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Review

Microplastics and nanoplastics in the environment: Macroscopic transport and effects on creatures

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ABSTRACT

Industrial progress has brought us an important polymer material, i.e. plastic. Because of mass production and use, and improper management and disposal, plastic pollution has become one of the most pivotal environmental issues in the world today. However, the current researches on microplastics/nanoplastics are mainly focused on individual aquatic, terrestrial and atmospheric environments, ignoring the fact that the natural environment is a whole. In this regard, the transport of microplastics/nanoplastics among the three environment compartments, including reciprocal contributions and inherent connections, and the impact of microplastics/nanoplastics on organisms living in multiple environments are research problems that we pay special attention to. Furthermore, this paper comprehensively reviews the transport and distribution of microplastics/nanoplastics in individual compartments and the toxicity of organisms, either alone or in combination with other pollutants. The properties of microplastics/nanoplastics, environment condition and the growth habit of organisms are critical to the transport, distribution and toxicity of microplastics/nanoplastics. These knowledge gaps need to be addressed urgently to improve cognition of the degree of plastic pollution and enhance our ability to deal with pollution. Meanwhile, it is hoped that the paper can provide a relatively complete theoretical knowledge system and multiple "leads" for future innovative ideas in this field.

1. Introduction

The invention of plastic has opened a new era, which has brought great convenience to our production and life due to its stable chemical properties, good insulation, light weight and durability characteristics (Gu et al., 2020). According to statistics, the global production of plastics is close to 360 million tons (Mt) in 2018 (Fig. 1A), and output is expected to double in the next 20 years. But, only 6–26% of these plastics are recycled, which means that up to 94% of the plastics probably be landfilled or enter the environment through various routes (Alimi et al., 2018; Nizzetto et al., 2016; Barnes et al., 2009). In this regard, the ocean may be an immense reservoir for plastics. PlasticsEurope estimates that 6–12 Mt of plastic enters the ocean every year, then there will be over 250 Mt of plastic accumulated in the ocean by 2025 (Wright and Kelly, 2017; Jambeck et al. 2015).

The most critical point is that the natural degradation of plastics is extremely slow. After physical, chemical and (or) biological action, large pieces of plastic will be broken into microplastics (MPs) (1 μm–5 mm) or nanoplastics (NPs) (<1000 nm) (Jahnke et al. 2017). In recent decades, as a new type of pollutant, MPs have attracted widespread attention in the academic world. Researchers have discovered the presence of MPs around the world, for example, 4601–5732 m of deep sea sediments in the western Pacific (240 items per kg dry weight of sediment) (Zhang et al., 2020a), and coral reefs in the Xisha Islands of the South China Sea (0.2–45.2 items/L) (Ding et al., 2019), even the snow in the mountains (Materić et al., 2020) and the north and south poles (Tekman et al., 2020; Peeken et al., 2018; Dawson et al., 2018) have been contaminated with different degrees of MPs/NPs. From the production and post-use phase of plastics, MPs/NPs are released into the environment at every stage. How many MPs/NPs are in the actual environment? How are MPs/NPs transported in the environment and what are their exchange volume? Although there are related reports (Kawecki and Nowack, 2019; Mai et al., 2019), small-scale simulation experiments do not fully reflect environmental conditions owing to the diversity of nature (type,

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shape, density, etc.) of MPs/NPs, the complexity of the environment and other factors, small-scale simulation experiments do not fully reflect environmental conditions, therefore these are still knotty problems.

Furthermore, some related researches on the impact of MPs/NPs on aquatic organisms are developing rapidly (Dauvergne, 2018; Avio et al., 2017; Koelmans et al., 2017; Eerkes-Medrano et al., 2015; Koelmans et al., 2014; Auta et al., 2017), and the interest in soil and atmospheric organisms is also increasing (Duis and Coors, 2016; Qi et al., 2018; Guo et al., 2020a; Roman et al., 2019). These researches, which mostly focus on species that are common in a certain environment (like fish, invertebrates, bivalves), have reported a wide variety of neutral and deleterious effects in various species. In general, MPs/NPs will limit the growth and development of organisms, increase mortality, disrupt endocrine metabolism, and even change gene expression, whereas like some filter-feeding animals, even if they digest a lot of MPs/NPs, which will not affect their survival (Huuskonen et al., 2020; Kalčíková et al., 2020; Bringer et al., 2020; Mohsen et al., 2020; Pedersen et al., 2020; Nanninga et al., 2020; Sökmen et al., 2020; Elizalde-Velázquez et al., 2020). Thus, the toxicity studies of MPs/NPs are still in the immature stage, scholars are not clear about the reasons for this difference, also face many technical challenges. So far, there is no uniform standard method for sampling, detection and risk assessment of MPs/NPs in

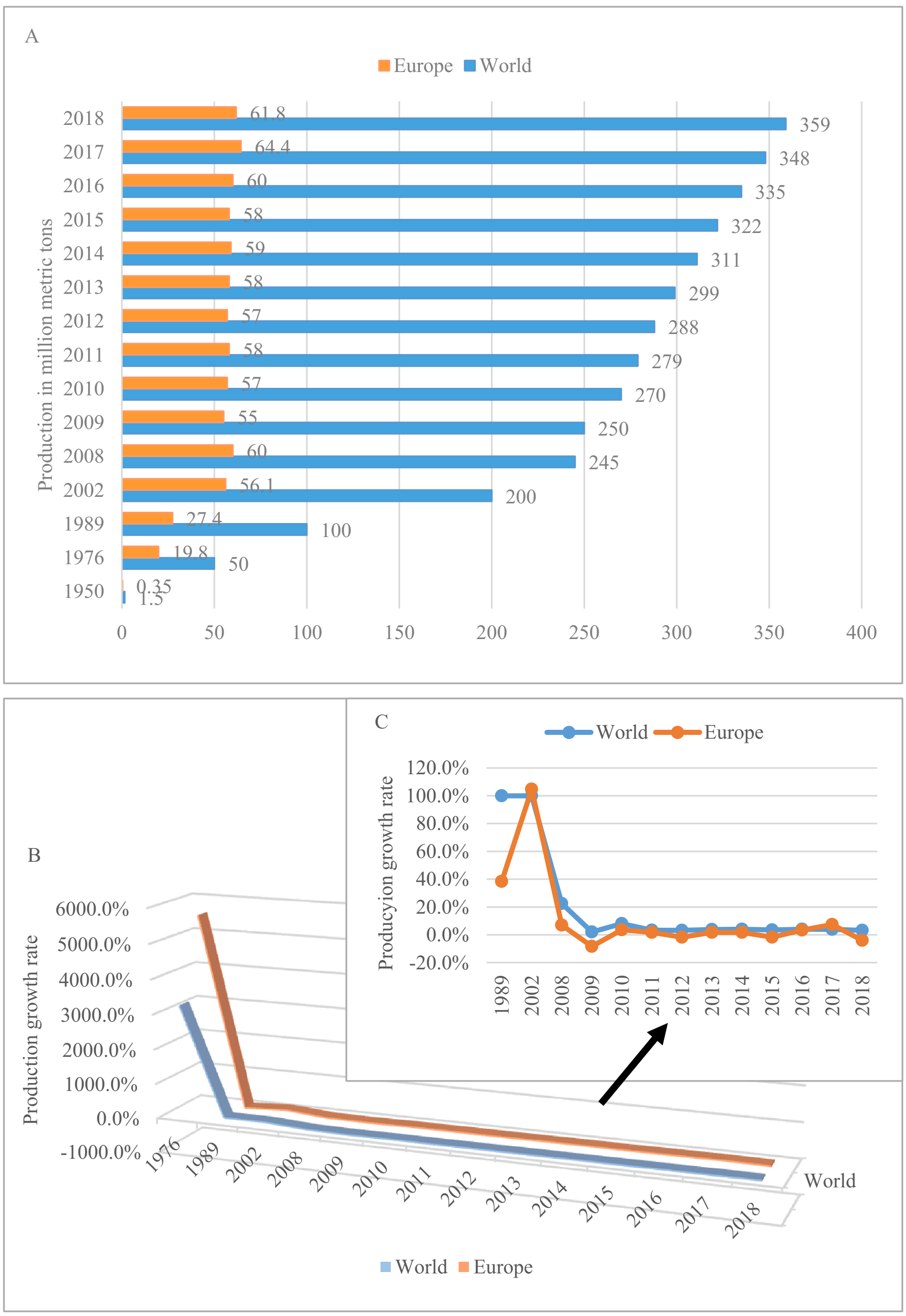

Fig. 1. (a) Plastics production in the world and Europe, including thermoplastics, thermosets, polyurethanes, elastomers, adhesives, coatings and sealants and polypropylene, but not polyethylene terephthalate, polyamide and polyacrylic acid. (b and c) Plastics production growth rate worldwide and in Europe.
Date comes from Lehner et al. (2019) and PlasticsEurope.

various countries, which makes it impossible to compare the research results and only give a general guess. It is unclear how much impact the entire ecological environment has (Rillig and Lehmann, 2020).

Herein, we summarize the existing research on the transport and toxicology of MPs/NPs in aquatic, terrestrial, and atmospheric environments. Through this review, we emphasize: 1) the mutual transfer and circulation of MPs/NPs in aquatic, terrestrial and atmospheric environment; 2) the interaction between MPs/NPs and biology, MPs/NPs and environment, biology and environment, which will ultimately impress the ecotoxicology of MPs/NPs; 3) the deficiencies of current research and knowledge framework. This review summarizes the research results of MPs/NPs from the entire biosphere, which not only provides a more complete and updated knowledge system for scientists in this field, but also provides a solid foundation for future research directions.

2. Kingdom of plastics: plastics are ubiquitous

2.1. The import way of plastics to environment

In general, plastics can be divided into two categories: Primary plastics, which are directly produced to this size range, such as MPs/NPs in personal care products or facial cleansers (Rochman et al., 2015; Hernandez et al., 2017); Secondary plastics, which are produced by the crushing of larger plastics or other productions, such as agricultural plastic mulch or car tires (Huang et al., 2020a; Capolupo et al., 2020). Plastics in the aquatic environment generally come from land sources, municipal drainage networks, fisheries, shipbuilding, and tourism (Mattsson et al., 2015; Kelly et al., 2019; Murphy et al., 2016; Yin et al., 2020; Jiang et al., 2019a; Wen et al., 2018). In terrestrial environment, plastics mainly come from agricultural plastic film covering, application of compost and excess sludge, irrigation of wastewater and car tires debris (Li et al., 2020a; Kolomijeca et al., 2020). While in the atmosphere, they are mainly derived from synthetic fibers (such as clothing, soft carpets and curtains) or coating material (Fig. 2) (Huang et al., 2020b).

