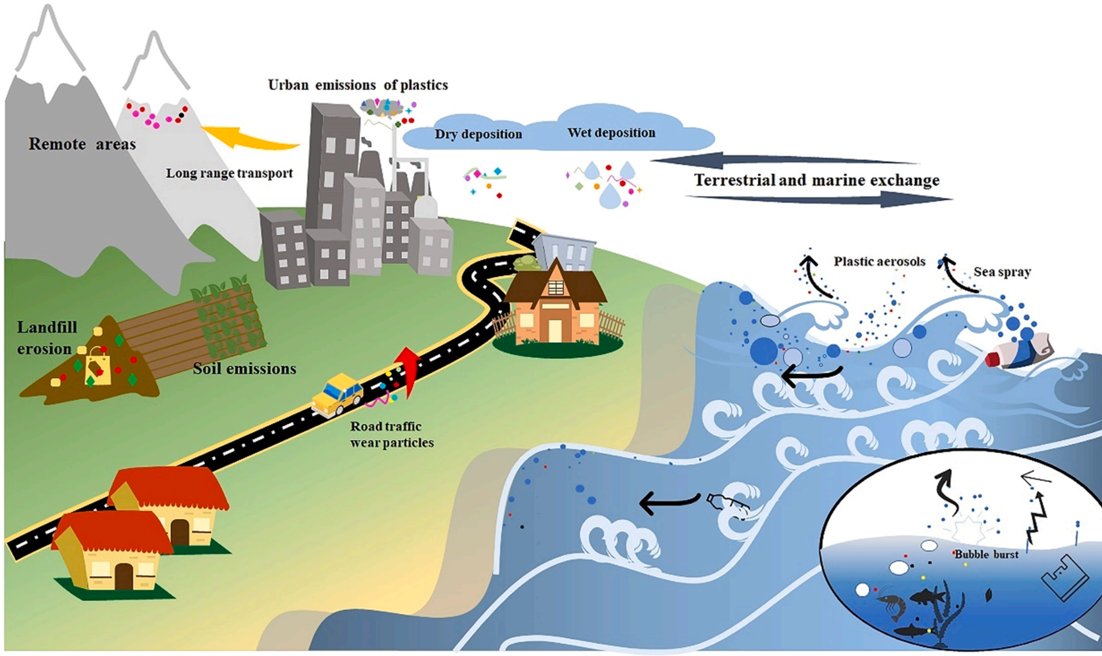

Fig. 4. Schematic diagram of the transport of microplastics between the atmosphere and the ocean.

(EASM) can transport airborne MPs back to southeastern China through the South China Sea with a flow rate of 212.97–213.433 kg/EASM/year (Wang et al., 2021d). Therefore, atmospheric MPs pollution is not a local phenomenon, but has regional and global impacts.

The concentration of MPs from land-based urban atmospheres is usually much higher than that of marine atmospheres because these regional atmospheric MPs are closer to the emission point source. Plastics emitted directly from urban population centers are unlikely to be transported over long distances, instead, they are deposited nearby. A small fraction of MPs can be suspended to high atmospheric altitudes for long-range transport under wind stress. Airborne MPs tend to be less dense than soil mineral particles and plastic particles are preferentially entrained by wind compared to natural soil substrates such as sand, which can determine their residence time in the air longer than dust agglomerates (Bullard et al., 2021; Sridharan et al., 2021). Airborne MPs are not easily suspended in the atmosphere for long periods of time and usually reach the ground through dry and wet deposition, which is a common transport mechanism for airborne MPs. Brahney et al. investigated dry and wet deposition of MPs in protected areas of the United States, where dry deposition is susceptible to global atmospheric dispersion and wet deposition is dominated by resuspension of MPs from the surrounding environment (Brahney et al., 2020). Roblin et al. collected wet and dry deposition samples of atmospheric MPs at precipitation monitoring stations far from cities in western Ireland, where wet deposition accounted for 70% of the total deposition and microfibers were more easily transported over long distances to remote areas than other shapes. Microplasticity abundance is significantly influenced by meteorological factors (wind speed, wind direction, rainfall, humidity), similar to those reported by Ding (Ding et al., 2021; Roblin et al., 2020). Dong et al. discovered that high altitude glacier belts on the Tibetan Plateau are also exposed to MPs pollution, they estimated and compared the mass load of MPs in lakes, atmospheric deposition fluxes and glacier runoff inputs, the concentration of MPs in atmospheric deposition is significantly higher than other pathways. The backward trajectory model indicates that MPs may be transported 800 km across the Himalayas to reach the Tibetan Plateau hinterland (Dong et al., 2021). Even so, most studies focused on atmospheric deposition, which is only a fixed passive method of collecting deposition.it is still difficult to simulate the transport process of atmospheric MPs, and their residence time in the air, settling velocity, transport distance, and source-sink dynamics need to be studied in-depth. In contrast to the transport and accumulation of MPs in other compartments, it is also necessary to pay more attention to the importance of the atmosphere as a reservoir and transporter of MPs.

Interestingly, it has been suggested in recent years that atmospheric MPs may be partially contributed by the oceans. MPs in the ocean surface microlayer can leave the ocean and be released into the atmosphere during bubble break-up sputtering and wave action caused by ocean turbulence and strong winds (Allen et al., 2020). Ferrero's investigation revealed a high degree of similarity between airborne and marine microplastics (high concentrations, same width, color, composition), which may be due to air-water interactions, as large amounts of sea spray continuously inject MPs aerosols into the atmosphere (Ferrero et al., 2022). Related experiments have also shown that bubble rupture causes plastic particles to escape from the water surface and released to the atmosphere, which is particularly important for nanoparticles. Besides, the material composition of the sea microlayer, bubble sizes and particle characteristics all affect its transfer efficiency (Masry et al., 2021). Future work should enhance micrometeorological measurements of oceanic atmospheric aerosol particles and further quantify fluxes at the water-air interface interaction.

3. Transport of microplastics and nanoplastics in biota

Plastics in the environment may gradually break down into a diversity of small particles and chemicals through synergistic environmental and biological stresses (Arp et al., 2021; Huang et al., 2021b). These particles are more mobile than the original material and are more readily and extensively uptake by biota in the ecological compartment. Exposure of biota to plastic debris has been widely reported, with the ingestion of MPs/NPs posing a variety of effects including oxidative damage, immune stress, and metabolic disorders that threaten the growth, development, and reproduction (Koelmans et al., 2022; Lehner et al., 2019; Li et al., 2021c; Santos Robson et al., 2021). These MPs and NPs retained in the organism can translocate to other circulatory systems and tissues through the gastrointestinal tract and achieve bioaccumulation (Ribeiro et al., 2019). Additionally, they can also interact with more species at different trophic levels and transfer along the food chain to higher trophic levels (Carbery et al., 2018). Owing to the multidimensional nature of MPs/NPs, their uptake pathways, transport mechanisms, bioaccumulation, and factors affecting their uptake, distribution, and accumulation are diverse, a systematic and specific study is needed to decipher these mechanisms.

