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The Effects of Microplastic Pollution on Aquatic Microorganisms: A review of the sources, fate, and effects

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Abstract

Microplastics provide a extensive surface for microbial colonization in aquatic ecosystems. The formation of microorganism-microplastic complexes, such as biofilms, maximizes the degradation of organic matter and horizontal gene transfer. Microplastic affect the structure and function of microbial communities. Dispersal of microplastic is concomitant with that of their associated microorganisms and their mobile genetic elements, including antibiotic resistance genes, islands of pathogenicity, and diverse metabolic pathways. The presence of microplastics in the marine environment poses a great threat to the entire ecosystem and has received much attention lately as the presence has greatly impacted oceans, lakes, seas, rivers and even the Polar Regions. In addition, Coastal and marine areas are constantly under continuous and increasing pressure from the activities of humans. Microorganisms play essential roles in the ecological fate of microplastics pollution, potentially yielding positive and negative effects. This review provides a holistic view of ongoing microplastics and related microbial research, which may be useful for future microplastic biodegradation studies.

Key words: Microplastics (MP), Biofilms, Microbial ecology, Aquatic ecosystems.

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1. Introduction

Pollutants such as pesticides, persistent organic pollutants (POPs), hydrocarbons, heavy metals, plastics, and microplastics impact the marine ecosystem. The highly dynamic nature of the coastal area as makes up the physicochemical properties of freshwater environments, estuaries, and lagoons with the oceanographic characteristics of adjoining seas. Hence, the evaluation of contamination and remediation of coastal and marine environments are one of the most complex and current issues in ecotoxicology and environmental management. Marine litter has become a global environmental problem affecting all parts of our oceans. Recently, plastic pollution has caught the attention of both the scientific community and the public. Increasing amounts of manufactured plastic polymers end up accumulating in landfills or the natural terrestrial and aquatic environments (Geyer et al., 2017). Environmental surveys show that accumulation of mega- and macro-plastic items stays constant or diminishes while that of microplastic increases (Hurley et al., 2018). It has been proven that, in the environment, this plastic litter is fragmented into particles of less than a few millimeters denominated as “microplastics” (MP), whose complete mineralization could last for centuries (Flemming et al., 2016). These particles can travel from land or wastewater treatment facilities to natural freshwater ecosystems, and finally, end up in the oceans (Battin et al., 2016), where they contribute to an estimated 4.85 trillion MP particles (Hurley et al., 2018). The higher surface area to volume ratio of MP increases the absorption of organic matter and represents a new habitat for diverse microbial assemblages, often referred to as the “plastisphere” (Zettler et al., 2013). However, very few studies analyze microbial activities in MP biofilms and their potential repercussions for ecosystem functioning.

Biofilms are comprised of complex, diverse and dynamic microbial communities that are sometimes surface-associated and embedded in a self-produced matrix of extracellular polymeric substances (Flemming et al., 2016). They are essential for sustaining both biodiversity and the functioning of ecosystems, especially in aquatic biomes inland (Harrison et al., 2018). Cell proximity together with an EPS matrix protecting them from multiple environmental stressors, provides conditions to maximize interactions between different and even phylogenetically distant groups (Demeter et al., 2016). These interactions result in a complex network of metabolic cooperation, which transforms organic matter and shape biogeochemical cycles with profound ecological implications for the functioning of entire aquatic food webs.

Microplastics are tiny ubiquitous plastic particles smaller than five millimeters (5 mm) in size and originate from two sources; those that are manufactured purposely for particular industrial or domestic application such as exfoliating facial scrubs, toothpaste and resin pellets used in the plastic industry (primary microplastics), and those formed from the breakdown of larger plastic items under ultraviolet radiation or mechanical abrasion (secondary microplastics). These small plastic particles enter the marine environment through several activities on land and in the marine environment. Microplastic beads present in facial cleansers, synthetic clothing, toothpaste, and scrubs get into the marine ecosystem through domestic and industrial drainage systems and wastewater treatment plants (Clark et al., 2016). Also, larger plastic particles from waste dumps that have been broken down into smaller fragments can be transported into seas which causes microplastic pollution (Alomar et al., 2016).

Several studies have demonstrated that marine organisms can take up microplastics often with great consequences as they can accumulate in the tissues, serve as vehicles for the transport of pathogens, and adsorb and accumulate toxic pollutants. Microplastics have the potential to cause many adverse effects such as cancer, impaired reproductive activity, decreased immune response, and malformation in animals and humans. Pollution of the marine environment by microplastic is a potential health and economic problem. Prevention and possible management measures have been listed as a challenge because these particles are very small and hard to visualize, which makes their manual remov-

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al very difficult, if not impossible. The persistence of microplastics will continue to increase. Reports have it that by the year 2050, there will be more microplastics in our oceans than fish.