Notably, there is a process of cyclic exchange of plastics among the three major environments. For example, plastics in the terrestrial environment is washed by surface runoff, followed by flowing into the ocean along the streams and rivers. Although the removal rate of MPs/NPs in wastewater treatment plants is more than 90%, a large amount of MPs/NPs are still left, and the application of irrigation and sludge has introduced plastics in water into the terrestrial environment (Sun et al., 2019; Raju et al., 2020; Edo et al., 2020; Gong et al., 2018; Huang et al., 2020c; Li et al. 2020b). In addition, due to weather such as rainfall, snowfall and wind, the plastic in the atmosphere will settle to the aquatic and terrestrial environment, or those on land and water surfaces will resuspend in the air (Liu et al., 2019b; Dris et al., 2015; Rezaei et al., 2019; Allen et al., 2019). At present, research on MPs/NPs is still focused on separate aquatic, terrestrial, and atmospheric environments. The future research on the exchange process of plastics in different environments should be embodied instead of just staying on the simple transport routes, (Zhang et al., 2020b; Wright et al., 2020), which helps us to better cognize the circulation of plastics and pollution control in the environment.

2.2. From macroplastics to micro/nanoplastics?

After entering the environment, plastics may degrade to microplastics or even nanoplastics under external pressure, which will change the original characteristics, structure and reactivity of the plastic (Alimi et al., 2018), making the research more complex and diverse. Plastics can be degraded through various processes, such as hydrolysis, oxidation, photodegradation, mechanical corrosion and biological degradation (Alimi et al., 2018; Guo et al., 2020b). The photodegradation induced by ultraviolet light exposure will form more O–functional groups (C–O, C–OH and CO) on the plastic surface, which makes the plastics brittle and increases the possibility of mechanical degradation (Mattsson et al., 2015; Ding et al. 2020). Recently, Zhu et al. (2020) explored the photodegradation mechanism of microplastics and found that a lot of reactive oxygen species (ROS) are generated after light irradiation, including $O_2\bullet-$, $^1O_2$, H_2O_2 and $\bullet OH$ (Fig. 3). These ROS quenchers can significantly inhibit photoaging effects. Besides, the microplastics will be broken into smaller particles by the stomach and

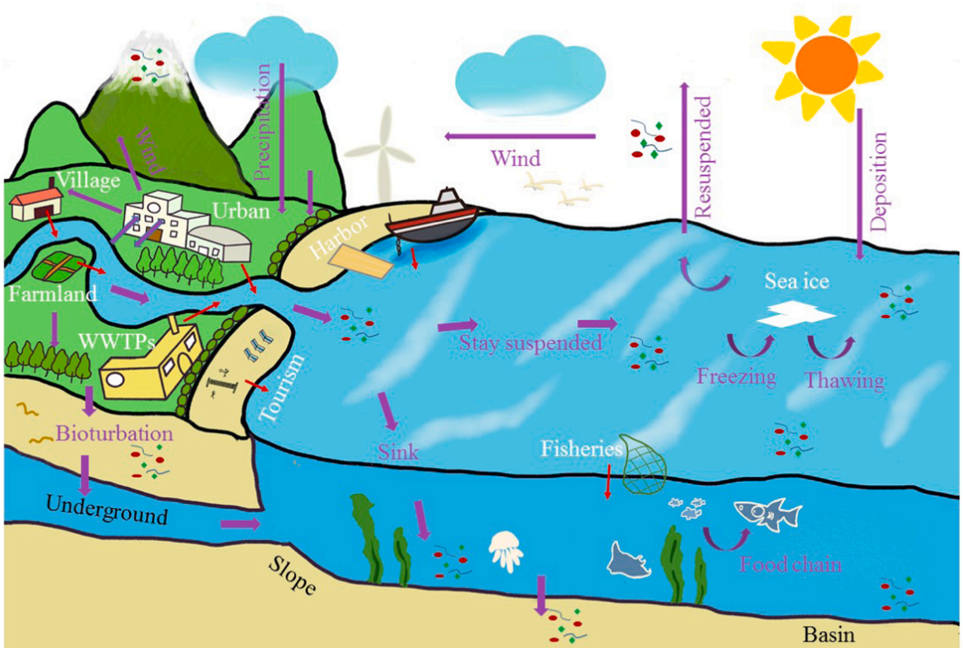

Fig. 2. The source and transport of microplastics/nanoplastics. The red arrow represents the source and the purple arrow represents the transport path. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Partly inspired by Liu et al. (2019d).

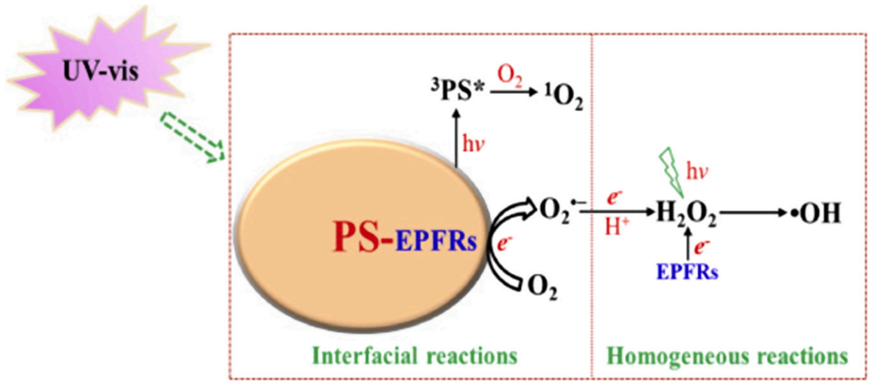

Fig. 3. Possible mechanism of formation of ROS in PS-MP suspension under ultraviolet light.
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intestines after being ingested by animals, and finally reintroduced into the environment through defecation (Cau et al., 2020).

Some studies revealed that light, heat, or bacteria can degrade plastics (Shosuke et al., 2016; Kim et al., 2020; Bandyopadhyay and Basak, 2007; Mehta et al., 1995). Twenty-five years ago, Mehta et al. (1995) found that foamed polystyrene melt at 160 °C and began to vaporize when temperature over 275 °C in the expendable pattern casting process, until 460–500 °C, foamed polystyrene (PS) could be completely volatilized. Bandyopadhyay et al. used zinc oxide (ZnO) as an UV absorber to provide energy of degrading bonds of PS and ultimately reached a maximum degradation rate of 18%. In 2016, Shosuke et al. (2016) successfully isolated a strain, *Ideonella sakaiesis* 201-F6, which could produce two enzymes to hydrolyze polyethylene terephthalate (PET) and the reaction intermediate, scilicet, mono (2-hydroxyethyl) terephthalic acid. However, these degradation conditions are limited to the laboratory scale; and most plastics are not effectively recycled, but are released into nature and form substantial MPs/NPs. Plus these plastic particles cannot fully receive sunlight or encounter bacteria that can degrade them in the actual environment. Therefore, degrading plastics is a more ideal situation, individuals believe that strictly controlled use of plastics is very critical and effective, which can also slow down the amount of MPs/NPs from the source.

Moreover, the current detection method cannot meet the qualitative and quantitative requirements of MPs/NPs in complex natural matrix. For example, when extracting MPs/NPs from samples, we need to digest organic matrix, but the commonly used alkaline, acid and H_2O_2 treatment will destroy the original properties of the plastic or influence the fluorescence signal of plastics (Schwaferts et al., 2019). And the smallest particle size that can be detected by Fourier Transform Infrared Spectrometer and Raman Spectrometer is 10 μm and 1 μm, respectively (Schwaferts et al., 2019). Perhaps, the faultiness makes us underestimate the quantity and potential impact of plastics in the environment. Consequently, under the background that the current technological research methods have not yet made major breakthroughs, the degradation of plastics is difficult to achieve. Can we establish a corresponding fragmentation model by exploring how macroplastics become MPs/NPs, including different types and shapes of plastics and under different external forces, to estimate the amount of MPs/NPs in the environment?

3. How plastics are transported in the environment

3.1. Aquatic environment

Human survival and activities are inseparable from water, the aquatic environment may be the largest reservoir of MPs/NPs. With water flow, MPs/NPs can be carried anywhere the water flows. The transport of MPs/NPs in the aquatic environment has been widely concerned. This process is not only related to the characteristics of the MPs/NPs themselves, but also depends on the physical and chemical properties of the aquatic environment, as well as hydrodynamics, attachment and uptake of aquatic organisms, which will directly affect the settlement, re-suspension and transportation distance of plastic particles, and ultimately affect their environmental fate.

Most MPs/NPs from land sources are discharged directly into rivers and lakes with the effluent from wastewater treatment plants or through surface runoff. Generally, small and light plastic particles are suspended on the upper water surface, while large and heavy plastic particles are deposited at the bottom of the water. However, there are a lot of natural inorganic/organic particles and microorganisms in the natural environment, which will aggregate (heterogeneous aggregation) with MPs/NPs (Dahms et al., 2020) or gather together of plastic particles themselves (homogeneous aggregation), and change the original density of plastics, then affecting the settlement and residence time of plastic particles. Hoellein et al. (2019) studied the deposition rate of three common microplastics (polypropylene pellets, polystyrene fragments, and acrylic fibers) in the stream. The experiment found that the deposition rate followed the general law of density and biofilm 'stickiness'. The deposition rate of debris was the highest, followed by fiber, and the smallest was globular. Moreover, biofilm colonization also increased deposition rate. Therefore, we speculate that the fibrous and spherical MPs/NPs will be further taken away by the river, posing a threat to a wider environment. In addition, some scholars have noticed that stream characteristics (water depth, flow and obstructions in rivers such as large weirs) can influence the migration of microplastics in the freshwater environment (Dahms et al., 2020), but compared with the marine, there are few studies on freshwater environment and most of them have not paid attention to the intrinsic relationship between hydrological characteristics of rivers and transport of MPs/NPs.

The deposited MPs/NPs will be temporarily or permanently stored in the sediment, while the suspended plastic will continue to flow to the ocean. When the river reaches the estuary, on the one hand, due to the sudden increase in the cross section of the estuary, the water flow speed drops swiftly. On the other hand, the continuous influx of tidal will hinder the river water. The seawater dissolves many strong ionizing sodium chloride, which generates lots of ions. The above three reasons will cause a large amount of sediment to form a delta, at the same time, some MPs/NPs are also trapped in the sediment and deposited here. For the special transition area of river-estuary, the estuary contains a high concentration of microplastics, but the concentration of microplastics in river sediments is much higher than that in estuaries. The characteristics of microplastics in estuaries and rivers show a similar trend, mainly based on the shape of thin films and fragments (Xu et al., 2020). This means that rivers may be more seriously polluted by MPs/NPs than oceans. Moreover, under the tidal currents caused by buoyancy, wind, and tides, the upper of the estuary is affected by the largest turbidity current, which contains a higher abundance of buoyant microplastic particles, and it will form MPs hot spots in certain areas of the estuary (Cohen et al., 2019). Of course, plastic waste generated by human activities (such as ports, fisheries, and tourism) is also directly discharged into coastal waters (Jang et al. 2020).