3.1. Uptake of microplastics and nanoplastics on different biota

3.1.1. Plankton

Phytoplankton are the basis for the integrated material cycle and energy flow in aquatic ecosystems, fixing half of the atmospheric carbon dioxide through photosynthesis and responsible for 45% of the Earth's primary productivity. However, phytoplankton are exceptionally sensitive to environmental hazards, so understanding the interaction of phytoplankton with MPs/NPs is essential to assess the impact of the ecological characteristics of the aquatic environment (Huang et al., 2021b; Larue et al., 2021). Larger MPs may be colonized and encapsulated by a host of microorganisms, including algae (Chlamydomonas, Chlorella), forming dense surface biofilms, which are usually bound together by intermolecular forces, while the attached microorganisms also secrete extracellular polymers (EPS) to enhance their adhesion (Wang et al., 2021b). For MPs and NPs, they may attach to the surface of phytoplankton impeding the transport of light, gases, and nutrients to the organism with adverse effects. Algae exposed to MPs/NPs may release sticky extracellular polymers (EPS) to induce the formation of heterogeneous aggregates. Expanded aggregates increase the density and weight of particles, contributing to their migration from the water into the sediment and increasing the probability of their uptake by benthic animals (Long et al., 2017; Mao et al., 2018).

Zooplankton often float in the water and cannot produce organic matter themselves, acting as an important link for transferring material and energy from primary producers to higher trophic levels. Currently, MPs particles were found in copepod, cladocera and ciliate, which interacted with MPs through surface adhesion or ingestion. Different species of zooplankton show different bioavailability of different shapes of MPs, and the polystyrene microspheres used in most experiments proven to be readily ingested by many species. In a recent study, it was demonstrated that all three zooplankton species selectively ingested certain MPs, with copepods *Calanus helgolandicus* consuming more debris, *Acartia tonsa* favoring fiber and *Homarus gammarus* preferring microbeads compared to others, which may be related to their unique feeding strategy (Botterell et al., 2020). Similarly, foraging strategies also determine the bioaccumulation concentration of MPs in them, a situ survey by Sun in the zooplankton fauna of the East China Sea found that omnivores had significantly higher bioaccumulation concentrations than carnivores and herbivores due to their selective diversity, which also implies a high retention rate of MPs in them (Sun et al., 2018). Nakano more carefully found that in the presence of both MPs and food, zooplankton preferentially ingested food, which is similar to the results of Rist's experiments, where Daphnia ingested MPs more efficiently in the absence of food and preferentially ingested 2 μm polystyrene beads compared to 100 nm (Nakano et al., 2022; Rist et al., 2017). Besides, color, aging and type of plastic particles are also critical factors in attracting zooplankton to ingest MPs, as they choose MPs of similar color and size to their natural prey, with copepods being more diverse in their choice of color. Female *Acartia longiremis*, juvenile copepods and adult *Calanus finmarchicus* preferred aged microbeads to the original material, probably due to the chemical exudates released from the biofilm formed on the aged plastic being more attractive (Kosore et al., 2018; Vroom et al., 2017). Polymer type may also be an important factor in determining zooplankton foraging. Kosore et al. pelagic surveys found that polyethylene (PE) was the most common type ingested by zooplankton, possibly due to its lower density than seawater floating on the surface, where it is easily accessible and ingested by zooplankton (Kosore et al., 2018). Additionally, Sipps et al. revealed in the estuary that the dominant species of copepods showed considerable appetite for polypropylene (PP) in addition to PE ingestion (Sipps et al., 2022). However, Xu's culture experiments concluded that there was no significant difference in the uptake rate of PS and PE microspheres by *T. longicornis* in copepods (Xu et al., 2022). As current studies mostly focus on single or minority species for common polymer ingestion investigations, future research work should be carried out on broader species, more types of polymers and even their leaching chemicals to fill the relevant knowledge gaps.

3.1.2. Macrophytes

Although plants have nano-thin phospholipid bilayer cell membranes, tough elastic cell walls and a continuously homogeneous pectin system that enable them to be highly impermeable to microplastic, a very few submicron microplastics and nanoplasctics might still enter the vascular system responsible for water transport via the foliage or root system and be rapidly transferred to the roots, stems, leaves and even fruit of the plant (Liu et al., 2020a; Schwab et al., 2020) (Fig. 5). Understanding the complex nature of microplastics/nanoplastics-biological interactions and their transport across biological barriers into plant tissues is therefore essential for assessing the toxicological impact of plastics on photosynthetic organisms and the risk of trophic chain contamination.

Plants can interact with MPs/NPs through two modes, root exposure and foliar exposure. Airborne plastic particles are usually trapped by the large and uneven surfaces of plants (Bi et al., 2020). The leaf blade normally consists of trichomes, stomata and a cuticle covering the surface (Avellan et al., 2021). Nanoparticles trapped by plant leaves may be attached and uptake by interaction with these structures, and the cuticle is usually viewed as the first natural defense of plant stroma tissue against invasive particulates, with the effective size of the cuticle pore diameter reported to be 0.6–4.8 nm, theoretically nanoparticles below 4.8 nm could directly penetrate the cuticle (Eichert and Goldbach, 2008; Eichert et al., 2008). In addition, the waxy coverings that infiltrate the stratum corneum form a variety of crystals on the surface of the stratum corneum to increase roughness to generate a strongly repulsive effect. Thus, lipophilic MPs/NPs have a high affinity for the waxy leaves to adhere to them (Avellan et al., 2021; Bi et al., 2020; Schwab et al., 2016). The high density of trichomes on the leaf surface may be an important factor in the capture efficiency of airborne particles, and also plays an important role in the exchange of liquids and gases at the bio-interface with the air (Avellan et al., 2021). However, there is insufficient evidence that trichomes are a transport pathway for NPs, but metals in ionic state can effectively accumulate in trichomes (Spielman-Sun et al., 2019). Micron-sized stomata are considered to be an efficient pathway for MPs/NPs to enter the mesophyll from the leaf surface. The physiological structure and geometry of stomata make the maximum penetration size of particles unknown, in general, the physiological activity of stomata depends on environmental conditions such as CO_2 concentration, light intensity, humidity, etc. Different plant species may also have varying stomatal sizes (Avellan et al., 2021; Lv et al., 2019). Numerous studies have demonstrated that stomata act as a pathway for the uptake of NPs, with modified polystyrene nanoplastics (22 nm PS-NH_2 and 24 nm PS-COOH) can enter the vascular system through the maize foliar stomatal pathway and transfer down to the roots (Sun et al., 2021). Eichert et al. found that 43 nm NPs in carboxylate-modified nanoplastics suspensions could pass through the stomata of broad bean leaves while 1.1 μm failed, probably due to the size exclusion limitation of the stomata (Eichert et al., 2008).

