Chapter

Why Microplastics Are Exceptional Contaminants?

Dalia Saad

Abstract

Due to the heterogeneous nature of the physiochemical properties of microplastics (MPs), their behaviour in the environment is quite complex compared to other contaminants. The variety of polymers, wide range of sizes, variable shapes and numerous colours influence their mobility, transport and distribution in the different environmental compartments. For example, different shapes and sizes are distributed differently, which influence their bioavailability and ecological impacts. The uptake of MPs by aquatic biota also depends, among others, on their characteristics. This book chapter aims to discuss the ecological and toxicological impacts of MPs in relation to their physical and chemical properties. The chapter starts with a brief introduction explaining the uniqueness of MPs as emerging contaminants and a driver of environmental change. The following two sections then provide deeper insights into their ecological impact at all levels of the ecosystem and highlight the complexity associated with their toxicological effects. Finally, the last section provides more discussion about their properties in the context of their environmental behaviour, fate, bioavailability and toxicity.

Keywords: microplastics, physiochemical properties, behaviour, bioavailability, toxicity

1. Introduction

Plastic pollution was one of the biggest environmental challenges until the discovery of microplastics (MPs) in the early 21st century. While plastics are easily visible and their environmental impacts are well documented, MPs are not visible and their ecological impacts are less understood [1].

MPs are exceptional pollutants with a broad range of individual properties. For instance, they are made of different polymers with different densities and chemical compositions (there are currently more than 5,300 types of synthetic polymers); they exist in variable shapes (fibres, fragments, foams, films, spheres, flakes, foils, sheets and granules) and are found in a wide range of sizes. These heterogeneous properties result in heterogeneous behaviour, fates and effects that are far more complex compared to other environmental pollutants. To add to this complexity, their properties and behaviour can also change over time, thus their ecological effects [1–3].

According to their physio-chemical properties, MPs are distributed differently in aquatic environments, which makes them available for uptake by a wide range of aquatic biota including plants. MPs are reported to interact with aquatic plants and accumulate into plants' tissues. This enables them to penetrate aquatic food webs at multiple trophic levels and ecological niches. Yet, the degree and type of effects that they cause when consumed by organisms depend on their properties including polymer type, size, shape and colour, as well as their constituent chemicals [4–8].

Due to their greater surface area, MPs have a propensity to adsorb other pollutants such as metals, pharmaceuticals and persistent organic pollutants (POPs). They also host pathogens, such as bacteria and viruses, thus, providing an additional pathway of exposure of aquatic species to contaminants. In other words, MPs can serve as a micro-vector for a mix of toxic chemicals and pathogens [9–14].

2. Ecological impact

Over the years, several studies across the globe have reported MPs in different environmental compartments including rivers, lakes, estuaries, oceans, harbours, groundwater and in the atmosphere, as well as in Antarctica. Once they enter the environment, their residence time lasts for decades due to their low degradation rates, resulting in long-lasting impacts [15–19].

In natural environments, MPs are exposed to a variety of degradation processes through different environmental conditions including weathering, biodegradation, oxidation, mechanical forces and phytodegradation. Phytodegradation of MPs is reported to produce greenhouse gases (GHGs), mostly, methane and ethylene, thus, contributing to climate change. The emission of GHGs by the degradation of MPs is relatively low, however, with continuous degradation, the same amount of MPs may release more GHGs over time [20–23].

In the atmosphere, MPs can be transported with winds around the earth. Airborne MPs may influence earth's climate by scattering and absorbing solar and terrestrial radiation, leading to atmospheric warming or cooling depending on particle size, shape and composition. However, the radiative effects of airborne MPs on climate are less understood [22, 24].

In marine environments, the widespread of MPs affects the light transmission, thereby influencing the efficiency of phytoplankton photosynthesis, which impacts both their growth and role in balancing the marine environment. Studies have shown that the photosynthetic rate of phytoplankton (*Dunaliella tertiolecta*) is reduced by 45% after being exposed to MPs. Additionally, MPs may influence the circulation of organic matter and nutrients, which affects the carbon stock of ocean [25].