However, the sediment near the coast is not stable, depending on the relief of the margin. The steep, tectonically active margins have narrow continental shelf and steep continental slope, its onshore storage space is small, thus shortening the residence time of sediment and microplastics (Romans et al., 2016; Kane and Clare, 2019). On the contrary, mature and passive margins have wider continental shelf and gentler continental slope, forming a longer and relatively lower relief catchment (Kane and Clare, 2019). At this margin, sediments may be affected by the vigor of along-shelf currents and other oceanographic perturbations, MPs/NPs will move and redistribute along the continental shelf (Wright et al., 2001; Mulder et al., 2012). As the energy of currents gradually weakens, the transport of sediments also stops slowly, and MPs/NPs retain a good layered distribution according to their own properties (Kane and Clare, 2019; Aller and Blair, 2006). Moreover, the longer residence time also promotes the fragmentation and degradation of large pieces of plastic, which poses a greater threat to the living organisms in the area. The above two marginal topography is likely to meet the canyon head. The difference is that the former dense sediment-laden water will pour down, triggering turbid currents (Hizzett et al., 2018) and bringing considerable MPs/NPs with different shapes and types directly into deep-marine realm, however, fibers may be trapped between settling sand-grains and finally buried in the deposits during transportation as a result of slender form (Pohl et al., 2020); while the latter has been slowly deposited, mainly lighter plastic particles and microplastic fibers enter the deep sea (Kane and Clare, 2019) (Fig. 4).

After entering the deep sea, gravity will guide the MPs/NPs to continue to sink into deeper marine realm, but all sorts of currents further complicate the transportation and distribution of plastics. Bottom currents can easily provide the shear force to transport MPs/NPs in surface sediments, which can isolate plastics in drift deposits and move with currents (McCave et al., 2017; Miramontes et al., 2019). In general, there is strong biological disturbance in drift deposits, forcing the plastic to transfer to deeper sediments. Contrary to bottom currents, thermohaline stratification and internal tides will inhibit the settlement of plastics, and resuspend the plastics in the ocean, which may then be carried to other areas (Kane and Clare, 2019). Meanwhile, the ingestion and defecation of the organism also strengthen the resuspension. The plastic floating on the surface of the ocean will be affected by Ekman and geostrophic currents and surface Stokes drift, forming MPs/NPs accumulation areas in some regions, which probably further increase the ecological risk of the region (Onink et al., 2019).

In the Polar Regions, there is another important transport mean that is rarely mentioned, and that is sea ice. During the growth of sea ice, it uses a vertical pattern to mark polymer composition and size classes of the microplastic particles in the drift trajectories of sea area (Peeken

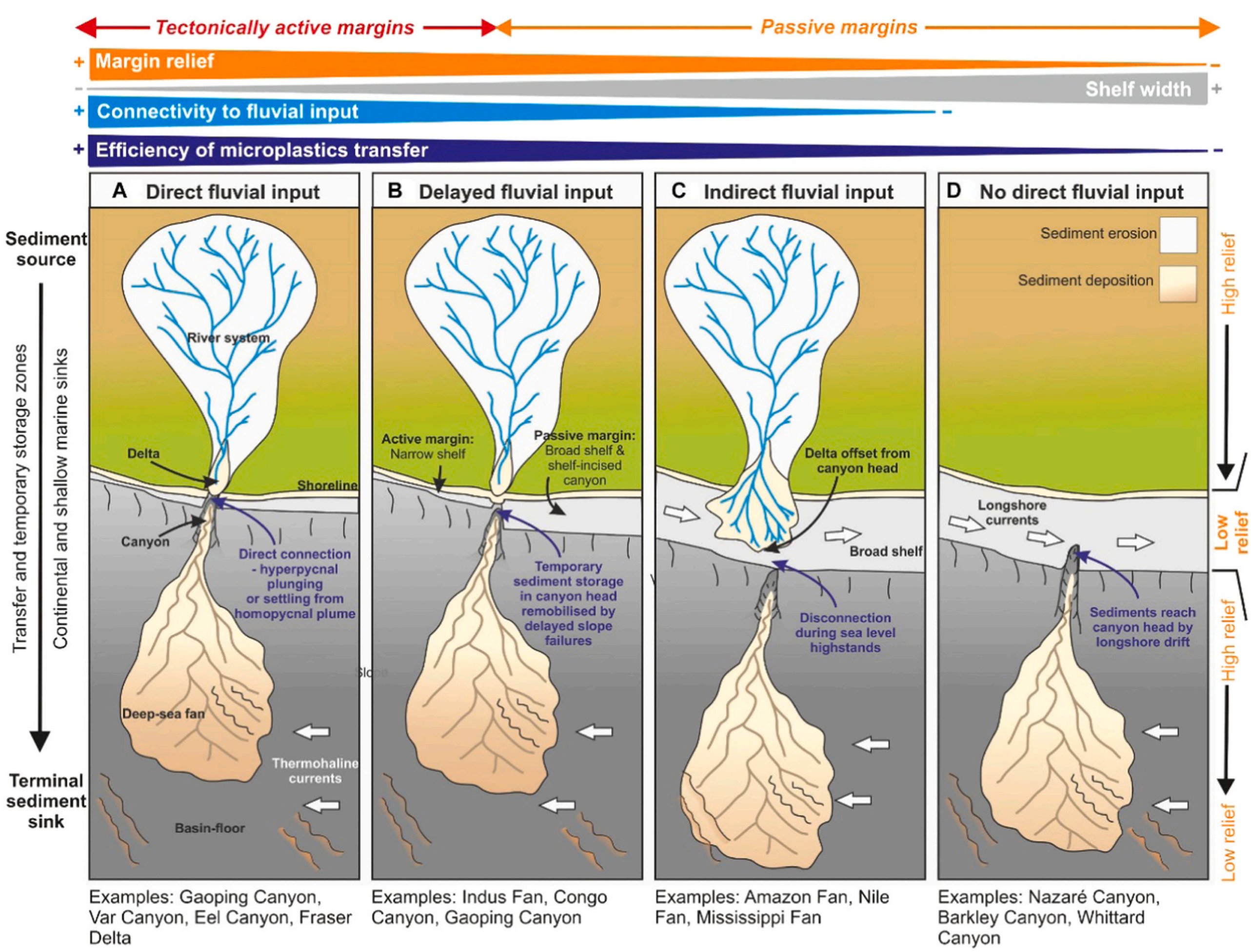

Fig. 4. The four situations in which microplastics are transferred from terrestrial to deep sea area, which mainly depends on the structure of the margin. (A) Direct fluvial input to the canyon head, (B) delayed fluvial input, because sediment is temporarily stored in the canyon head, (C) indirect fluvial input as the canyon diverge from the estuary, (D) no direct fluvial input, longshore currents bring sediment.
Reprinted with permission from Ref Kane and Clare (2019). Copyright (2019), Kane and Clare.

et al., 2018; Geilfus et al., 2019). However, the trend of global warming in recent decades has intensified the melting of sea ice, and these unquantified sinks of microplastics are re-releasing substantial microplastics into the ocean (Obbard et al., 2014; Von Friesen et al., 2020). This has to make scientists re-examine the dynamics, accumulation and potential toxicological effects of microplastic pollution (Hoffmann et al., 2020). Combined research from different regions, we have a general understanding of the transport trend of MPs/NPs (Fig. 5), but the specific distribution is still unclear. In the future, field investigations need to be strengthened, and labeled particles can be used to simulate transportation to predict the distribution of plastics in the actual environment.

3.2. Terrestrial environment

The MPs/NPs in the terrestrial environment are mainly transported by external forces, such as water flow, animals and human activities (Fig. 6). Soil, as everyone knows, is a complex ecosystem with intricate pore structures and rich biological communities, which also makes the relevant research differ from the actual natural environment. The development of modern agriculture results in the extensive use of agricultural membranes and sludge, as well as the changes in irrigation methods, leaving plenty of MPs/NPs on the soil surface. Moreover, due to the disturbance of farming, harvesting and other agronomic practices on the soil, the plastic on the surface may migrate downward or spread around. Additionally, the infiltration process of water flow such as rainfall or irrigation from top to bottom in the soil renders MPs/NPs transfer downward along the soil voids, and eventually possibly enter the groundwater (Wong et al., 2020; Panno et al., 2019). Moreover, earthworms, one of the most representative animals in the soil, have a layer of viscous body fluid on their body surface. MPs/NPs may adhere to earthworms, and the movement of the earthworms causes the spatial transport of plastics (Rillig et al., 2017a). Recently, Rong and co-workers proposed that bacterial community could slow down the transport of plastic particles, because the biofilm narrowed the path and increased the surface roughness of the medium, as well as O–H and N–H groups present on cell surfaces were highly likely to form hydrogen bond with plastic particles (He et al., 2020).

Recent research has focused on investigating the factors that affect the transport of MPs/NPs in the soil by setting up experimental devices. O'Connor et al. (2019) conducted a sand column experiment to study the infiltration process of microplastics in the soil. Polypropylene (PP) and polyethylene (PE) microplastics with different sizes and densities were used in the experiment, the results showed that the microplastics all moved downward in the range of 1.5–7.5 cm. It is considered that the vertical migration of microplastics is likely to be affected by the flushing, and the transportation distance is mainly related to the length of the path of the interconnected pore space. The dry-wet cycle of sand is also a key factor, as demonstrated by the works reported by Rillig's and Zhang's group (Rillig et al., 2017b; Zhang et al., 2019). Of course, there is still a big difference between the column experiment and the actual soil environment, but this kind of simulation experiment helps us to further understand the transport mechanism of MPs/NPs in soil. In addition, researchers also found that the presence of microplastics changed the bulk density, water holding capacity, structure and hydrodynamic of soil (de Souza Machado et al., 2018, 2019), conversely, which may convert the transport of MPs/NPs in the soil (Guo et al., 2020b). MPs/NPs affect the soil environment, and soil in turn acts on the movement of MPs/NPs. The two influence each other, and the concrete reason is that further research should be done in the future.

Besides soil properties, the characteristics of MPs/NPs (such as size, shape, and aging) concern their transport. The results of the study showed that the retention rate of nanoplastics (187 ± 22 nm) in the column was 48.5 ± 7.8%, while microplastics (about 30 μm) reached 94.4 ± 6.1%, indicating that nanoplastics were easier to transfer downwards than microplastics and might penetrate the soil layer into the groundwater system (Keller et al., 2020). O'Connor et al. (2019) also found that the smallest 21 μm PE microplastic had the deepest transfer distance. However, some authors hold the opposite view. Due to the lower energy barriers between the smaller microplastics and the surface of sand particles, the smaller size plastics (0.6, 0.4 and 0.1 μm) showed stronger inhibition on the fluidity of microplastics (Dong et al., 2018). The difference may be attributed not only to the decrease of energy barriers between microplastics and environmental media, but to the aggregation of microplastics. Homogeneous aggregation between plastics or heterogeneous aggregation between plastics and other substances (such as organic matter and soil particles) will increase the size of aggregates and influence their transport process. On the other hand, it had been reported in many papers that fibrous microplastics are more difficult to transfer than spherical or granular ones (Keller et al., 2020), because they are thin and long, which makes them easy to lose direction along the streamline, and are easily entangled with soil particles to form blocks (Li et al. 2020a). It is worth noting that the hydrophilicity of aged NP surface is improved after oxidation, which makes NP easier to move, and also enhances the combination with polar and non-polar pollutants, further increasing the contaminant-mobilizing ability of PS NPs (Liu