The transport of MPs/NPs in plant roots is relatively well studied compared to the foliage, as it is generally accepted that they can enter roots and cause damage to plant tissues (alteration of cell membranes and endomolecules, reactive oxygen species-induced cytogenotoxicity and gene expression) (Maity and Pramanick, 2020; Rillig et al., 2019). Charged NPs in the vicinity of the root system are readily uptake by the roots and accumulate on the root surface as the root hairs are capable of secreting small molecules of organic acids and mucilage (Zhou et al., 2011). Sun confirmed that the uptake and internalization of negatively

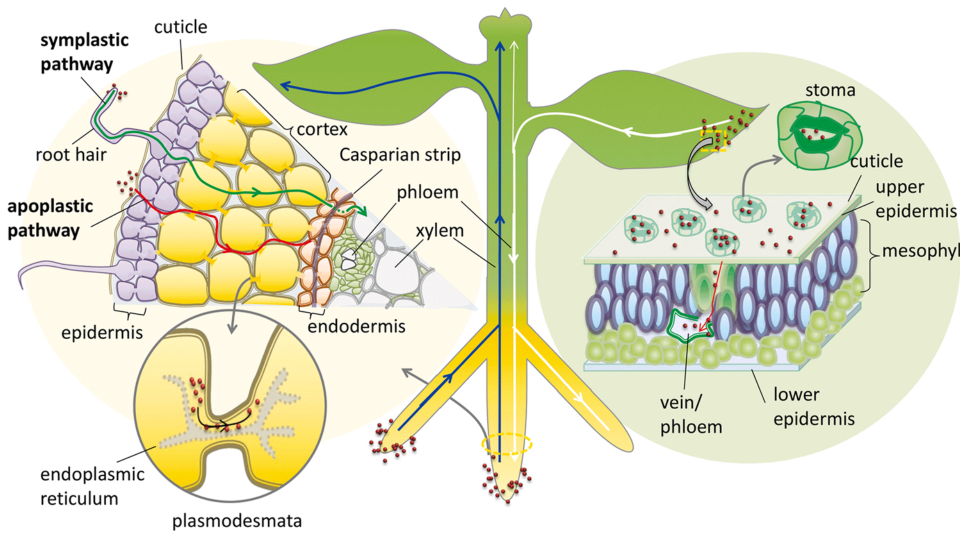

Fig. 5. Schematic diagram of the uptake and translocation pathways of NPs in plants. Copyright (2019), Royal Society of Chemistry. Reprinted with permission from Ref (Lv et al., 2019).

charged nanoplastics in the root system were higher than that of positively charged particles due to root secretions and electrostatic interactions (Sun et al., 2020). The vascular system of plants is mainly composed of the phloem (symplasms) and xylem (apoplasts), which are probably the two basic pathways of root uptake in higher plants (Schwab et al., 2016). There are numerous experiments in which the presence of MPs/NPs in apoplasts can be observed by STEM (Scanning Transmission Electron Microscope) and LSCM (Laser Scanning Confocal Microscope). For example, fluorescent polystyrene at 200 nm in Arabidopsis roots, PS microspheres of 80 nm and 1 μm in roots, stems and leaves of rice seedlings and microplastic beads of 5–50 μm in birch roots (Austen et al., 2022; Liu et al., 2022; Sun et al., 2020). Hence, MPs/NPs are transported to other morphological organs by apoplasts. The other pathway is symplasm transport in the phloem, which is an intercellular transport pathway. The cell wall separates the plant cell into separate individual cell compartments, and symplasmic transport can occur through intercellular filaments to adjacent cells or across the cell membrane to the cytoplasm (Lv et al., 2019). These plant cell transmembrane transports are not only a way of nutrient uptake by plant roots but may also be internalized by NPs, for example, through cytokinesis. Onelli studied the endocytosis of tobacco cells by probe-labelled gold nanoparticles, which were eventually internalized into protoplasts (Onelli et al., 2008). Etxeberria confirmed the liquid-phase endocytic uptake by plant cells using polystyrene nanospheres (Etxeberria et al., 2006). There are still many technical and physiological unknowns regarding the integrated mechanisms of uptake and translocation of NPs by plant roots, such as how to identify the transfer pathways of symplasms and apoplasts, the maximum scale particle size that can be tolerated at the inter-root interface, and the rate of transfer of NPs by apoplasts and symplasms.

3.1.3. Bivalves and Crustaceans

Bivalves are widely distributed in the ocean and freshwater that play an important role in ecosystem function. There are two ways of feeding: filter feeding and deposit feeding, both of which are closely related to the structure and function of their gills. On the one hand, they can endocytose plastic particles into the gills through the microvilli on the gill surface and transfer them to the digestive organs under the movement of cilia, on the other hand, benthic species extend their labial whiskers to reach the bottom sediment, the mucus secreted by labial whiskers and the action of cilia will send the particles to the mouth and labial flap to finally reach the stomach and intestine (Pedersen et al., 2020; Sendra et al., 2021b). Normally, they selectively ingest the encountered MPs, with the gills and labial tentacles recognizing and sorting the particles, delivering nutritious particles to the mouth for ingestion, while particles that cannot be used as food are covered by the mucus of the feeding organs and are not passed through the digestive tract but excreted directly as pseudo-feces.(Zhang et al., 2019). Even though the ingested MPs pass through the digestive tract of bivalves, larger MPs are transported to the midgut by the cilia of stomach walls and then excreted with faeces, while smaller MPs remain in the gastrointestinal tract for relatively long periods of time (Goncalves et al., 2019). One investigation found that mussels exposed to high concentrations of microplastics for 24 h retained up to 95% of the ingested MPs, which may be due to the difficulty of removing MPs from the mussel in a short period of time, but another investigation found that after 72 h of purification, only 15.4% of the plastic particles remained in the shell cavity of the *Pacific oyster* (Graham et al., 2019; Pedersen et al., 2020). Oysters and mussels ingest a higher proportion of small spheres compared to large spheres, and even plastic particles smaller than 19 μm in size can be ingested or rejected on their own depending on their surface properties (wettability, surface charge), oysters also periodically adducted their valves to eject MPs of varying shapes and sizes from the mantle cavity (Ward et al., 2019). Apart from ingestion, MPs can also accumulate on the soft tissues of mussels through adhesion, and investigations showed that the MPs adhered to mussels may account for more than half of the total MPs in the whole tissue(Kolandhasamy et al., 2018). Li et al. found that MPs could even fuse to the byssus of mussel, as the adhesion proteins injected into the ventral sulcus may further interact with surrounding MPs to embed them into the mussel's byssus threads during byssus formation, but it is not known whether this mechanism can enter the tissues of organisms(Li et al., 2019).

Crustaceans, including planktonic copepods, isopods, euphausiaceas and decapods, were shown to be able to ingest and accumulate MPs (Botterell et al., 2020). Similar to bivalve mussel filter feeding, some decapods such as shore crabs expel water from their surroundings through the respiratory system and MPs may pass through ventilation and enter the gills of the crab. Accumulation of microplastics in crab gills may show high heterogeneity, with more uptake in the posterior gills than anterior gills, probably attributed to greater surface area in the posterior gills that enables more advantageous accumulation of MPs in the lamellae (Watts et al., 2014). Although gills serve as an uptake pathway for particulate debris, many evidences indicate the abundance and size of MPs in tissues and organs: viscera > gills > muscle (Wang et al., 2021c; Zhang et al., 2021b). Since they evolved a self-cleaning behavior (gill cleaning) during long natural evolution. In addition, the location of gills in their bodies and the exchange of gases with water via tiny gaps mean that it is difficult for larger size plastic particles to enter the gills (Zhang et al., 2021b). Antarctic krill filters water in the feed basket to obtain forage during ingestion, this rapid ingestion makes it impossible to distinguish food from MPs, which is carried to the mandibles for chewing and cutting and enters the stomach through the short esophagus (Dawson et al., 2018b). Many crustaceans have similarly developed gastric mills and mouthparts designed for mechanical destruction, where swallowed food and prey are broken down by the churning action of gastric mills, triturated particles then pass through the complex bristle filters that allow only small particles to reach the digestive diverticulum (Cau et al., 2019, 2020). However, for larger indigestible particles, they rapidly constrict the passage between the stomach and midgut forcing the food upwards and opening the esophagus to allow the food to expel, which is called regurgitation (Saborowski et al., 2019).