In terrestrial ecosystems, MPs can cause significant environmental changes with potential consequences on soil function, plant growth, soil biota and microbial communities; ultimately, MPs have the potential to impact the biodiversity. When dispersing in the soil matrices, MPs form aggregates and cause alteration in the physical properties of the soil, including water holding capacity, soil bulk density and soil structures. For example, MPs can create channels for water movement in the soil, thus, accelerating the evaporation of soil water. This further leads to destruction in the soil structure, which may result in desiccation cracking on the soil surface. The impact of MPs on the soil is not limited to the physical properties, MPs can also affect soil chemistry, for instance, by altering the levels of dissolved organic carbon,

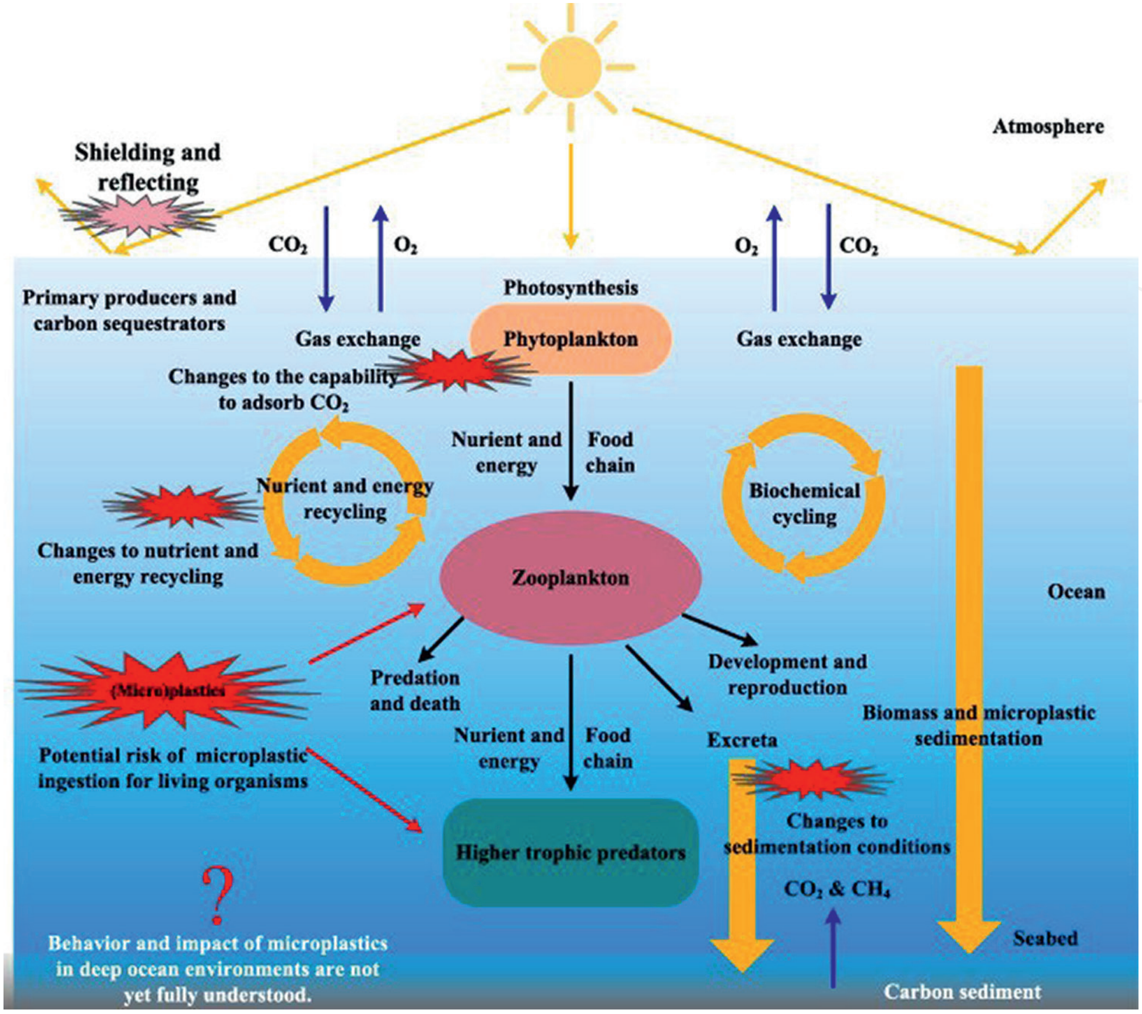

Figure 1.
Ecological impacts of MPs. Source: Shen et al. [20].

phosphorus, and nitrogen. This leads to changes in the nutrient cycling processes in the soil. There is also a growing body of evidence suggesting that MPs can affect soil-plant interactions, which in turn impacts plant growth. Several studies have reported significant changes in plant biomass, leaf and root traits and tissue elemental composition [26–36]. In short, MPs have profound effects on the ecosystem at all levels (**Figure 1**).