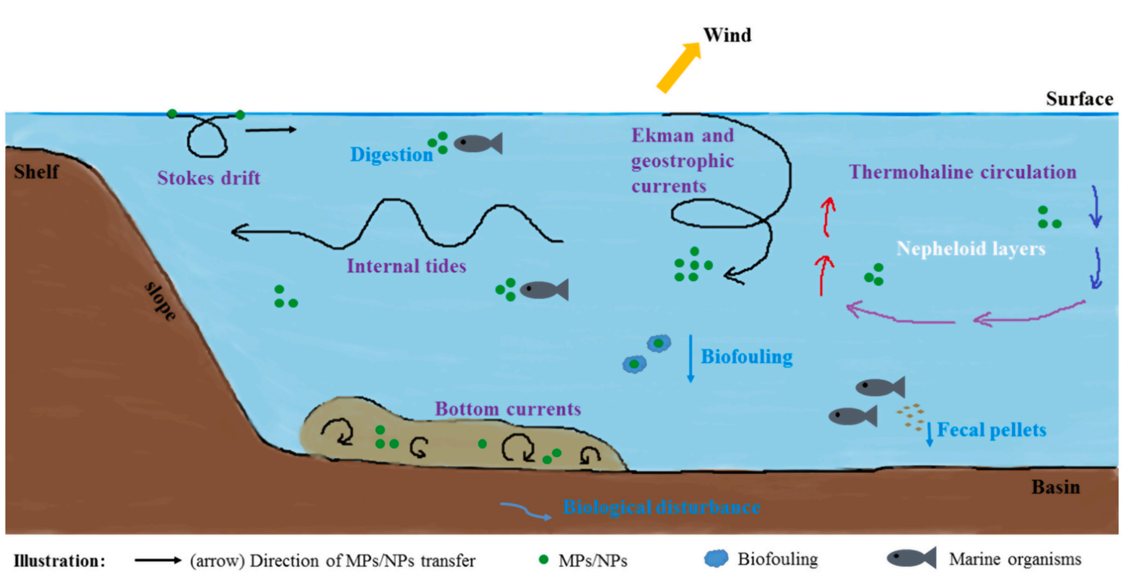

Fig. 5. The part transport routes of microplastics/nanoplastics in the marine.

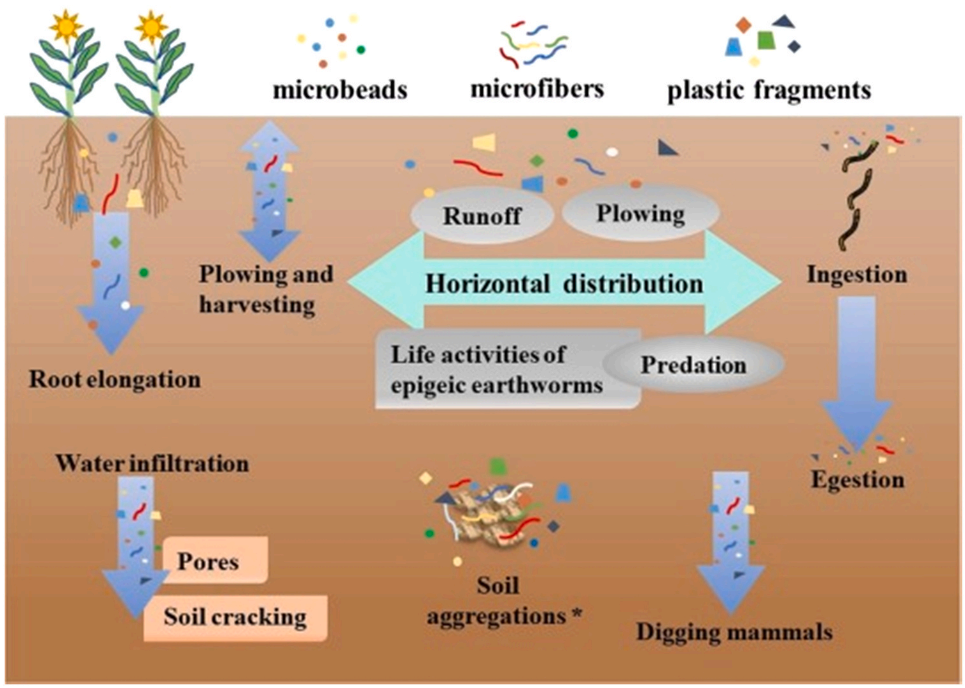

Fig. 6. The factors influencing the transport of microplastics in soil. Vertical arrows illustrate the vertical migration of microplastics. Reprinted with permission from Ref Guo et al. (2020b). Copyright (2020), Elsevier Ltd.

et al. 2019a).

So far, most of the simulated soil environment is still using glass beads and sand. However, China alone contains a variety of soil types, such as red soil, brown soil, black soil, as well as woodland and grassland and other terrestrial environments. Future research needs to study the transfer of MPs/NPs under diverse terrestrial conditions, which helps us to expand our cognition of the threat of MPs/NPs to terrestrial environment.

3.3. Atmospheric environment

The research on MPs/NPs in the atmospheric environment is roughly divided into the following three categories: suspended atmospheric microplastics (SAMPs), atmospheric fallout, dust (indoors or outdoors) (Huang et al. 2020b). For MPs/NPs in outdoor environments, their transport is mainly affected by meteorological conditions, such as wind speed, wind direction, humidity, rainfall, and snowfall (Ambrosini et al., 2019; Rezaei et al., 2019; Allen et al., 2019; Wang et al., 2020a). While MPs/NPs in indoor environments are mainly affected by human activities, human walking, the use of air conditioners, and temperature and humidity all influence their distribution (Zhang et al., 2020c; Mukai et al., 2009; Rosati et al., 2008; Huang et al., 2020d). In a recent study, the spatial and temporal trends of MPs in different indoor environments (dormitory, office, and corridor) were verified (Zhang et al., 2020c). In addition, the airflow caused by window ventilation can also cause the exchange of indoor and outdoor microplastics (Zhang et al., 2020b), and the abundance of indoor microplastics (1.1–59.4 MPs/m^3) is much higher than that of outdoor (0.3–1.5 MPs/m^3) (Dris et al., 2017). Liu et al. (2019b) collected SAMPs over Shanghai city and found that the wind direction had a significant effect on their distribution, and relatively high humidity would also lead to their settlement. Liu et al. (2019c) collected indoor and outdoor dust in 39 major cities in China, it seems that rainfall affected PET MPs (polyethylene terephthalate) concentrations in outdoor dust, but had little effect on PC MPs (polycarbonate). The author did not explore the reason carefully, probably because fiber MP abundance has a significant relationship with PET concentration, and the rainfall promotes the flux of atmospheric fallout, resulting in the wet deposition of fiber particles, including PET MPs (Liu et al., 2019c; Dris et al., 2016).

However, the factor of population density is still controversial. Studies of Liu et al. (2019c), Wright et al. (2020) and Yukioka et al. (2020) showed that it affected the distribution of microplastics, but Liu et al. (2019b) believed that there was no obvious relationship. This may be due to the nature of the microplastics. Non-fibrous microplastics are more susceptible to human activities, and fibrous suspended microplastics are more likely to be transported with the wind. This speculation is consistent with the research results (Materić et al., 2020). The authors found PET microplastics on snow pits and snow surfaces in the Austrian Alps. It should be noted that, similar to lake sediments, the accumulation of microplastics in ice cores may provide evidence of temporal variability due to the low temperatures of glaciers and the lack of human access (Zhang et al., 2020b; Turner et al. 2019).

However, the research on atmospheric microplastics is still in the prophase. Due to the inconsistency of sampling and detection methods, and the lack of data, the comparability and repeatability between studies are poor. Most scholars agree that atmospheric plastics also contribute to plastics in the aquatic and terrestrial environment, but the interlinkages, source-pathways and contribution degree among the three major environmental compartments are unclear. In the future, cooperation between countries around the world needs to be strengthened (Zhang et al., 2020b).

3.4. Transport among the three major environmental compartments

The entire natural environment is composed of aquatic, terrestrial, and atmosphere environment. The aquatic environment is one of the basic elements of the environment. It is an important place for human society to survive and develop, and also the most severely disturbed and destroyed area by human beings. On the surface of the earth, soil is an integral part of the biosphere, providing nutrients and water for terrestrial plants, which is a significant place for photosynthesis and energy exchange of plants. The atmospheric environment, not to mention, living creatures cannot live without the atmosphere for a moment. The movement of the air and the changing activities of the air pressure system cause the continuous exchange of energy and matter between the ocean and land, between the north and south, and between the ground and the upper air. Therefore, we believe that MPs/NPs not only exist in aquatic, terrestrial, and atmospheric environments, but also transport between the three environment compartments.

The occurrence, distribution, and composition of MPs within the marine atmosphere are still relatively unknown. Liu et al. (2019d) collected 89 samples of SAMPs in the Western Pacific Ocean, and divided sampling area into three regions based on the distance from the coastline, including the nearshore, pelagic, and remote region. At the same time, the hybrid single particles Lagrangian integrated trajectory (HYSPLIT) model was used to trace the source of fine particles. In general, with the increase of distance from the coast, the concentration of SAMPs gradually decreased and eventually reached the plateau. Among them, 26 samples were not contaminated by SAMPs, and 88% of these samples were from pelagic and remote areas. For the two sampling times of day and night, there was no significant difference in the data of the abundance of SAMPs in the marine atmosphere environment. The relatively low abundance of SAMPs at night might be due to the higher relative humidity on the sea surface at night, which led to the deposition of SAMPs into the ocean. The experiment also analyzed the morphological characteristics and polymer composition of the SAMPs in the samples. Regardless of the distance, day or night, most SAMPs were fibrous, and PET comprised 57% of verified microplastic particles. Thus, the temporal and spatial variability of SAMPs may be mainly controlled by the polymer density and the relative humidity of the surrounding environment. The HYSPLIT model also clearly confirmed the general emission sources and dispersion patterns of SAMPs. The SAMPs in the coastal areas came from South Korea and Northeast China. It was speculated that the SAMPs from the pelagic area might be caused by emissions from Japan, and for the southeastern part of the remote region, a potential source of SAMPs could be the adjacent Mariana Islands. Assuming that all these SAMPs are diffused from nearby continents, the authors estimated that about 1.21 tons of SAMP entered the marine ecosystem in the study area each year, and more SAMPs might enter the sea water on rainy days. This document further validates our hypothesis that through the flow of the atmosphere, MPs/NPs in the terrestrial environment will continuously transport to the aquatic environment, affecting the survival of more organisms.

Previous studies have noticed the dry and wet deposition of atmospheric MPs/NPs, so are there other paths for MPs/NPs in the atmospheric environment to transport to the terrestrial environment? Based on the high capture rate of atmospheric particulate matter by plant leaves, Bi et al. (2020) believed that the plant canopy could intercept part of airborne microplastics, which might play an important role in the fate of atmospheric microplastics (Fig. 7). For example, fibrous microplastics were more likely to be entangled with trichomes and the lipophilic surface of microplastics would enhance the affinity of microplastics with waxy cover on the surface of plants, all of which increased the possibility of plants intercepting atmospheric microplastics (Bi et al., 2020). Therefore, it was necessary to consider the throughfall, stemflow, and litterfall flux via leaf litter or leaf wash-off from rainfall event when evaluating the flux of microplastics in the atmosphere (Bi et al., 2020). In addition, the impact of microplastics on the terrestrial environment and the threat of vegetables and grains to human health needs to be reconsidered.