3.1.4. Fish

MPs/NPs usually interact with fish via direct feeding, indirect nutrient transfer, dermal absorption and respiratory exposure (Huang et al., 2021b). Feeding is the first step in the entry of MPs into the fish body, however, fish have unique feeding strategies that determine their uptake of MPs. Filter-feeding fish normally do not exhibit significant capture behavior due to their need to passively filter water to obtain a diet of mainly phytoplankton. In contrast, predatory fish are prone to accidentally swallowing plastic particles similar to food when attacking prey, so swallow-feeding fish may ingest more particles than filter-feeding fish (Li et al., 2021a; Ory et al., 2018). Fish at different life stages have varying intake rates of MPs, which also implies an increased risk of exposure to MPs when shifting from an invertebrate-based diet in juveniles to a shrimp and benthic fish-based diet in adults (Collard et al., 2019; Ferreira et al., 2019). Due to their high energy requirements, top predatory fish have to hunt for prey to sustain their life requirements, which inevitably results in secondary uptake of MPs. A survey found that fish acquire 3–11 times more MPs through nutrient transfer than from the water column, suggesting a greater risk of MPs exposure through the food chain (Hasegawa and Nakaoka, 2021). Moreover, the habitat in which fish live is also a driving factor for their uptake of MPs. Fish ingestion of plastics was highly heterogeneous across regions: estuarine > marine > coastal (Savoca et al., 2021). Different water layers of species preferentially ingest nearby plastic debris, with demersal fish more likely to ingest MPs in the shallow water, while pelagic fish consume plastics below the mixed layer (Collard et al., 2019). Therefore, the correlation between the incidence of biological ingestion of MPs and geography should also be included within future research investigations.

Apart from entering the fish body through ingestion, MPs in the water column can also be adsorbed on the gill and skin surfaces. A survey revealed that the overall number of MPs was significantly higher in the skin and gills than digestive system (Karbalaei et al., 2021). Generally plastic abundance in gills can be explained by filter feeding behavior, while the skin may secrete large amounts of mucus (a viscous gel composed of water, proteins and polysaccharides) to adsorb MPs (Abbasi et al., 2018). In addition, laboratory-based studies suggest that seawater (pH, salinity and contact time) is considered as a suitable medium that may facilitate the adsorption of MPs in aquatic animals (Kolandhasamy et al., 2018; Murugan et al., 2022). Fish periodically open or close their opercular and mouths during respiration to introject water into the oral cavity and then pump it through the gill cavity to obtain oxygen, this unintentional behavior leads to passive inhalation of MPs, when the accumulation of plastic in fish mouths exceeds the tolerance threshold they show a strong rejection behavior, namely spontaneously coughing up MPs mixed with mucus (Li et al., 2021a). This is similar to the observation of Christian Ory that juveniles striped killifish and tomcods would spit out the millimeter-sized microspheres they captured (Ory et al., 2018). Highly developed sense of taste can also limit unintentional intake of plastic pellets, as they change the position of the pellet in the mouth repeatedly to taste the pellet and quickly spit it out when it is found to be distinct from edible food (Roch et al., 2020). Those aged plastics have different microbial communities colonizing their surfaces rendering them more food-like to be swallowed, MPs with sharper edges may cause fish uncomfortable and be rejected (Ory et al., 2018; Xu and Li, 2021).

3.1.5. Top predators

Top predators are constantly sampling the environment due to their foraging and prey patterns, whether directly ingested or by trophic transfer from contaminated prey, rendering microplastics highly bioavailable in these high trophic levels. Marine turtles, as common mega vertebrates in the ocean, exposed to MPs during foraging, nesting and migrating. Unlike other animals, visual predation strategies lead them to erroneously ingest these plastic debris as their typical prey jellyfish, primary producer surface retained MPs via electrostatically bound cellulose and mucus layer adhesion may also be ingested by herbivorous marine turtles (Duncan et al., 2019; Schuyler et al., 2014). Furthermore, MPs in the vicinity of turtle nests may enter sea turtle eggs by osmosis to affect embryonic development and pose a threat to the sustainability of the population (Zhang et al., 2021a). Certain large filter feeders (basking sharks, manta rays and whale sharks) filter large amounts of seawater to obtain food, and they ingest thousands of microplastics per day, with 32 ± 24 microplastics per 6 g detected in whale shark feces while basking sharks consume approximately 13,110 microplastics per day (Fossi et al., 2014; Zantis et al., 2022). Thus, they are often considered to be the leaders in microplastic exposure in the marine ecosystem. pinnipeds (seals, sea lions and walruses) and odontocetes, which employ raptor feeding strategies, most likely accumulate MPs via trophic transfer. seals exhibited high correlation with MPs in their food, mackerel. Propylene and ethylene were both the most common types (Nelms et al., 2018). In addition, the comparable size frequencies and polymer composition found in beluga whales and their prey suggest that these MPs were likely transferred from one trophic level to the next (Moore et al., 2022). As land is the beginning of plastic accumulation, microplastics are likely to interact initially with terrestrial biota in terrestrial ecosystems, but current reports on terrestrial organisms are limited to invertebrates, birds and small mammals, the majority of species that ingest microplastics tend to be confined to anthropogenic landscapes. Reports of wild predators in terrestrial habitats are rare, hence there is an urgent need to understand the potential impact of these particulate debris on species diversity as well as ecosystems.

3.1.6. Human

The omnipresence of MPs/NPs in the environment and consumer products renders human exposure to these particles inevitable. Although there is no direct, valid evidence that these latent particles cause harm to humans, successive reports have revealed the accumulation of these particles in the human body (Amato-Lourenco et al., 2021; Ragusa et al., 2021). Multiple in vitro experiments have also demonstrated various toxicological effects of these small, highly permeable particles on cells (inflammation, oxidative stress, genotoxicity, apoptosis and necrosis) (Huang et al., 2021a; Prata et al., 2020). Due to the long-lasting properties of particles, their component monomers, endogenous additives and carried chemical contaminants also cause local leaching risks under prolonged exposure.