3. Toxicity

The toxicity of MPs comes from (i) their chemical constituents, which include both the polymers (polyaromatic hydrocarbon) and the chemical additives; (ii) the environmental pollutants adsorb onto their surfaces; (iii) pathogens colonized onto their surfaces.

During plastic processing and manufacturing, a variety of chemicals are added to enhance/adjust their properties and to make them into materials fit for intended purposes. Most of these chemicals are toxic and harmful to the environment, such as dyes, phthalates, flame retardants, pigments and stabilizers. Some of these additives tend not to be strongly bound within the matrix of the polymer and they can potentially desorb and be leached out into the host environment [37–39].

On the other hand, due to their small size and greater surface area, MPs have a tendency to adsorb wide range of contaminants from the surrounding media. Pollutants such as persistent organic pollutants (POPs), metals, pesticides and pharmaceuticals are readily bound to MPs. In natural environments, and depending on the prevailing environmental conditions, MPs may act as a sponge removing and/or concentrating these contaminants. It is reported that the concentrations of contaminants on the surface of MPs may reach up to 100-fold higher than the concentrations reported in the surrounding media. Once MPs are ingested, these concentrated contaminants can be released inside organisms. Arguably, the virgin MPs will release plastic additives, while the aged MPs will most likely release adsorbed pollutants. Most of these chemicals are reported to be toxic; for instance, POPs are known to be carcinogenic, while metals are known as endocrine disruptors. Additionally, in aquatic environments, MPs are susceptible to biofouling different pathogens/microbial organisms including fungi, bacteria and algae colonize MPs' surfaces and form biofilms. Therefore, MPs act as carriers or micro-vector for transporting a complex mixture of contaminants (**Figure 2**). The leaching of additives from plastic combined with the chemicals adsorbed to plastic renders MPs a 'cocktail' of toxic contaminants. When particles containing adsorbed chemicals are ingested by an organism, pollutants can be released [9–11, 38, 41–47].

The toxicological effects of the uptake of MPs by several aquatic biotas are reported in a variety of exposure studies, including both physical and bio-chemical changes. For instance, MPs were observed to cause oxidative stress, immune destruction and alterations in the level of enzyme activity, tissue morphologies, kidney functions, gene expression and the total protein and glucose. Further, MPs may inhibit weight gain and growth. This, in addition to physical changes, such as abnormally impaired movement coordination, increased respiration and abnormal swimming patterns [48–53].

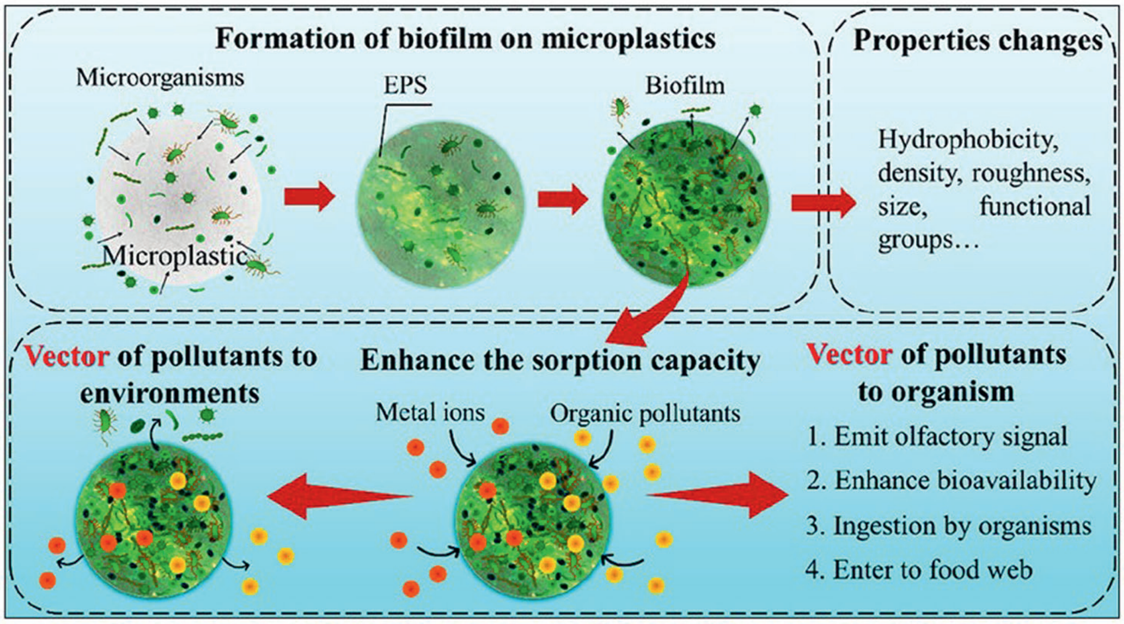

Figure 2.
Interaction of MPs with co-existing pollutants. Source: Wang et al. [40].