It can be seen from the above that atmospheric transportation may play a more significant role in the transportation of MPs/NPs between the three major environment compartments. Due to the atmospheric circulation and the small size of MPs/NPs, the atmosphere as a carrier facilitates the transportation of MPs/NPs and accelerates their circulation among each environment compartments (Fig. 2). The amount of MPs/NPs input into the environment that we estimate may not be accurate. First of all, the total production of MPs/NPs has not yet been fully counted; secondly, some release and transport pathways are still unknown. Therefore, the transport between the three major environment compartments further complicates the pollution degree of MPs/NPs to the environment. In the future, we need to stick to the transfer of MPs/NPs between different interfaces. Various countries and regions should strengthen research in this field, so as to ensure strong data support for

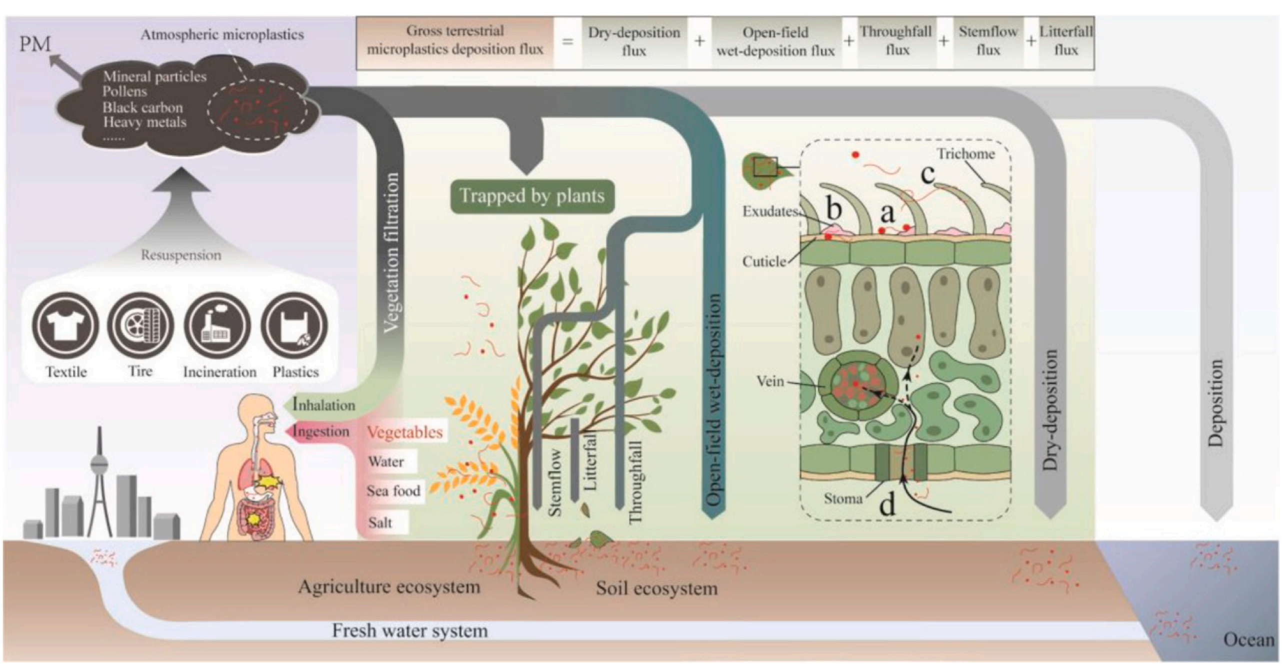

Fig. 7. Sources, transport paths, behavior and fate of atmospheric microplastics and the interaction with terrestrial green plants. Red colored dots and curves indicate atmospheric microplastics and microfibers. (a) Microplastics attached on leaf surface, (b) microplastics imbedded in leaf cuticle layer, (c) microfibers entangling with trichomes, (d) microplastics entering a leaf through stomata. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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another researches and model establishment.

4. Effects of micro/nano-plastics to living creatures

Scientists believe that the earliest living creature on the earth live in water, and approximately 71% of the earth's surface is covered by water. As the indispensable resources for human survival, water and soil also breed a great many rich lives. But as mentioned above, the environment contains a lot of microplastics or nanoplastics, which poses a huge threat to the living organisms. Since the concept of "microplastics" was first proposed in 2004 (Thompson et al., 2004), scientists have conducted tentative research on the negative impact of MPs/NPs on organisms. From the perspective of the whole organism, MPs/NPs have an impact on the growth, development and reproduction of organisms, and even causes the death of individuals. In terms of life operation, due to the small size, nanoplastics tend to trigger oxidative stress reaction of organisms, affect the production of pigments or enzyme activities, cause endocrine disorders and metabolic disorders, bring different degrees of cytotoxicity, neurotoxicity and(or) genotoxicity. Simultaneously, through the spread of food chain, these impacts are accumulated and amplified step by step from individuals to populations to communities and finally to ecosystems, which may further deteriorate the fragile environmental system (Ma et al., 2020), with the detail discussed as following.

4.1. Microplastics

The impact of microplastics on *Lemna minor*, a common floating plant in water, was studied. Kalčíková et al. (2017) specifically selected PE microbeads in cosmetics. At a concentration of PE microbeads of 0–100 mg/L, leaf growth and photosynthesis were no significantly affected, but root growth was obviously inhibited. The different performance of plant vegetative organs depends on the growth characteristics of duckweed itself. The leaves float on the water surface while the roots extend into the water to absorb nutrients, so the latter is more disturbed by the microplastics. Li et al. (2020c) chose PS plastics with different sizes (0.1, 0.55 and 5 μm) to expose green algae (*Chlorella pyrenoidosa*) to a series of concentrations of solutions. Microplastics exhibited size-dependent growth inhibition rate, but 5 μm PS MPs had little effect on *C. pyrenoidosa*'s growth. Size-dependent toxicity also existed in microalgae, smaller microplastics will significantly affected fertility and growth of algae, and at the same time, photosynthesis would also be disturbed (Chen et al., 2020).

With regard to aquatic animals, Vroom et al. (2017) studied the uptake of PS MPs by four different zooplanktons (generally living in the intertidal zone to a depth of 4 m), polystyrene beads were aged by soaking in natural local seawater for three weeks. The results showed that the ingestion of microplastics was related to the size of plastics, and there were differences between interspecies and life stages, microplastics with different shapes and surface roughness had different mechanical damage to the intestine as well. It was important that part of the microplastics ingested had been excreted with feces within 2–4 h. The same phenomenon of defecation also occurred on periwinkles (*Littorina littorea*), a gastropod living in the coastal and estuary habitats from the upper intertidal zone to about 40 m deep. Gutow et al. (2016) selected 10 μm PS microbeads, 1–100 μm PS fragments and polyacrylic fibers as the research object. The periwinkles could not distinguish between seaweed (*Fucus vesiculosus*) with adherent microplastics and clean algae without microplastics, and microplastics were also found in feces, which may promote the transfer of microplastics between different organisms or long-term deposition and accumulation in sediments. However, Pedersen et al. (2020) found that 10–45 μm high density polyethylene (HDPE) plastic beads at a concentration of 0–0.8 g/L reduced the filtering rate of quagga mussel (*Dreissena bugensis*) only at high concentrations. But the ingestion of a large amount of microplastics did not affect their oxygen consumption, reproduction and survival. These studies show that the filtering and digestion behaviors of animals are closely related to the degree of influence of microplastics on animals. If animals can reduce their ingestion of plastic particles or speed up defecation, which will effectively alleviate the toxicity of microplastics. In addition, it is distressing that microplastics are found in blubbers and skins of baleen whales that live at depths of 200–300 m and rarely approach to near coast zone (Fossi et al., 2012; Besseling et al., 2015; Fossi et al., 2017). Microplastics have been detected even in the original deep-sea sediments (Zhang et al., 2020a; Woodall et al., 2014), indicating that the impact of microplastics on the ecological environment may exceed our expectations. The water is all collected in the ocean, MPs/NPs may exist in different depths of the sea. So the research on the surface water organisms is still far from enough. This not only helps to understand the impact of MPs/NPs on the whole ecological environment with the vertical pattern, but also provides data support for the establishment of toxicity assessments in the future.

Scholars pay close attention to the risks of microplastics in the aquatic environment, but relatively little on the terrestrial environment. At present, they are mainly concentrated on the following three aspects: microorganisms, plants, and animals. Previous studies have found that microplastics can be used as a new type of carrier to enrich bacterial communities that are different from the surrounding water, the bacterial communities also include certain pathogens and antibiotic resistant genes (ARGs) (Wu et al., 2019; Zettler et al., 2013; Wang et al., 2020c). We suggest that microplastics may change the soil microbial communities during transport process, even though this research area is still blank in the soil. de Souza Machado et al. (2018) explored the effects of different microplastics (polyacrylic, polyamide, polyester and polyethylene) on soil biophysical properties. The results showed that microbial activity varied with the type and concentration of microplastics, and the microbial community probably might be altered, which may further affect the growth of plants. This is consistent with Powell and Rillig (2018) view that plant growth performance was largely dependent on the accumulation of microorganisms in the roots, including N-fixers, pathogens and mycorrhizal fungi. It follows that microplastics can indeed affect the growth of plants by affecting the microbial community structure. de Souza Machado et al. (2019) also reported that microplastics significantly changed the total biomass, root and leaf traits and tissue elemental composition of spring onion. The degree of influence was determined by the types of microplastics, and microplastics with similar shape to other natural soil particles showed a less impact.

Of course, researchers are also concerned about terrestrial animals. Several reports confirmed that microplastics could accumulate in the intestines tract of earthworms (Gaylor et al., 2013; Wang et al., 2019a, 2019b) and the growth rate was significantly reduced and the mortality rate also increased at 28, 45, 60% w/w microplastics (Huerta Lwanga et al., 2016). Then microplastics would gradually accumulate along the food chain, and eventually threaten human health. However, the concentration of microplastics used in this study is obviously higher than the actual condition, and their conclusions may not be consistent with most actual environment. Other studies have shown that exposure to lower concentrations of microplastics had basically no effect on the survival of earthworms (Hodson et al. (2017): 0.35%W/W, Rodriguez-Seijo et al. (2017): 1000 mg/kg), but microplastics also caused immune system and pathological response of earthworms (Rodriguez-Seijo et al., 2017). In addition to earthworms, recent researches have also proved the adverse effects of microplastics on other organisms. The movement of springtails (*Lobella sokamensis*) was restricted in soil contaminated with microplastics (Kim and An, 2019). This means that microplastics may block the gaps and hinder the movement of terrestrial animals. In a word, the interaction among microplastics, soil properties and soil organisms must be happened. Microplastics change the properties of the soil and bring negative impact on organisms, the adverse reactions of organisms will affect the soil properties and the transport of plastics (Kim and An, 2019; Lozano and Rillig, 2020). The internal relationship and mechanism of the three need exhaustive study, so that we can be more aware of the ecological effects caused by microplastics at the level of the entire macroscopic system.