MPs/NPs commonly enter the body via three pathways of exposure (Inhalation, ingestion and subcutaneous absorption). Airborne suspended MPs may enter the respiratory system and inhaled MPs are deposited into the lungs depending on their aerodynamic equivalent diameter (AED), as AED is influenced by diameter and density, especially polymers with AED$\leq$ 10 μm and low density (polyethylene) have high potential to penetrate the human lower respiratory tract (Wieland et al., 2022). This was also confirmed in a recent investigation in which the presence of polymers and fibers was found in a human lung tissue sample with an average size of 8.12–16.8 μm, with the smallest particles being 1.6 μm of polyethylene (Amato-Lourenco et al., 2021). The body responds to MPs that reach the deep lungs, where lung macrophages and mucociliary escalator clear them from the lungs. Macrophages internalize them and transfer them to the circulatory system for eventual distribution to different organs, while mucociliary escalator delivers larger airborne MPs to the gastrointestinal tract for eventual excretion via the feces (Prata, 2018; Wieland et al., 2022). Moreover, ingestion is also a major pathway for MPs/NPs to enter the body, since MPs are widely present in environmental media, they are incorporated into food products consumed by humans and enter the body via the digestive tract. Currently traces of MPs have been found in aquatic products, salt, drinking water and other foods (honey, beer, etc.), even though humans can intentionally avoid or reduce the consumption of certain foods, exposure to contaminated drinking water, air and salt is inevitable (Cox et al., 2019; Wright and Kelly, 2017). A survey also evaluated the human load from these three dietary exposure routes, inhalation (0–3.0) × 10^7, salt (0–7.3) × 10^4, drinking water (0–4.7) × 10^3 (Zhang et al., 2020b). Human fecal samples also verified the possible sources of MPs in addition to drinking water and food, processing and packaging of food and dust exposure (Schwabl et al., 2019; Yan et al., 2022). As a protective barrier for the body, the skin protects against external mechanical damage, chemical agents and pathogenic bacteria. As using cleaning care products containing NPs or water contaminated with NPs leads to their contact with the skin, NPs may penetrate the subcutaneous tissue through sweat glands, hair follicles and injured skin areas, (Lehner et al., 2019; Zhang et al., 2019). Jatana et al. found that chemical ingredients in commercial skin care lotions (glycerol, urea and a-hydroxy acids AHAs) could enhance the penetration of 5.8 nm NPs into mouse and human skin (Jatana et al., 2016). Vogt also found that 40 nm nanoparticles could penetrate cells through the hair follicle pathway (Vogt et al., 2006). but currently there seems to be no direct evidence that particles larger than 100 nm can penetrate intact skin, probably due to the barrier protection of the skin by the stratum corneum.

3.2. *Cellular internalization: journey of nanoplastics entering the cell*

Research indicated that microplastics seemed to be hardly absorbed into tissues via the gastrointestinal tract (Lehner et al., 2019). By contrast, nanoplastics, the smallest members of the plastic kingdom, are often visually less impactful than microplastics and aggregates. But their unique small size enables them to penetrate biological barriers, to circulate in the blood as well as reach cells and even subcellular compartments. Their extremely high mobility, reactivity and small size permit them to interact strongly with cells in countless ways, with this interaction at the nano-biological interface regulating cellular machinery and altering the fate of cells (Kihara et al., 2021). Interactions between the nano-biological interface (especially extracellular polymers) lead to the formation of multiple biomolecular complexes on the surface of the nanoparticles, which result in an “ecological corona” that can reduce membrane permeability and enhance particle internalization and attachment to cells (Junaid and Wang, 2021). Due to the size, surface chemistry and charge of the particles, their interaction with surrounding biological components (phospholipids, proteins and carbohydrates) strongly influences the uptake of nanoplastics by cells (Brewer et al., 2020; Chithrani and Chan, 2007; Junaid and Wang, 2021; Ramsperger et al., 2020). Therefore, the investigation on the intracellularization of NPs is an indispensable first step in understanding their nanotoxicology on cells.

Cellular internalization of NPs involves complex biomolecular interactions and highly regulated mechanisms (Fig. 6). When NPs reached the extracellular membrane, they can interact with the extracellular matrix and plasma membrane to enter the cell, mainly by active endocytosis and passive permeation. Endocytosis includes pinocytosis (caveolin-mediated endocytosis, clathrin-mediated endocytosis and caveolin/clathrin mediated non-dependent endocytosis) and phagocytosis (Behzadi et al., 2017; Galloway et al., 2017; Liu et al., 2021a; Wang et al., 2012). Phagocytosis occurs mainly in specialized phagocytic cells such as macrophages, dendritic cells and neutrophils. Phagocytosis is initiated when NPs are identified by phagocytic receptors (Fcy receptors, complement receptors and other protein receptors). Certain opsonins such as immune proteins, serum proteins and complement proteins adsorb to the surface of NPs and further induce receptor-mediated phagocytosis and particle internalization (Swanson, 2008). Phagocyte surface receptors can recognize endogenous foreign particles larger than 0.5 μm (Liu et al., 2020b). Hence, larger particles are more likely to be absorbed by phagocytes. For example, 1–3 μm particles in the alveoli are primarily cleared by phagocytes, and the maximum uptake by macrophages in the mouse peritoneal cavity can reach 1–2 μm (Behzadi et al., 2017; Geiser et al., 2005).

Caveolae as small pits in the cell membrane are also the most prominent and abundant surface subregions of the plasma membrane of many mammalian cells, which is formed by the concerted action of many lipid-interacting proteins to produce microstructural domains

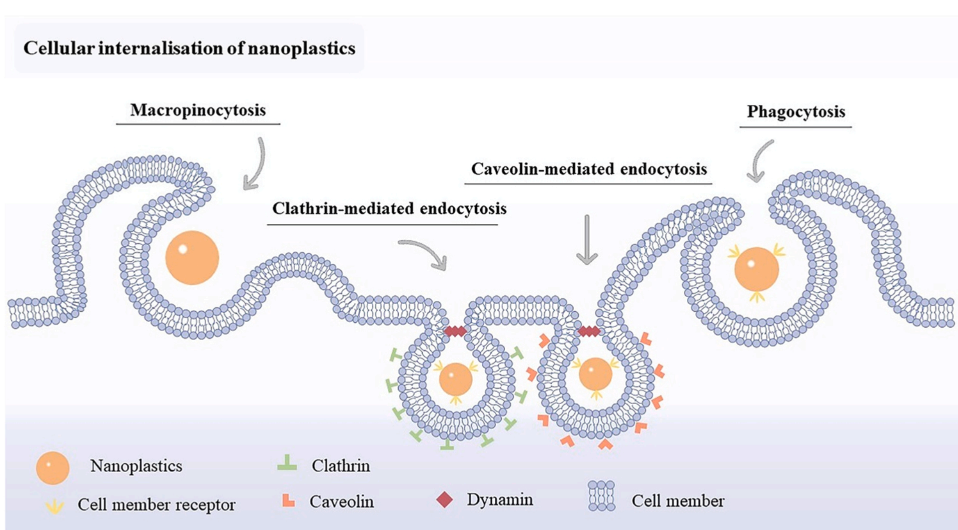

Fig. 6. Schematic diagram of different cellular internalisation of nanoplastics: Caveolin-mediated endocytosis, Clathrin-mediated endocytosis, Macropinocytosis, Phagocytosis.