2. Microplastics in marine sediments

Microplastics with a density greater than that of seawater sink in sediments where they accumulate (Alomar et al., 2016), while those with a low-density float on the sea surfaces (Suaria & Aliani, 2014). An increase in density, through biofouling by organisms in the marine environment, can result in the sinking of microplastics. As biofouling progresses, the density of the plastic material also increases, and once the density becomes greater than that of seawater, the plastic material sinks to the bottom of the sea (Andrady, 2011; Reisser et al., 2013). Marine sediments have the potential to accumulate microplastics (Nuelle et al., 2014), and have demonstrated long-term sinks for microplastics (Cózar et al., 2014). Very high concentrations of microplastics now occur within marine sediments; such plastics can make up 3.3% of sediment weight on heavily impacted beaches (Van Cauwenberghe et al., 2015a, 2015b; Boucher et al., 2016). It is a fact that deep sea areas, submarine canyons, and marine coastal shallow sediments are sinks for microplastics.

3. Microplastic alters the ecology of aquatic microbial populations

Ecologists have long emphasized the importance of human activities for microbial dispersal across the globe (Wilkinson., 2010; Zhu et al., 2017). Human interference on Earth´s biomes accelerated after the mid-20th century and caused substantial alterations in the structure and function of microbial communities, perceptible as pronounced changes in human microbiota or biogeochemical cycling of elements (e.g., carbon, nitrogen, and phosphorus), and distribution of specific genes (e.g., antibiotic resistance genes) (Zalasiewicz et al., 2016). An exponential increase in the production of synthetic plastic polymers and their omnipresence in the environment coincides, among other factors, with the period of increasing industrialization and the observed changes in the planet´s microbiome (Zalasiewicz et al., 2016).

Evidence from the last five years strongly indicates that MP microbial communities in the environment exhibit a different composition and structure than other natural aquatic habitats (e.g., natural particulate organic matter, water column, and sediments) (Kettner et al., 2017). Moreover, in vitro studies by (Ogonowski et al., 2018) corroborated that the same initial aquatic microbial community results in different bacterial communities when growing on plastic polymers compared to other natural or inert substrates, indicating a material-dependent sorting effect, especially during the early stages of particle colonization (Ogonowski et al., 2018). Recently, the importance of microbial community structure for predicting microbial functions in ecosystems becomes increasingly evident (Graham et al., 2016). Therefore, it is relevant to study the potentially numerous consequences of anthropogenic MP pollution for emerging changes in the structure and function of microbial communities during the contemporary Anthropocene, and its potential risks for human and environmental health

Properties of plastic likely drive the development of biofilm communities on MP in aquatic ecosystems (e.g., polymer type, additives or absorbed pollutants, and size of particles). Other factors of influence could be the biological interactions among colonizers, environmental conditions, weathering of the material, and transport among environmental matrixes (biota, particulate material, water column, and sediments) (Rummel et al., 2017). Thus, differences in community structure development on MP biofilms among marine and freshwater systems are expected. In addition, freshwater systems (rivers and lakes) are closer to sources of MP and other types of pollution, as they are among the most human-altered environments (Kopf et al., 2018). Meanwhile, the oceans are considered the main long-term sink for MP (Rochman., 2018), and interactions occur with the entire planktonic microorganisms that contribute to a significant part of the biomass production worldwide (Giovannoni & Vergin., 2018). Therefore, MP impacts can reach different dimensions within these two systems.

Impacts of microplastics on aquatic ecosystems can include the spread of "invasive" spe-

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cies and thus changes in microbial biogeography (Andrady, 2017). Ecologically, these two effects are linked to the loss of biodiversity and the spread of pathogens (Keswani et al., 2016).

Although microbes are less limited by dispersal processes at broader geographical scales than higher organisms, observations at finer resolution scales show the dispersal shape of the ecological structure of microbial communities (Gibbons, 2017). Indeed, geographical variation in the structure of MP microbial communities has been frequently observed in aquatic ecosystems (Amaral-Zettler et al., 2015), indicating the high potential of MP as vectors for transferring microorganisms between even distant habitats, including pathogens or toxin-producing microbes. These hypotheses are supported by the expected longevity of MP in the environment (Peng et al., 2017) by laboratory studies where plastics potentiate the survival of specific groups of microorganisms and their mobile genetic elements (Eckert et al., 2018) studies that have found potential human or animal pathogenic bacteria on MP (Kirstein et al., 2016). However, more long-term and different-spatial scale studies are still required to comprehensively evaluate the relevance of MP for microbial dispersal and biogeography.