4. Characteristics of MPs: implications on their behaviour, bioavailability and toxicity

The unique nature of MPs is clearly illustrated in comparison with other environmental pollutants. While toxicity of other contaminants is merely dependent on their composition, that of MPs is more complex. The toxicity of MPs includes the particle-related toxicity, which is driven by size, shape, colour and the polymer type; and the chemical toxicity, which is driven by adsorption-desorption kinetics of additives, and co-existing pollutants [6]. This section reviews the implications of MPs' characteristics in their behaviour and fate, and further highlights the consequences of these implications on their bioavailability and potential toxicity.

4.1 Size

The size of MPs influences their distribution in the environment, dispersal in water column, magnitude of buoyant, biofilm formation and sedimentation. It also determines the extent of their impacts on soil properties, bioavailability, plant growth, GHGs emission rates and their potential health risks [21, 54–56].

For instance, their impact on the climate depends to a great extent on their size. For example, the larger surface area of the small-sized MPs increases the emission rate of GHGs. Meaning, with the frequent degradation of MPs, the very same amount of MPs will continue to release more and more GHGs [23, 24].

In terrestrial environment, small-sized MPs are more likely to block soil micropores, absorb by plants and be consumed by soil organisms compared to larger MPs. In addition, they are transported through the soil to groundwater more easily than larger MPs [57].

In aquatic systems, the size range of MPs overlaps with the preferred particle size ingested by a wide range of aquatic biota, including filters, detritus and suspension feeders. In addition, some organisms such as diatoms can aggregate on the surfaces of small-sized MPs and construct biofilms that could be attractive to organisms causing a higher probability of being mistakenly ingested. Smaller MPs generally have larger surface area, which makes them a good carrier for other pollutants such as heavy metals [5, 58–62].

In terms of toxicity, pollutants' adsorption and release from MPs depend, among other parameters, on the total surface area and thus on the size of the particles. The greater surface area of small-sized MPs thus facilitates the adsorption of other pollutants from the surrounding environment, resulting in additional health risks [63]. Consequently, small-sized MPs are considered to be more harmful to aquatic organisms. Hamed et al. [51] examined the effects of varying sizes of MPs in fish, and they observed toxicological effects including oxidative stress, biochemical changes and immune destruction. These toxicological effects were found to be augmented with decreasing MP size, thus, implying a direct correlation between the toxicity of MPs and their size. Additionally, the small size may facilitate their translocation into other organs. For instance, MPs have been reported in tissues, muscles and organs, confirming their ability to be translocated into these parts of the body, and it was noted that translocation rates increased with decreasing particle size [64–66]. This represents higher potential for health risks and higher level of toxicity if small MPs are regularly translocated into other parts of the body.

4.2 Shape

MPs' shape is a key attribute affecting their behaviour in the environment. It influences biofouling, rising and fall velocities and drag force. Thus, the shape plays a significant role in the sedimentation of MPs [67–69]. The shape of MPs is also important with regards to their impact on soil properties.

Some studies have suggested that MPs with different shapes may affect soil properties differently. For instance, fibres and films may have more significant effects on soil properties compared to beads and spheres [57, 70, 71]. This was explained by Rillig et al. [72] that the pollutants with dissimilar shapes to soil particles may have stronger effects. This was further supported by Lozano et al. [57]; they reported different effects on soil based on different shapes. They observed different effects caused by different shapes; according to their findings, fibres increased water-holding capacity, films decreased soil bulk density, while foams and fragments increased soil aeration and porosity.

In terms of bioavailability and toxicity, the shape of MPs is essential to prey perception by visual predator and the preference for certain MP shapes by several aquatic organisms have been reported in several studies. For instance, Saad et al. [5] and Yuan et al. [73] observed that common carp fish and goldfish preferably consumed fibrous MPs in the presence of other shapes, whereas, Hurley et al. [74] and Schessl et al. [75] reported an absence of pellets in the freshwater worm *Tubifex tubifex* and bivalves *(Dreissena polymorpha and D. bugensis)* despite their presence in the environment. This confirms the role of MPs shape in their bioavailability to different aquatic organisms.