with specific structural and lipid components (Parton, 2018). Caveolin-mediated endocytosis plays an essential role in biological processes such as transcytosis, intercellular signaling and regulation of structural cellular changes (e.g. membrane tension, lipids and fatty acids) (Behzadi et al., 2017). Many cells for example adipocytes, endothelial cells and fibroblasts all internalize granular material via caveolae. Liu et al. experiments revealed that 50 nm Ps microspheres could fuse with caveolin within the caveolae and be transported to the Golgi apparatus and endoplasmic reticulum (Liu et al., 2021a). Sendra's experimental phenomena also confirm this, as 50 and 100 nm NPs internalized via caveolin-mediated endocytosis pathway are usually close to the nucleus, which is the region of endoplasmic reticulum distribution (Sendra et al., 2020). Lysosomes in the cytoplasm capture these NPs and direct them into lysosomes, which contain various degradative enzymes that degrade them (Sendra et al., 2021a). But it appears for NPs that rely on the caveolin-mediated endocytosis mechanism to enter the cell could avoid the lysosome fusion (Behzadi et al., 2017). This may be due to caveolae vesicles releasing their contents into endosomes, which are then converted into caveosomes. The caveosomes can detach from the lysosomes and move along the cytoskeleton to reach other organelles (Parton, 2018).

Clathrin-mediated endocytosis commonly occurs in the region of the plasma membrane rich in clathrin, a triple-legged structure consisting of three light chains and three heavy chains, which are unique proteins that assemble with other proteins to form complex structures that deform the membrane and transform from the flattened plasma membrane to a "clathrin-coated pit", eventually the membrane invaginations form vesicles that separate from the plasma membrane and allow for further intracellular transport (Brown and Petersen, 1999; Kaksonen and Roux, 2018; Ungewickell and Branton, 1981). It has been suggested that clathrin-mediated endocytosis is capable of tolerating the passage of particles below 200 nm, probably due to the fact that the endocytosis process engulfs a certain amount of extracellular fluid that effectively forms a vesicle volume of 100–150 nm in diameter (Doherty and McMahon, 2009; Ehrlich et al., 2004). Microspheres smaller than 200 nm can be internalized through pits formed by clathrin (Rejman et al., 2004). In addition, cellular endocytosis of NPs may have different regulatory mechanisms; depletion of cholesterol on the Caco-2 cell membrane inhibited the caveolae-mediated endocytosis mechanism but significantly increased the internalization rate of NPs, probably as a result of clathrin-mediated endocytosis can be cholesterol-independent (Xu et al., 2021). Significant deviations in clathrin-mediated endocytosis at different cell cycles. The clathrin-mediated capacity of S-stages was much higher than that of G_0/G_1 and G_2/M stages during 24 h continuous time in algal cells (Yan et al., 2021). Finally, in contrast to the mechanism of fractal caveosomes-mediated endocytosis, NPs entering via this pathway tend to be degraded by lysosomes (Kuhn et al., 2014). Caveolin/clathrin independent endocytosis may occur in cells without caveolin and clathrin, requiring mainly the involvement of a specific lipid component (cholesterol) and protein insertion into the endosome contributing to the formation of invaginations and thus facilitating vesicle formation (Behzadi et al., 2017; Sandvig et al., 2011). However, uptake of NPs by cells via this pathway seems to be uncommon.

Lastly, besides active endocytosis, some nanoparticles such as nanoplastics can also be internalized by cells via passive permeation. Yacobi et al. discovered by confocal laser scanning microscopy that 20 nm carboxylate-modified nanoplastics could enter cells by passive diffusion through the phospholipid bilayer of the cell membrane (Yacobi et al., 2010). Geiser also found that instead of entering rat lung tissue cells by common endocytosis, titanium dioxide nanoparticles entered the cells by adhesion and diffusion, without binding to the membrane (Geiser et al., 2005). Passive permeation, which is not triggered by receptor-ligand interactions, might be the mechanism of internalization by van der Waals forces, spatial interactions and electrostatic synergies. Furthermore, particle line tension and thermal capillary waves also play an important role in controlling the internalization of NPs into cells (Behzadi et al., 2017; Chen et al., 1997).

3.3. Bioaccumulation, biomagnification and trophic transfer of microplastics and nanoplastics in biota

In recent years, ingestion of MPs/NPs in hundreds of species and across multiple trophic levels has been well documented. There is widespread interest in the toxicokinetic of MPs/NPs, particularly whether they are capable of bioaccumulating in organisms and biomagnifying upstream along trophic levels. Because bioaccumulation and biomagnification are important concepts in risk assessment to determine the extent of contaminant migration in food webs, there remains considerable uncertainty regarding the current assessment of bioaccumulation and biomagnification potential of plastic contamination. Besides concerns about fate in food webs, evidence suggests that plastic transfer can occur along the food chain from prey to predator (Zhao et al., 2018; Zhu et al., 2018) (Fig. 7). Low trophic levels and simple food web transfer may be more pronounced, which may be due to enhanced risk of lower trophic level exposure.

3.3.1. Bioaccumulation potential of microplastics and nanoplastics

Bioaccumulation occurs as a result of direct exposure of organisms to the environment (air, water, soil) and indirect exposure to contaminated food resulting in net uptake of contaminants (Bour et al., 2015). In other words, to achieve bioaccumulation, contaminants must be retained in the tissues of the organism, with concentrations increasing over the entire life cycle of the organism (McIlwraith et al., 2021). Ecotoxicology reveals that MPs and NPs are accumulating in a variety of organisms. Consequently, understanding their bioaccumulation potential is crucial for environmental risk assessment.

Evidence indicates that MPs/NPs can contribute to the bioaccumulation and toxicity of coexisting contaminants including persistent organic pollutants, pharmaceuticals and personal care products (PPCPs) and heavy metals in living organisms (Deng et al., 2020; Sun et al., 2022). However, controversy exists regarding the bioaccumulation of the particles themselves. Several studies suggested that size affects the accumulation of plastics in organisms. PMMA nanoplastics were present throughout the growth and developmental stages of barnacle larvae and were readily absorbed by cells and tissues (Bhargava et al., 2018). 50 nm PS nanoplastics more penetrated into the zebrafish chorion and embryo and accumulated in the body than 200 and 500 nm (Lee et al., 2019). In some mammals, this size dependence is even more pronounced, with smaller plastic particles rapidly translocating and entering the circulation, 50 nm were internalized into mouse kidney cells, while 4 μm were much less abundant in tissues than other particle sizes and mostly distributed in the intercellular space and renal tubules (Meng et al., 2022). In another investigation, Antarctic krill exposed to polyethylene MPs failed to exhibit bioaccumulation, which may account for the inability of MPs to rapidly cross biological barriers and the quick scavenging strategy of crustaceans (Dawson et al., 2018a). In addition, shape seems to be another effective factor in determining bioaccumulation. In some histopathological experiments, non-spherical microplastics with longer residence time in the intestine than spherical ones, while microfibers embed easily in the tissues compared to other shapes (Qiao et al., 2019). For example, microfibers can penetrate deep into the human lung, avoiding clearance mechanisms and sustaining retention (Wright and Kelly, 2017). Additional factors such as hydrophobicity and surface chemistry may also affect tissue cell uptake. Hydrophobic plastic particles repelled by mucus cells render them unlikely to soak into cells. Mucus in the gastrointestinal tract facilitated particle aggregation, and incidental substances on particles such as surfactants reduced mucus viscosity and increased particle absorption (Wright and Kelly, 2017). Some particles with positively charged surfaces interact well with negatively charged lipid-based cell membranes, which also increases the likelihood of absorption (Zhang