4. Microplastic influence evolution by increased horizontal gene transfer

HGT involves three different mechanisms for the movement of genetic material between organisms, other than by transmission from parent to offspring (Soucy et al., 2015). Among these, conjugation requires direct cell-to-cell exchange from a donor to a recipient, while transduction and transformation represent virus-mediated transport and environmental uptake

of DNA, respectively (Drudge & Warren, 2012). All these mechanisms have provided microorganisms with the ability to adapt to changing conditions rapidly. Consequently, the incorporation of those genetic changes in their genomes cause an accelerated evolution of microbial life (Linz et al., 2007). There is a high potential for MP biofilms to transfer mobile genetic elements among habitats, including some genes of human origin.

Microplastic particles are in close contact with humans daily, e.g., in personal care products, drinking water, food, and other types of environmental exposure in the aquatic, terrestrial and atmospheric realms. This situation calls for the urgent need for evaluating their effects on humans following the manifold and differing types of exposure (Hirai et al., 2011). Several important questions have been identified, e.g.(i) to what extent are MP particles entering and subsequently accumulating in the human body? (ii) How do our bodies react when exposed to MP and itsassociated contaminants? Although several indications exist that HGT in the human microbiome is strongly related to human health, HGT between MP biofilms and human microbes has been greatly neglected, yet it may represent another relevant hazard of this emergent universal pollutant. Microplastic could potentiate the distribution of antibiotic resistance determinants in the environment and eventually harm humans and farm animals, as part of other massive anthropogenic interventions in the environment, e.g., solid waste and wastewater discharges (Zhang et al., 2016). Also, an adaptation of Vibrio spp. (often persistent on MP in aquatic ecosystems) to the biofilm lifestyle and other HGT-induced changes areof potential relevance for the development of pathogenic variants and their successful

transfer to the human microbiome.A dsorption of chemical substances by MP, e.g., antibiotics, could provide selective conditions which further induce HGT processes in the natural environment. As sorption can vary widely among polymers, substances, and environmental conditions, potential influences on HGT among MP-associated microbes should be determined in more detail.

5. Fate of microplastics ingested by marine organisms

Different studies did demonstrate that microplastics can be taken up by different marine organisms and once ingested;

5-1. Can be eliminated from the organism through excretion or production of pseudofaeces, thereby having no long-lasting effect on the organism (Browne et al., 2008).

Microplastics can remain within the organism and translocate between tissues as Hall et al. (2015)

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and Van Cauwenberghe and Janssen (2014) found in bivalves and scleractinian corals, respectively.

5-2 Microplastics can be retained and have negative effects on the organisms that ingest them. Laboratory studies have shown the adverse effects of microplastic ingestion. Microplastics can increase toxicological stress in fin whales (Fossi et al., 2016) and affect algal growth (Sjollema et al., 2015). It is known to cause liver toxicity and inflammation, and cause the accumulation of lipids in the liver of fish (Wang et al., 2019). Microplastics can also serve as a vector for the assimilation of persistent organic pollutants (POPs) and heavy metals by marine organisms and the environment (Chua et al., 2014; Brennecke et al., 2016), and reduce the feeding activity of invertebrates (Besseling et al., 2012).

5-3. Lastly, organisms that have ingested microplastics and have microplastics inside them may subsequently be fed upon by other higher animals in the food web thereby, transferring the microplastics to other animals at the trophic level.

6. Interactions between plastics and microorganisms

Microbial assemblages in marine sediments may catalyze metabolic reactions that contribute to the absorption, desorption, and breakdown of microplastic-associated compounds or even the breakdown of the debris itself. Moreover, microplastics may function as sites for the colonization of micro-organisms that possess the capacity to influence the ecology and resident microflora of higher organisms following their ingestion (Deines et al., 2007; Graham and Thompson., 2009). A general summary of the potential yet primarily uncharacterized interactions between microplastics, plastic-associated additives, contaminants, microbial assemblages, and higher organisms is provided in Figure 1.