Further, MPs' shape is pertinent to their potential toxic effects due to the different retention time, accumulation and physical damage. For example, fibres are reported to have longer intestinal residence time and accumulation, stronger acute toxicity and intestinal epithelial cell necrosis compared to other shapes in zebrafish, amphipods and grass shrimp. This could be attributed to the non-spherical shape, which is more easily embedded in tissue and takes longer time to pass through the gut. It is known that the longer the particles remain within the organism, the greater the potential to release associated toxins [76–79].

4.3 Surface morphology

The surface morphology of MPs influences their interaction with the surrounding environment. For instance, adsorption/desorption of co-existing pollutants as well as biofilm formation are influenced, to a great extent, by the surface nature of MPs. Ultimately, surface morphology impacts the distribution and sedimentation, thus bioavailability of MPs [80].

Cracks, pitting, flaking and fracturing result in an increased surface area, which increases the emission of GHGs. The increased surface area also facilitates the adsorption of other pollutants as well as the formation of biofilms. As a result, MPs may become a cocktail of pollutants with varying toxicity effects [10, 11, 23, 30, 47, 81].

4.4 Colour

A variety of colourant agents such as pigments and dyes are widely used during plastic manufacturing, these colourants contain some toxic chemicals. Coloured MPs are, therefore, considered to have higher potential health risks compared to non-coloured MPs [82].

The uptake of coloured MPs by aquatic biota is well documented and exposure studies have suggested that aquatic organisms may actively prey on plastic particles that possess similar colours to their natural prey. For instance, the preferential uptake of certain colours (MPs with artificial food-like colours) was reported in common carp (*Cyprinus carpio*). The authors observed an increase in the number of ingested food-like MPs with increasing concentrations of MPs in the water, while no increase in the number of non-food-like colours was observed [83]. Similarly, Ory et al. [84] reported significant uptake of MPs with artificial food-like colours by palm ruff (*Seriolella violacea*) more often than other colours, whereas MPs of other colours were mostly co-ingested when floating close to food pellets. Another study by de Sá et al. [85] reported a preferential uptake of white MPs by common goby (*Pomatoschistus microps*), compared to black and red MPs. The authors attributed this to the similarity in colour with the brine shrimp (*Artemia nauplii*), a prey that is commonly consumed by the common goby.

4.5 Chemical composition

Generally, MPs consist of a high molecular polymer as the main body and a variety of additives such as stabilizers, plasticizers, flame retardants and colouring agents as auxiliary materials. These various potential compositions determine their properties such as density and degradability, behaviour and environmental impact. For instance, their distribution in different environmental compartments is greatly influenced by polymer density. MPs with low density are buoyant, while those of high density tend to sink into sediments [37, 68].

The chemical composition of MPs also influences their interaction with the co-existing contaminants. For instance, the tendency of MPs to adsorb metals depends mainly on the functional groups pendent on the backbone structure of the polymer [86–92]. Ultimately, the chemical composition of MPs shapes their toxicological effects.

It is reported that the effect of MPs on soil properties varies based on the polymer type. The polymer type further influences the degradation of MPs, as a result, MPs may release the contaminants that are adsorbed onto their surfaces. The degradation also increases the emission rate of GHGs by MPs. The rate of GHGs emission also depends on the polymer type, for instance, polyethylene is found to emit higher GHGs compared to a number of other polymers [22, 30, 34, 80, 93].

5. Concluding remarks

The ubiquitous detection of MPs in different environmental compartments has made them a prominent environmental concern. Due to the chemical modification of plastic materials, receiving environments are potentially exposed to a cocktail of pollutants (polymers, leached additives and degradation products). This chapter provided a brief overview of the environmental challenges associated with MPs. The complexity of their ecological impact is discussed in light of their heterogeneous physicochemical characteristics.

Over the past decade, monitoring and ecotoxicological studies have improved our understanding of their nature and potential health risks. However, a better understanding of their long-term effects is needed. Considering that MP pollution is a symptom of human-made environmental change and a valid example of society-nature interaction, their mitigation requires a lot more than technological innovation. For instance, strategies such as reuse, design for recycling, improved waste management, standardized labelling and sustainable consumption are important. However, such strategies are only effective through social action and regulations. Examples include behavioural change campaigns to reduce the use of single-use plastics and policy measures to reduce the use of microbeads.

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Conflict of interest

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