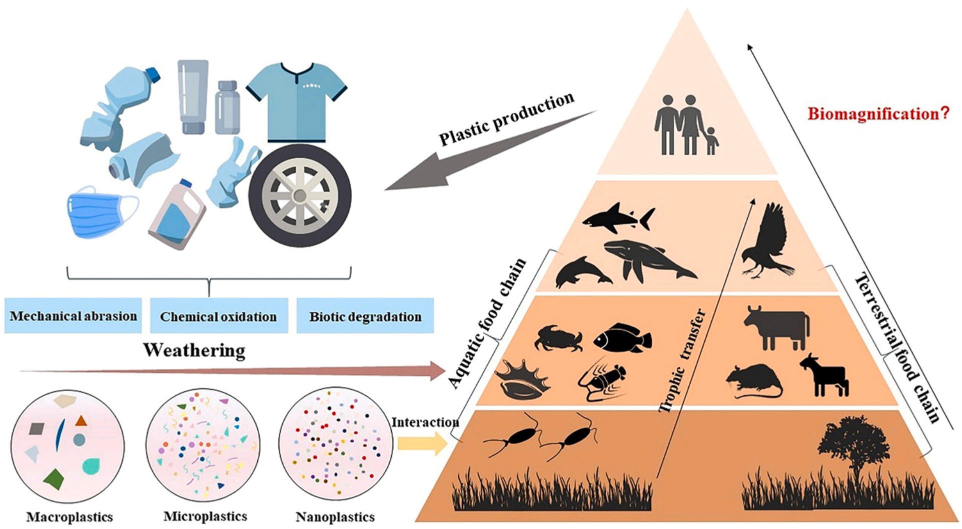

Fig. 7. Schematic diagram of the fragmentation and erosion of plastics into microplastics and nanoplastics and their biological interactions with the food chain.

et al., 2019). Briefly, the bioaccumulation potential of MPs/NPs in organisms generally correlates with particle characteristics and the organism's strategy for xenobiotic removal. With smaller particles easily crossing biological barriers for distribution and accumulation in tissues and organs. Various species have unique excretion modes, for example, crustaceans with gastric grinders that filter small particles into the digestive diverticulum or expel larger particles by regurgitation, bivalves that can adopt pseudo-feces to expel unavailable particles directly, higher organisms with developed digestive systems that have more complex clearance mechanisms.

However, some in situ habitat-based surveys presented low or no bioaccumulation relative to laboratory-specific and controlled conditions (Dawson et al., 2018a; Garcia et al., 2021). Because many species or individuals within species with low or even zero loads, bioaccumulation of MPs didn't support environmental concentrations in the corresponding habitats. More importantly, the procedural approach to quantifying environmental bio-plastic contamination also affects our assessment of bioaccumulation, especially for NPs, which currently still pose a major methodological gap for the detection, identification and quantification of NPs in the environment.

3.3.2. *Are microplastics and nanoplastics biomagnifying along the food chain?*

Biomagnification is usually defined as an increase in the concentration of pollutants along the food chain from low to high trophic levels (Bour et al., 2015). Only when bioaccumulation of contaminants and trophic transfer across the food web from prey to predator occurs can biomagnification be possible. Presently, the biomagnification potential of MPs/NPs in food webs is not well established. Mainstream views that MPs/NPs may not biomagnification along the food chain have been confirmed in certain experiments. No biomagnification occurred in the trophic transfer from filter-feeder mussels to predator marine crabs, with lower concentrations of MPs in crabs than in mussels, whose experimental results were explained by the authors as being due to excretion from the crab's digestive organs to reduce the body load (Wang et al., 2021c). Similar results were confirmed in another report where He constructed simple aquatic ecosystems in the laboratory and examined and tracked trophic transfer behavior in biota with palladium-doped NPs, which were highly bioaccumulation in the biota but didn't manifest trophic amplification, probably due to trophic dilution of NPs during food chain transfer (He et al., 2022).

To be precise, for MPs/NPs to biomagnify, they must first be dispersed and accumulated in biological tissues, as is the case with hazardous metals and their compounds (Wu et al., 2020). Although reports claim that MPs/NPs were able to translocate from gastrointestinal tract to blood, brain and muscle, the majority of these reported accumulated plastics remained in the digestive organs and were effectively depurated shortly (Dawson et al., 2018a). We observed that the limited studies were exclusively on single species or simple food chain trophic transfers, trophic dilution would be particularly important as grazing fluxes at lower trophic levels have difficulty accumulating more plastic particles on their own than their prey. However, whether this trophic dilution becomes intense with increasing trophic position in a continuous complex food web remains unknown. Especially for larger species, larger body size leads to lower food assimilation rates inducing more predation. Simultaneously the long lifespan of top predators results in a much higher load of MPs than other trophic niches. The contribution of transfer efficiency through food chains to higher trophic levels remains problematic to assess, and it seems unconvincing to extrapolate biomagnification of MPs/NPs only from individual trophic levels or simpler food chains. Future research should urgently collect evidence on the uptake, retention and depuration rates of plastic particles by macrofauna to examine the biomagnification potential in more complex food web relationships. In addition, there exists significant disparities in bioaccumulation and biomagnification of MPs/NPs between aquatic and terrestrial ecosystems. The extensive partitioning of MPs/NPs may play an important role in the contribution of aquatic organisms, whereas terrestrial animals for the uptake process of MPs/NPs is a predatory relationship, with biomagnification due to this trophic transfer possibly being more significant.

3.3.3. *Trophic transfer of microplastics and nanoplastics via prey-predator interactions*

Trophic transfer is described as the movement of pollutants towards upstream ecological layers as a result of predation on prey by predators, has been widely acknowledged and as the topical issue of interest in ecotoxicology. Current laboratory and some in situ investigations have demonstrated that MPs/NPs can undergo trophic transfer via the food chain (Table S3). Most studies employed direct stepwise feeding strategies to demonstrate the biotransfer of plastic particles, early experiments showed that mysid shrimps can achieve trophic transfer by feeding on microsphere-marked zooplankton (Setala et al., 2014). In another experiment mussels exposed on 0.5 μm polystyrene microspheres fed to crabs showed a significant increase of microspheres in the digestive and reproductive organs of the crabs after 24 h, indicating that trophic transfer was taking place (Farrell and Nelson, 2013). Even in relatively complex food chains with multiple trophic levels this trophic transfer may continue, Chae et al. constructed four trophic levels of aquatic food chains to assess the fate of fluorescent nanoplastics in the food chain, revealing that NPs can adhere to the surface of primary species and readily pass along the food chain, ultimately present in the digestive organs of all consumers (Chae et al., 2018). While a few site experiments also determined plastic movement in the food web by comparing correlations of particle characteristics at each ecological niche. Scat of pinniped seals and their primary food, Atlantic mackerel, were highly correlated in terms of MPs characteristics, namely similar color and polymer type. This suggests that MPs can be transferred from fish to higher predators at trophic levels (Nelms et al., 2018). Similar analysis was observed in freshwater ecosystem food chains, where the abundance of microplastics in species (sandworm, mollusks, crustaceans and fish) was positively correlated with their respective trophic levels (Wang et al., 2021a). Overall, they all demonstrate trophic transfer, but mostly studies are restricted to quantifying the loads of particles within organisms, with large gaps in knowledge remaining about how plastics move through food chains and how trophic interactions regulate the fate of plastics between predators and prey.