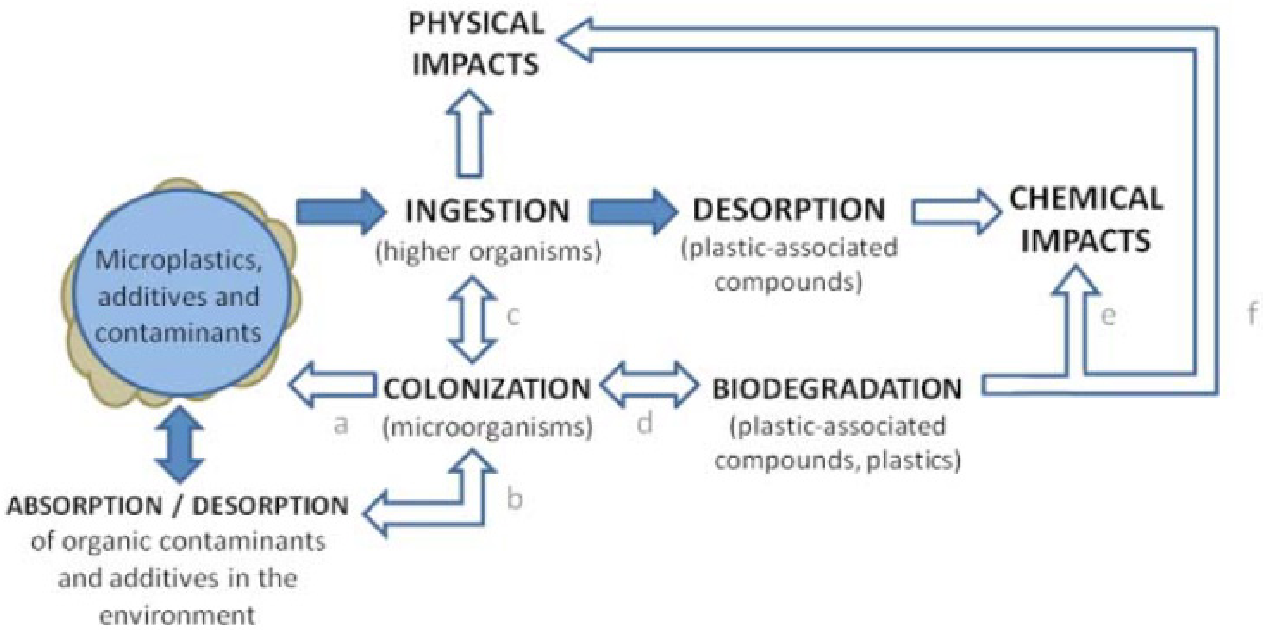

Figure 1. Aschematic illustrating potential interactions between marine microorganisms (bacteria,archaea, and picoeukaryotes) and synthetic microplastics in relation to the wider environmental impacts of this debris. The filled arrows indicate interactions for which experimental evidence exists, and the white arrows correspond to interactions that have not been explored within marine sediments. The colonization of microplastics by microbial assemblages may (a) occur directly, (b) depend on the presence of plastic-associated organic compounds, (c) occur following ingestion by higher organisms and/or become influenced by the gut microflora, (d) mediate activities contributing to the biodegradation of plastic-associated chemicals or the plastics themselves, potentially influencing the extent and severity of the (e) chemical and (f) physical impacts of microplastics on higher organisms.

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Despite long-standing evidence for the ability of floating fragments of plastic to function as-sites for microbial attachment and the subsequent formation of plastic-associated biofilms, the interactions between microorganisms and plastic debris in aquatic ecosystems have received limited attention. In fact, evidence for the ecological impacts of plastic debris on micro-organisms in these environments is largely restricted to demonstrations of the colonization of and survival on polymer surfaces by bacteria and algae in sea-water. Detailed accounts of our understanding concerning the prerequisites and mechanisms underlying the microbial biodegradation of plastics have been provided by Chiellini et al. The biodegradability of synthetic polymers is thought to depend on the type and chemical properties of the plastic, the environment (season-ality and the availability of oxygen)and metabolic interactions within plastic-associated biofilms (Artham et al., 2009; Bonhomme et al., 2003; Gilan et al., 2004). Although research into the biotransformation of plastics has focused on microorganisms from terrestrial habitats, a limited number of experiments have characterized the capacity of microbial assemblages in the water column to utilize synthetic polymers as a resource for growth.

Only two studies have examined the potential for sediment microorganisms in the marine ecosystem to biodegrade plastic debris (Kumar et al., 2007). Overall, the rates of degradation of plastics in marine systems are likely to be significantly lower than in their terrestrial counterparts due to the low availability of oxygen and light (Barnes et al., 2009). Moreover, unequivocal evidence for the biodegradation of plastics is yet to emerge because it is unclear whether microbial activities actively degrade plastic, exploit plastic-associated chemicals, or both.

7. Conclusion

Microplastic pollution, together with gas greenhouse emissions and antibiotic resistance, has the potential to be among the most pressing planetary boundary threats shortly. However, the evaluation of MP-induced effects on human and environmental health is still in the early stage. As presented in this critical review, the repercussions of altering Earth and human microbiomes require long-term analysis and a more microbial ecology perspective. The magnitude of the potential effects of Microplastic on organisms' health and overall ecosystem functioning is still to be determined. Microbial communities are among the first living things to interact with Microplastic, from their emission to the environment to their final destination (sinking and deposition in sediments or accumulation in biota). Consequently, they also link organic matter and elements from abiotic compartments (including plastics) to the rest of the aquatic (and all other) food webs. The effects of Microplastic interactions with aquatic microbiomes and higher organisms therefore should be accounted for in any hazard or health risk assessment of microplastic pollution.

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