At the present stage, studies on the toxicity of organisms in the atmospheric environment are mostly focused on human beings. It is important that microplastics intake through atmospheric fallout may even be more frequent compared to MPs-contaminated food (Catarino et al., 2018). Dust intake is also one of the key ways for humans to be exposed to particles, especially for special populations, such as infants (Huang et al., 2020b) and workers (Setyawati et al., 2020). The estimated daily intakes (EDIs) of PC and PET MPs via indoor and outdoor dust ingestion was calculated. It was found that the daily intake of babies was as high as 889 fibers/kg-bw/day, while the daily intake of adults was one order of magnitude smaller, which might be related to the longer time the baby stays indoors (Liu et al., 2019c). People may also inhale microplastics through the dust on the street. Under normal circumstances, the EDI values of MPs via street dust ingestion ranged from 0.6 to 4.0 for children and from 0.3 to 2.0 particles/d for adults in Tehran, Iran (Dehghani et al., 2017). Nevertheless, in some heavily polluted areas, such as Asaluyeh County, Iran, higher EDI values of MPs for children and adults were 0.7–103.3 and 0.3–51.7 particles/d, respectively (Abbasi et al., 2019). It can be seen that humans may have been exposed to the pollution of plastic particles, but we still don't know how much impact they will have.

4.2. Nanoplastics

In the previous section, the paper discussed the biological impact of microplastics, and what impact will nanoscale plastics have. Algae are a kind of ubiquitous protist in the aquatic environment. They use various chloroplast molecules (such as chlorophyll, carotenoids, phycobiliprotein) for photosynthesis to create an oxygen-rich environment. Planktonic algae is a very important link in the marine food chain, the survival of all higher aquatic organisms ultimately depends on the existence of algae. González-Fernández et al. (2020) used 50 nm amino-functionalized polystyrene nanoplastics ($PS–NH_2$ NPs) to study the effects on pigments and fats in diatoms (*Chaetoceros neogracile*) at concentrations of 0.05 and 5 μg/mL. After 4 days of exposure, they found that the content of pigments and fats in diatom cells changed, the thylakoid lipid class and fatty acid composition were readjusted, and diatom had developed different adaptation mechanisms to cope with the stress introduced by nanoplastics. Bellingeri et al. (2020) also found that 90 nm carboxylic-functionalized polystyrene nanoplastics (PS–COOH NPs) shortened the length of diatoms chains at the concentration of 0–50 μg/mL, which affected the biogeochemical cycle of carbon. This may be due to the adsorption of plastics on the fultoportula processes (FPP) at the end of diatoms (This lathy structure is responsible for the formation and maintenance of diatom chains).

While understanding the impact of nanoplastics on aquatic plants, more research has focused on their impact on aquatic animals. In a typical nanoplastics environment with a concentration of 1 μg/L, Liu et al. (2020) found that 75 nm PS had a multigenerational physiological effect on *Daphnia pulex* (generally living in fresh water of 0.5 m depth), even though some improvement was observed in the recovery experiment, but the reproductive and stress defenses of *Daphnia pulex* were obviously weakened. In another research, Bhargava et al. (2018) suggested that nanoplastics (polymethyl methacrylate, PMMA; 45 nm) could be accumulated in the body of throughout stage of growth and development from larval to adult stages of *Amphibalanus Amphitrite*. Zebrafish (*Danio rerio*) (like to forage in the upper waters), which has 87% similarity to human genes, was also negatively affected by nanoplastics. Nanoplastics not only produced neurotoxicity to the nervous system (Chen et al., 2017), but also damaged oxidative DNA in the brain (Sökmen et al., 2020). Furthermore, owing to the interaction of nanoplastics with plasma proteins of oocyte, PS nanoplastics could be transferred from the mother to the offspring through accumulation in the egg (Pitt et al., 2018).

Combining all the discussion above, we have summarized the literature on the impact of MPs/NPs on marine animals. From Table S1, it can be seen that MPs/NPs have different degrees of impact on marine animals living in different depths. Among them, fish, bivalves, and crustaceans have been studied more (Fig. 8). For one thing, this may be due to the physical characteristics (such as size, color, density and shape), chemical characteristics (such as functional groups, crystallinity, stability and surface charge) of plastics and their spatiotemporal heterogeneity (Ma et al., 2020; Triebskorn et al., 2019; Shen et al., 2019; Xue et al., 2020). Thus, the plastics that are accessible to organisms are different. For another, the growth habit of the organism themselves (for example, living environment, predation preference, activity behavior and so on) is also a vital factor. There are a large quantity of natural microparticles in the environment, and MPs/NPs only account for a small part (Ogonowski et al., 2018). How much MPs/NPs can be exposed to aquatic animals in the actual environment is still a problem worthy of study. Even if, as we speculate, organisms are greatly affected by direct or indirect ingestion (predation) of MPs/NPs, but the extent and number of toxicity endpoints affected are also different (Jacob et al., 2020). In addition, the water area where marine organisms survive in these studies are mostly concentrated in the epipelagic zone, that is, the outermost waters of the ocean, from the surface to 200 m (Fig. 9). In this layer, most of the visible light in sunlight can be irradiated, which may further break up the microplastics, release more additives and enhance the toxicity to the organism (Wang et al., 2020b). This probably exists in freshwater ecosystems as well, or even worse. However, many studies have not taken this into consideration.

Altogether, although the current research results have established a meaningful theoretical basis. Future experiments need to consider the existence of natural particles and foods, set up plastics with different particle sizes, concentration ranges, and diverse electrical properties (positive, negative, and neutral), and provide greater living space for experimental organisms and so on. The experimental conditions are more appropriate to the actual situation, and help to deepen the general understanding of the biological effects of MPs/NPs. The type of investigated organisms should also be extended to more abundant populations. The water is all collected in the ocean, MPs/NPs may exist in different depths of the sea. So the research on the surface water organisms is still far from enough. This not only helps to understand the impact of MPs/NPs on the whole ecological environment with the vertical pattern, but also provides data support for the establishment of toxicity assessments in the future.

For the terrestrial environment, scholars also go further into nanoscale plastics. Sun et al. (2020) synthesized two functionalized PS nanoplastics, namely $PS–SO_3H$ (55 ± 7 nm) and $PS–NH_2$ (71 ± 6 nm), and then Arabidopsis thaliana was planted in the soil mixed with these two nanoplastics. Studies found that two types of nanoplastics could affect many growth phenotypes of Arabidopsis thaliana. After seven weeks, the aboveground fresh weight of Arabidopsis thaliana exposed to 1.0 g/kg $PS–SO_3H$ was 51.0% lower than that of the control plants. The growth of the root system was also inhibited. Moreover, through RNA-Seq transcriptomic analyses, nanoplastics treatment would reduce the disease resistance of plants. Surprisingly, when people turned more attention from microplastics to nanoplastics, researchers were surprised to detect that plants can uptake nanoplastics (Sun et al., 2020; Li et al., 2020d; Jiang et al., 2019b). In the latest study, the author used two fluorescently labeled nanoplastics, red fluorescence-labeled carboxyl-modified polystyrene nanoplastics (PS–COOH; 200 nm) and green fluorescence-labeled amino-modified polystyrene nanoplastics ($PS–NH_2–F$; 200 nm), to verify whether nanoplastics could be adsorbed by plants (Sun et al. 2020). The results showed that nanoplastics could accumulate in plants depending on their surface charges. Both positively charged and negatively charged nanoplastics could accumulate in Arabidopsis thaliana, but the absorption and transportation pathways of nanoplastics with different charges in root tissue were different. PS–COOH NPs were mostly adsorbed on border cells and arranged along the

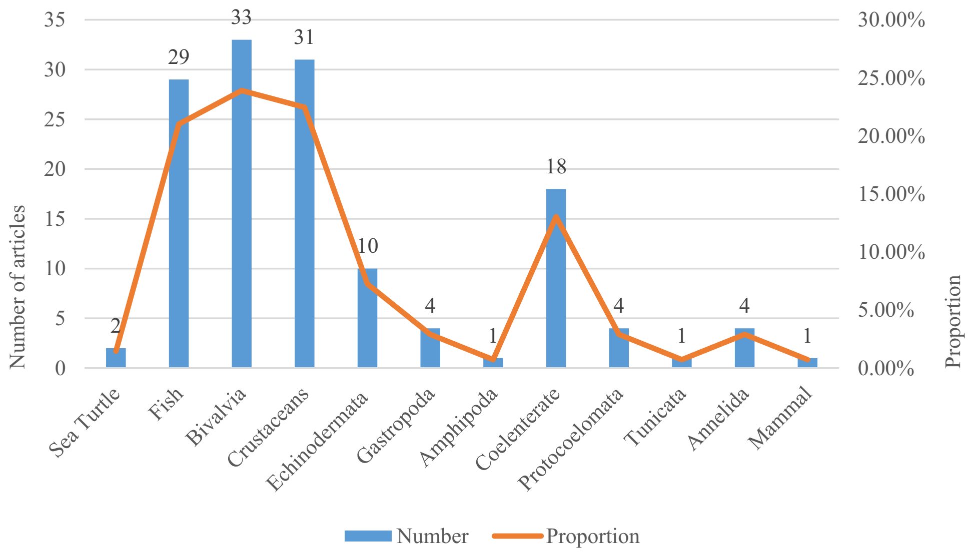

Fig. 8. The respective number of articles of using various types of marine animals in all experimental animals.

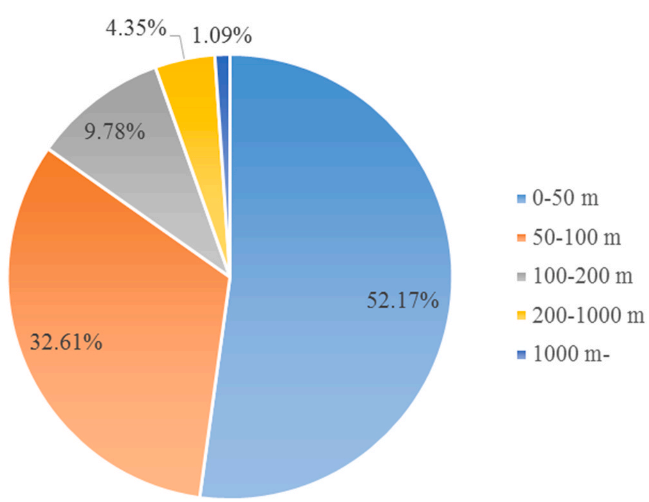

Fig. 9. The proportion of marine animals living at different depths. For animals with a usual depth range, the usual depth range shall prevail. Then divide the scope by the deepest depth of life. Marine animals without depth range are not included in the statistics.

root surface in the root tip. Moreover, a large number of red fluorescence plastics attached to the root surface and root hairs as well as in the intercellular space. While PS–NH_2–F NPs were mainly observed in the root epidermis and root hairs. And although there were not many positively charged particles absorbed, they were more harmful to plants. In addition, the study emphasized that Arabidopsis thaliana could uptake and transport nanoplastics with size less than 200 nm regardless of the surface charge. Li et al. (2020e) also found that wheat and lettuce could absorb plastic particles of 0.2 μm and 2 μm, which breaks the inherent idea that micron-sized plastics are "impossible" to exist in daily vegetables and crops. The vital thing is, the possibility of uptake and accumulation of plastic particles as well as the subsequent negative physiological effects should also be studied in other species of plants, especially in root crops (such as carrots, turnips and parsnips) (Sun et al. 2020). Soil plants are the basic link of other foods, and the accumulation of plastic particles in plants may have a harmful impact on other food chains, which has a huge test for the production, quality and safety of the entire food web.