Bioaccumulation in prey and the depuration capacity and rate of predators regulate the process of plastic trophic transfer (Huang et al., 2021b). When organisms take in more than they excrete, they accumulate plastic. However, most plastics reportedly remain in the gastrointestinal tract, with a few nanoparticles crossing the gastrointestinal barrier and dispersing to other tissues (Clark et al., 2022; Wootton et al., 2021). Residence time of plastic particles in the digestive organs vary according to species, with secondary consumers such as plankton retaining particles relatively long, while top predators may excrete most of their plastics rapidly due to the demands of allometric growth (Cole et al., 2013; Watts et al., 2014; Zantis et al., 2022). In addition, animals with complex tissues are more likely to accumulate plastic than undifferentiated animals (Provencher et al., 2019). Certainly, each species has unique decontamination strategies to eliminate intestinal debris that can help restore exposed organisms and reduce the risk of contaminants (Ribeiro et al., 2019). Once plastics are integrated into the organism and passed towards higher trophic levels, whether trophic transfer is sustained will depend on the rate of depuration at the next trophic level (Au et al., 2017; Carbery et al., 2018). rapid depuration rates that reduce plastic trophic transfer may also decrease the possibility of plastic particles translocating from the gastrointestinal tract to other tissues and organs (Elizalde-Velazquez et al., 2020). Current studies on the kinetics of particle depuration in organisms are mainly focused on lower trophic levels such as bivalve and crustacean species, whereas the paucity of data on higher animals makes it difficult to assess the trophic transfer of plastics to the top of the food chain.

4. Conclusions and perspectives

4.1. Conclusions

In summary, the transport processes and drivers of MPs in abiotic compartments are spatially and temporally heterogeneous. In contrast to terrestrial ecosystems, fluid media in atmospheric and aquatic ecosystems accelerate the mobility of MPs, with sustained ocean currents and atmospheric circulation readily driving the long-distance transport of these small-scale, highly mobile polymers, while MPs in soils are transported along horizontal and vertical directions by synergistic physical, chemical and biological processes. Plastic particles in the macroscopic compartment pose an unavoidable exposure risk to biota due to their long-range transport, ubiquity and persistence. These particles can be uptake by multiple species at different trophic levels through direct or indirect routes. Most particles are ingested by organisms and retained in the gastrointestinal tract and excreted with feces. The bioaccumulation potential of NPs may be higher than MPs because NPs more readily penetrate biological barriers to disperse and accumulate in other tissues via active endocytosis and passive diffusion. MPs/NPs may be difficult to biomagnify like other pollutants due to nutrient dilution in the food chain. Although MPs/NPs have been demonstrated to occur trophic transfer in simple food chains under controlled laboratory conditions, the lack of valid evidence of indirect ingestion prevents any real proof that trophic transfer is retained in nature, the ability of organisms to purify particles also simultaneously affects their trophic transfer in the food chain.

4.2. Prospects and challenges

Despite the growing number of studies currently reported on the transport of MPs/NPs in abiotic and biotic compartments, many issues remain to be pondered and addressed.

(1) Currently, most studies focus on the transport of MPs in individual compartments, ignoring the fact that the biosphere as a whole. Ocean-land-atmosphere interactions have accelerated the transport of MPs over distances that allow for regional or global transport, yet there is still a great deal of ambiguity about the transport fluxes and source-sink dynamics among compartments. Future research should develop global conceptual transport models and combine high-resolution spatial and temporal transport data to describe the planetary plastic cycle.

(2) The environmental behaviors of MPs/NPs in ecological compartments are critical to understanding their transport and fate. For example, MPs/NPs can occur heterogeneous aggregation in both water and soil environments to influence their transport processes, however, most studies were based on using highly homogeneous particles under controlled laboratory conditions to study their environmental behaviors, which is not fully representative of heterogeneous particles in actual environments. In addition, the aerodynamic behavior of MPs as emerging air pollutants is not well understood and it is unknown whether they can interact with aerosol particles to achieve similar behavior. Whether ageing affects the mobility and stability of plastic particles also needs to be investigated in depth.

(3) In addition to focusing on the macroscopic transport of plastics, we should also turn our attention to the dynamics of small plastic particles at the microscopic level. Many macroscopic measurements of plastics often rely on understanding from the microscopic level, especially at the interface scale, for example air-water and sediment-water interfaces. The movement of plastic particles at the interface is determined by a variety of microscopic forces. This microscopic movement of plastics, triggered by geochemical forces, needs to be considered by the scientific community.

(4) Although the accumulation of plastics in biota is well established and marine organisms were given considerable attention, terrestrial and freshwater species are currently not well studied. Most reports are limited to quantifying which species ingest MPs, and lack deeper thinking on why they ingest. Future research on plastic ingestion should be explored from an ecological perspective, such as whether migration and breeding of species affects ingestion rates, whether animals learn empirically to avoid excessive plastic ingestion. The foraging behavior of different species in response to plastic also needs to be represented at multiple levels of species.

(5) Although some reports have discovered the presence of MPs/NPs in non-digestive tissues and speculate that they may originate from digestive system transfer, there is no understanding of the accumulation patterns and translocation mechanisms of MPs/NPs within organisms. Meanwhile, the mechanism and rate of purification of exogenous particles by organisms is not grasped. The current thorny problem is the lack of effective analytical methods to identify these plastic particles within organisms, and

more accurate and practical procedural methods need to be developed.

(6) Trophic transfer of MPs/NPs in simple aquatic food chains may be occurring, but trophic transfer based on in situ surveys of food chains needs to be further validated, and transfer effects in terrestrial food chains need to be investigated. In addition, the transport and fate of biologically ingested plastics in the food chain needs to be considered.

(7) We also should reflect about the potential impact of factors on the transport of MPs/NPs under global climate change, such as hydrological phenomena due to changes in river flows, extreme storm occurrences, changes in biota structure and function (microbiology, foraging strategies and food webs).

5. Environmental implication

This review discusses the movement of plastics on Earth from both abiotic and biotic perspectives in order to gain a deeper understanding of the overall paradigm of the "plastics cycle".

This paper analyses the processes and drivers of microplastic transport within macroscopic compartments. We focused on summarizing the uptake pathways of microplastics and nanoplastics by different biota in the ecological compartments. Then, we analyze the different mechanisms of cellular internalization of nanoplastics in organisms. Finally, we assess the bioaccumulation potential and biomagnification effects of microplastics and nanoplastics, highlighting evidence of trophic transfer of microplastics and nanoplastics along the food chains.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2022.129515.

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