Lei et al. (2018) reported that polystyrene nanoplastics could introduce size-dependent toxicity, resulting in a reduction in the survival rate, length and life cycle of nematodes (*Caenorhabditis elegans*). Nanoplastics also altered the movement behavior of nematodes, the frequency of body bending and head thrashing and crawling speed was raised. The author explained the experimental results at the genetic level as well. The down-regulation of genes (unc-17 and unc-47) obviously destroyed neurons (cholinergic and GABAergic neurons), which led to the change of motor behavior. And the up-regulation of genes (gst-4) indicated that oxidative stress was induced. Meaningfully, the experimental data illustrated that antioxidants (curcumin and oligometric proanthocyanidins) could effectively alleviate the negative effects caused by (nano) microplastics. However, some scholars believed that the influence of plastic particles had a good relationship with the total surface area of the beads per volume and additives oozing out of plastics (Mueller et al., 2020; Heinlaan et al., 2020). Therefore, we need to pay more attention to other influencing factors besides particle size in future experimental design to avoid bias. It is not difficult to see from the research results that the response of the body triggered by nanoplastics is much larger, and can even change the gene expression. Moreover, because of the poor degradability of MPs/NPs and human life cannot be separated from plastics, they will exist in the environment for a long period of time (Turner et al., 2020). It is worth considering whether certain organisms will evolve to adapt to such living environment.

Human beings are a more complex organism, and researchers currently use human cells for preliminary exploration. In vitro alveolar epithelial cells experiments had found that PS nanoparticles could be absorbed, and the absorption rate was determined by the particle size (Lehner et al., 2019). The cellular pathway of nanoplastics absorption is mainly endocytosis, including phagocytosis and macropinocytosis, as well as clathrin- and caveolae-mediated endocytosis (Doherty and McMahon, 2009; Ziello et al., 2010; Khalil et al., 2006; Huang et al., 2019). And nanoplastics could be translocated to other tissues through the circulatory system (Borm and Kreyling, 2004), causing pro-inflammatory or oxidative stress (Lehner et al., 2019). Even these results can not fully explain the negative impact of nanoplastics on humans, at least there is no direct evidence that nanoplastics can cause certain diseases (Gouin et al., 2020).

4.3. The combined effect of plastic particles and other pollutants

The above literature studies the effects of MPs/NPs on aquatic organisms alone, but there may be a variety of pollutants in the actual environment (Deng et al., 2020; Xue et al., 2018, 2019; Huang et al., 2016). When these pollutants are combined with MPs/NPs, how much impact on aquatic organisms? Kim et al. (2017) investigated the combined toxicity of two types of microplastics and heavy metal Nickel (Ni) to *Daphnia magna*. Compared with exposure to Ni and PS, the movement of *Daphnia magna* exposed to Ni and PS–COOH was more strongly inhibited as a result of the lower negative potential of PS–COOH and the stronger binding ability to Ni. Furthermore, PS had a slight antagonistic effect on the toxicity of Ni, while the combination of PS–COOH and Ni had a slightly synergistic effect, which indicated that the aging microplastics might cause greater toxicity. Microplastics and two persistent organic pollutants (POPs) were also used by Tang et al. (2020) to study the joint toxicity of bivalves, and the results showed that the toxicity of POPs was generally aggravated by smaller microplastics (500 nm) and mitigated by larger ones (30 μm). The authors believed that, firstly, the toxicity of nanoplastics was greater; secondly, the smaller nanoplastics had a larger surface area, which could adsorb more pollutants, resulting the "Trojan horse" effect to enhance the toxicity of POPs; thirdly, nanoplastics were more difficult to rapidly excrete from the body through the intestinal tract than microplastics, which ultimately led to the appearance of such experimental results. However, Grigorakis and Drouillard (2018) pointed out that microplastics ingested in food and persistent organic pollutants associated with microplastics might lead to similar or lower bioaccumulation potential than in the absence of microplastics. From the above, we can see that the combined toxicity of plastic particles and other pollutants is not a simple synergistic relationship as we think, which involves factors such as the type, size (Rowenczyk et al., 2020), surface charge and concentration (Li et al., 2020c) of the plastic, thus affecting the bioavailability of pollutants. The presence of food in the actual environment may slow down the toxicity of MPs/NPs.

It is worth noting that the soil simultaneously contains some toxic heavy metals or organic pollutants (for instance pesticides, polychlorinated biphenyls, surfactants). Plastic particles adsorption of heavy metals and organic pollutants is not uncommon. Thus, after plant absorption, whether these pollutants will enhance the negative impact on plants is still worth pondering. Dong et al. (2020) conducted a hydroponic experiment to assess the combined toxicity of polystyrene (PS) and polytetrafluoroethylene (PTFE) with arsenic (As), and found that PS and PTFE reduced the absorption of As by rice seedlings, and the concentration of absorbed As decreased with the increase of the microplastic concentration. This might be due to the competition of adsorption sites on the roots or the inhibition of root activity by microplastics (Deng et al., 2019; Gong et al., 2017; Wang et al., 2018). The vital thing is, the possibility of uptake and accumulation of plastic particles as well as the subsequent negative physiological effects should also be studied in other species of plants, especially in root crops (such as carrots, turnips and parsnips) (Sun et al. 2020). Soil plants are the basic link of other foods, and the accumulation of MPs/NPs in plants may have a harmful impact on other food chains, which has a huge test for the production, quality and safety of the entire food web.

Similarly, MPs/NPs may increase the risk of terrestrial animals being exposed to pollutants. As early as 2013, polybrominated diphenyl ether (PBDE), a sort of flame retardants and released from polyurethane foam (PUF), had been demonstrated to accumulate in earthworms (Eisenia fetida). These earthworms may transfer PBDE to predators or translocate them from the site of application/disposal (Gaylor et al., 2013). However, recent studies found that, similar to plants, under environmental conditions, microplastics reduced the accumulation of arsenate, PAHs and PCBs in earthworms, and also decreased the conversion rate of As (V) to As (III) (Wang et al., 2019a, 2019b). These results break our traditional conception that plastic particles and other pollutants have a synergistic effect on biology, adsorption competition appears to be more dominant than size factors. Of course it's just a guess, we need to further explore why these plastics will reduce the bioavailability of other pollutants in later study? In addition to competing for adsorption sites, what are the other reasons? Recently, Wang et al., (2020d) have made a new discovery about the combined toxicity of plastics and other pollutants. Studies to date have neglected the potential fact that microplastics are generally contaminated before their entry into soil. The author emphasized that the importance of the sequence of contamination between plastic and soil. Whether microplastics serve as facilitators or inhibitors of HOC bioaccumulation lies on the fugacity gradient of HOCs between soil and microplastics.

In aquatic and terrestrial environments, the combined toxicity of MPs/NPs and other organic pollutants has been studied. We also know that there are other gaseous pollutants, such as PCBs (Zhao et al., 2020; Zheng et al., 2016) and mercury (Lepak et al., 2020), in the atmospheric environment, which may be adsorbed on MPs/NPs and then enter the human body together with MPs/NPs. The impact of atmospheric MPs/NPs, their chemical components and their adsorbed pollutants on human being and ecosystem health are unknown, but the potential of MPs/NPs to influence human and ecology is of concern. There is almost no research on this aspect and further investigation is needed imminently.

4.4. *Creatures living in multiple environments*

Some animals in nature do not always live in the same environment. For instance, amphibians, like frogs and toads, larvae tadpoles live in water, live on algae. And then gradually develop into young adults that can live on land, they mainly in the grasses near the water, and sometimes can hide in the water, too. Frogs feed majorly on insects, but also eats some viviparous, snails, small shrimps, and small fishes and so on.

With respect to evaluating the toxicity of microplastics to amphibians, tadpoles are often used as experimental objects. In one of Araujo and Malafaia (2020) research, *Physalaemus cuvieri* tadpoles were exposed to 60 mg/L of polyethylene microplastics for 7 days. The results showed that the accumulation of microplastics in the tadpoles affected their behavior. When tadpoles encountered natural enemies, they would show locomotion issues, anxiogenic effect symptoms and anti-predatory defensive response deficit. The defensive behavior of tadpoles against predators and their social behavior would be influenced by these behavioral changes. At the same time, the bioaccumulation of pollutants in the liver of tadpoles caused a series of histopathological transformations, such as blood vessel dilation, infiltration, congestion, hydropic degeneration, hypertrophy and hyperplasia (Araujo et al., 2020). Moreover, the shape, size (both diameter and area) and volume of hepatocytes also become deformed. These experiments have improved our understanding of the impact of microplastics on these amphibians. Plastic pollution affects the survival and reproduction of tadpoles and which may pose a certain threat to the ecological balance.

In another study, Carlin et al. (2020) investigated the amount of microplastics in the gastrointestinal tract of 18 species of birds from the esophagus to the large intestine. Different concentrations of microplastics were found in the gastrointestinal tract of each experimental individual. The average concentration of microplastics contained in each bird was 11.9 ($\pm$ 2.8) particle number per bird, or 0.3 ($\pm$ 0.1) particle number per gram of GI tract tissue. And microfibers accounted for 86% of total microplastics. In addition, the GI tract tissue of *Buteo lineatus* contained remarkably more abundant of microplastics, than in fishfeeding *Pandion haliaetus*, *Buteo lineatus* consumes small mammals, snakes, and amphibians. Therefore, the level shift of the food chain may be an important pathway for birds to ingest microplastics.

Now, the research on the function of MPs/NPs on this class of animals is still immature, so we should keep our eyes on the gap. Because the life trajectories of these animals span aquatic, terrestrial, and atmospheric environments, MPs/NPs may have different effects on different life stages of creatures. And we know that organisms are interconnected and inseparable, once "a link goes wrong", it will affect the survival of the entire species and eventually spread to the ecosystem in this region. Furthermore, the movement or migration of animals will bring MPs/NPs to the places where they live, disrupt the balance of material exchange. All in all, a clear understanding of the transport and distribution of MPs/NPs in aquatic, terrestrial, atmospheric environment and among various environments is an important cornerstone for us to explore the impact of MPs/NPs on biology, ecology and the whole biosphere (Fig. 10). From the type of plastic used in the experiment to the size to the concentration, it is necessary to refer to the actual environmental conditions, so that the experiment has more practical reference significance. The establishment of various models, whether for transport or risk assessment, requires a lot of data and practical verification. Therefore, more efforts and interest should be devoted to the research of MPs/NPs pollution, and the cooperation of scientists from various countries is highly desired.

5. Regulatory policy

As mentioned above, scholars have realized the seriousness of MPs/NPs pollution. In addition to continuing to strengthen research, "source control" is also much critical, and as such, relevant policies and measures are urgently needed to control plastic pollution. In January 2018, Europe adopted the "European Strategy for Plastics in a Circular Economy" for the first time, which changed the European Union's way of designing, producing, using and recycling of plastic products. Better design of plastic products, higher plastic waste recycling rates, more and better quality recyclates will help boost the market for recycled plastics, and will help protect our environment, reduce marine litter, greenhouse gas emissions and our dependence on imported fossil fuels. In May of the same year, the European Commission proposed to formulate new rules for 10 common disposable plastics products and fishing gear containing plastics, so as to avoid or reduce the environmental impact of specific plastic products. In addition, PlasticsEurope also put forward a voluntary commitment "Plastic 2030", which aimed at preventing leakage of plastics into the environment and improving the resource efficiency of plastic products and circularity of plastic packaging, including "Zero Plastics to Landfill", "Zero Pellet Loss" and other initiatives.

Since China issued the "Plastics Restriction Order" in 2008, some regions have achieved good results and raised people's awareness of environmental protection, but this is far from enough. In January 2020, the Ministry of Ecology and Environment issued the "Opinions on Further Strengthening the Control of Plastic Pollution", which set three phased goals. For instance, prohibiting and restricting the production, sale and use of some plastic products (such as ultra-thin plastic shopping bags with thickness less than 0.025 mm, disposable foam plastic tableware and daily chemical products containing plastic beads). At the same time, we should promote the use of non-plastic products (such as paper bags and degradable shopping bags) and standardize the recycling and disposal of plastic waste. Besides, Japan, South Korea, Thailand and other countries have successively introduced stricter policies.

Compared with the previous laws and regulations, these policies focus on the whole life cycle, covering the entire process and each link of the production, circulation, use, recycling (including mechanical recycling, chemical recycling, energy recovery) and disposal of plastic products, which is conducive to the establishment of a long-term mechanism to control plastic pollution. It is momentous to prevent the transfer of low-end plastic products from economically developed places to backward ones, from places with strong supervision and utilization competence to those with weak supervision and utilization competence. This can not only achieve a circular economy, but also protect our earth home, and ultimately reach the sustainable development goals.

6. Conclusions and research priority

As an important chemical material in this century, plastic polymers are inseparable from people's lives. It is precisely because of the huge demand for plastics and inappropriate or even neglected disposal and recycling that our planet is becoming a "plastic kingdom". Wherever plastic is used, it is possible to release plastic into the environment, then plastics may break into microplastics or nanoplastics under external environmental forces, which are different from the original bulk plastics in physiochemical properties. The existing knowledge system has shown how MPs/NPs are transported in the aquatic, terrestrial and atmospheric environments, which is closely related to environmental conditions (such as hydrodynamics, porosity, weather conditions, natural particles and biological colonization, etc.) and the nature of plastics (like shape, density and surface area). Importantly, this article emphasizes the transfer of MPs/NPs among three major environment compartments, with material exchange and energy circulation at all times. However,

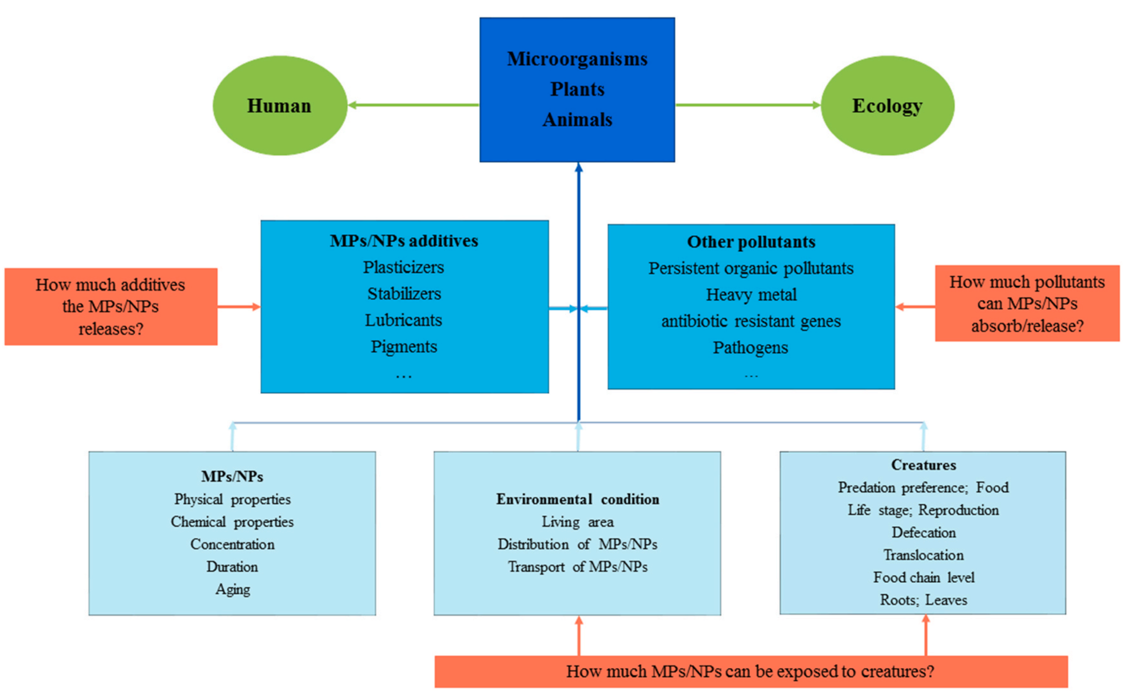

Fig. 10. The factors affecting the toxicity of microplastics/nanoplastics to creatures.

there is still a lack of research in this field. Only with a more comprehensive, systematic and in-depth understanding of the transport and distribution of MPs/NPs in the natural environment can we better deal with global plastic pollution.

In addition, the existence of MPs/NPs has a large or small impact on the organisms, ranging from microorganisms, plants and animals to human who are inseparable from oxygen. It not just affects the growth, development, and reproduction of populations, but also triggers the adjustment of the body's internal operations to deal with plastic pollution. Furthermore, such as amphibians and birds, etc., they live in different environments, and are affected by different environments. But this kind of research is still rare, and generally only study a certain life stage, which cannot comprehensively evaluate the toxicity of plastic pollution to creatures across different environments. It is worth mentioning that MPs/NPs will accumulate with higher trophic levels along the food chain after ingestion, ultimately reach to humans. However, the impact of MPs/NPs on humans is still at the preliminary stage. Meanwhile, the combined toxicity of MPs/NPs and other pollutants has also received special attention from scholars. As mentioned before, MPs/NPs do not enhance toxicity as we have speculated, but inhibit the toxicity of other pollutants to a certain extent.

Among the factors affecting the toxicity of MPs/NPs, the characteristics of MPs/NPs are an integral part, which also determines their distribution in the environment to a certain extent. Only after we fully understand the transport process of MPs/NPs can we estimate their distribution, thereby predicting the MPs/NPs that creatures can come into contact with and the impact on creatures. The world is so large and complex that the pollution situation cannot be taken in the lump. The idea of "adjusting measures to local conditions" is particularly important, even if it cannot solve the problem fundamentally. In addition, as a carrier of other pollutants or microbiota, the nature of MPs/NPs are not same at the virgin plastic particles during the transport process (like size, density, hydrophobicity, and so on) and the impact on biology are more diversified. The research on MPs/NPs have been carried out for more than ten years, and there is a relatively mature knowledge framework for the marine environment, but many aspects are still blank. First of all, there are few studies on transport and biotoxicity of MPs/NPs in the atmospheric and terrestrial environment and at the interface between water and sediment. Secondly, the lack of a unified standard makes it inconvenient to compare experimental results. Thirdly, the research results are scattered and which is not convenient for analysis and comparison. Perhaps in today's intelligent information age, the establishment of a global database can make up for the deficiency. Appropriate models also allow us to predict transport and toxicity.

Based on the above discussion, we list the future research priority:

(1) Due to the material cycle in the natural environment, the contribution and source-pathway of MPs/NPs in aquatic, terrestrial, and atmospheric environments to the other two, and the interlinkages among the three major environment compartments need to be investigated. Based on the above data, a global transport and distribution model of MPs/NPs can be established, in order to accurately evaluate the pollution status of MPs/NPs.
(2) Actually, most of the experiments focus on the marine environment and lack of research on the freshwater environment. Plastic pollution comes from human and the freshwater environment is more closely related to us. Therefore, while the ocean has been heavily polluted, is the freshwater environment more seriously polluted? Furthermore, how do the meandering river courses, the plants on both sides of the river bank, the rapid and slow flow of water, and the dams built by humans affect the transportation of MPs/NPs?
(3) We need to understand the toxicity of MPs/NPs on more organisms. In addition to algae, zooplankton, earthworms, fish, which are now often used as experimental objects, we also need to add amphibians, birds, deep-sea animals, and humans, etc. By comprehensively assessing the toxicity of various organisms, we hope to use certain species as biological indicators to warn that plastic pollution has exceeded the threshold.
(4) Whether the toxicity of MPs/NPs originates from chemical toxicity or particle toxicity should be found out. Then, MPs/NPs themselves could release additives or adsorb other pollutants. The amount of release and desorption is the key to additional toxicity in vivo, which is distinct from simply exposing the experimental objects to chemical solutions.
(5) While considering the toxicity of MPs/NPs, we should focus part of our efforts on their impact on the ecosystem. Similar to the "carbon and nitrogen cycle", the conceptual framework of the "microplastic cycle" could be established (Rillig and Lehmann, 2020). Most of the carbon in MPs/NPs comes from petroleum, which will accumulate in the environment due to its non-degradability, thereby changing the earth's carbon storage and affecting the carbon cycle. In addition, the feedback of the ecosystem to MPs/NPs should not be ignored, such as net primary productivity of plants and flux of greenhouse gases (Rillig and Lehmann, 2020).
(6) Since microbial colonization occurs on every submerged surface, understanding the biofilm formed on the surface of MPs/NPs is of importance (Rummel et al., 2017). First, what is the effect of biofilm on the hydrodynamics of plastics by changing the density of plastics? Secondly, biofilms change the chemical properties of plastics. Compared with MPs/NPs without colonization, how do the adsorption and chemical partition of other pollutants differ? Thirdly, pathogens or ARGs will be enriched in biofilms, what are the different toxic effects once ingested by organisms?
(7) Facing the above problems, experimental setup is of vital importance. So as to ensure the objectivity and accuracy of the research results, we should set the experimental conditions as close as possible to the actual environmental conditions, involving the types, size range, concentration range, aging degree and electrical properties of MPs/NPs, exposure duration and the coexistence of food/natural particles. Moreover, the research should inform property indexes of sampling sites in detail and sampling methods, the concentration units of MPs/NPs should be unified and standardized as well, which will help to compare the various studies and deepen the consensus (Jacob et al., 2020).

In short, the challenge for research is to deeply explore the transport and distribution of MPs/NPs in the whole natural environment, as well as the interaction with the natural environment and organisms in the complete life cycle, so that scientists can scientifically evaluate plastic pollution and help the government formulate effective governance policies. Meanwhile, exchanges and cooperation between different disciplines in different fields and disciplines should be strengthened.

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.

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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.2020.124399.

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