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Review

The present and future of microplastic pollution in the marine environment

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ABSTRACT

Recently, research examining the occurrence of microplastics in the marine environment has substantially increased. Field and laboratory work regularly provide new evidence on the fate of microplastic debris. This debris has been observed within every marine habitat. In this study, at least 101 peer-reviewed papers investigating microplastic pollution were critically analysed (Supplementary material). Microplastics are commonly studied in relation to (1) plankton samples, (2) sandy and muddy sediments, (3) vertebrate and invertebrate ingestion, and (4) chemical pollutant interactions. All of the marine organism groups are at an eminent risk of interacting with microplastics according to the available literature. Dozens of works on other relevant issues (i.e., polymer decay at sea, new sampling and laboratory methods, emerging sources, externalities) were also analysed and discussed. This paper provides the first in-depth exploration of the effects of microplastics on the marine environment and biota. The number of scientific publications will increase in response to present and projected plastic uses and discard patterns. Therefore, new themes and important approaches for future work are proposed.

1. Introduction

In 1972, E. J. Carpenter and K. L. Smith became the first researchers to sound the alarm on the presence of plastic pellets on the surface of the North Atlantic Ocean. In their publication in *Science*, they stated: "*The increasing production of plastic, combined with present waste-disposal practices, will probably lead to greater concentrations on the sea surface… At present, the only known biological effect of these particles is that they act as a surface for the growth of hydroids, diatoms, and probably bacteria*". Not surprisingly, only months later, the ingestion of those same polyethylene pellets by fish was reported (Carpenter et al., 1972). The prediction by Carpenter and Smith (1972) is the focus of the scientific community that is studying the smallest plastic debris pollution sizes (Moore, 2008; Barnes et al., 2009; Thompson et al., 2009; Ryan et al., 2009; Andrady, 2011). Several million tonnes of plastics have been produced since the middle of the last century (more than two hundred million tonnes annually) (Barnes et al., 2009; Thompson et al., 2009; Andrady, 2011). Speculation exists over how much of this plastic will end up in the ocean, where it suffers degradation and fragmentation (Barnes et al., 2009; Andrady, 2011). In the environment, microplastic debris (<5 mm) proliferates, migrates and accumulates in natural habitats from pole to pole and from the ocean surface to the seabed; the debris is also deposited on urban beaches and pristine sediments (Moore, 2008; Barnes et al., 2009; Thompson et al., 2009; Ryan et al., 2009). This type of pollution is ubiquitous and persistent in the world's oceans and openly threatens marine biota.

Plastic means "malleable" or "flexible". Indeed, these synthetic materials can be moulded into virtually any shape (Moore, 2008). Plastics are versatile materials that are inexpensive, lightweight, strong, durable and corrosion-resistant. They have high thermal and electrical insulation values (Thompson et al., 2009) and are incredibly practical. Plastics are formed by long chains of polymeric molecules that are created from organic and inorganic raw materials, such as carbon, silicon, hydrogen, oxygen and chloride; these materials are usually obtained from oil, coal and natural gas (Shah et al., 2008). Currently, the most widely used synthetic plastics are low- and high-density polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET). Altogether, these plastics represent ~90% of the total world production (Andrady and Neal, 2009). Thus, it is widely

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accepted that the majority of the items polluting coastal and marine environments are comprised of these materials (Andrady, 2011; Engler, 2012).

Most synthetic polymers are buoyant in water (e.g., PE and PP). Consequently, substantial quantities of plastic debris that are buoyant enough to float in seawater are transported and eventually washed ashore (Thompson et al., 2009; Andrady, 2011; Engler, 2012). The polymers that are denser than seawater (e.g., PVC) tend to settle near the point where they entered the environment; however, they can still be transported by underlying currents (Engler, 2012). Additionally, microbial films rapidly develop on submerged plastics and change their physicochemical properties (i.e., surface hydrophobicity and buoyancy) (Lobelle and Cunliffe, 2011). If these fragments sink, then the seabed becomes the ultimate repository for the plastics (including those that were initially buoyant) (Barnes et al., 2009).

Polymers are rarely used as pure substances. Typically, resins are mixed with additives to enhance their performance (Andrady and Neal, 2009; Teuten et al., 2009). Considerable controversy exists over the extent to which additives that are released from plastic products (e.g., phthalates and bisphenol A) adversely affect animals and humans (Andrady and Neal, 2009; Thompson et al., 2009; Teuten et al., 2009; Lithner et al., 2009, 2011). More information is available from Thompson et al. (2009) and Cole et al. (2011), among others.

Additionally, the hydrophobic pollutants available in seawater may adsorb onto plastic debris in ordinary environmental conditions (Thompson et al., 2009; Cole et al., 2011). The majority of these pollutants are persistent, bioaccumulative and toxic; thus, they are of particular concern for human and environmental health (Engler, 2012). Plastics not only have the potential to transport contaminants, but they can also increase their environmental persistence (Teuten et al., 2009). This highlights the importance of plastic as vehicles of pollutants to marine biota and humans (Teuten et al., 2009; Tanaka et al., 2013).

Small plastics enter the environment directly, whereas larger items are continuously fragmenting (Barnes et al., 2009). Primary-sourced microplastics (Arthur et al., 2009) are directly released to the environment in the form of small (μm) pellets that are used as abrasives in industrial (shot blasting) (Gregory, 1996) and domestic applications (e.g., Fendall and Sewell, 2009); they can also be released by spilling virgin plastic pellets (mm) (Thompson et al., 2009). Facial cleansers that are used by millions of people, especially in developed countries, contain PS particles (μm) that directly enter sewage systems and adjacent coastal environments (Zitko and Hanlon, 1991; Gregory, 1996; Fendall and Sewell, 2009). Moreover, laboratory experiments using *Sphaeroma quoianun* indicated that isopods can produce millions of PS fragments, which resemble plastic pellets, when incrusted in buoys in the Pacific Ocean (Davidson, 2012).

Larger plastics eventually undergo some form of degradation and subsequent fragmentation, which leads to the formation of small pieces (Shah et al., 2008; Costa et al., 2010; Andrady, 2011). Degradation is a chemical change that reduces the average molecular weight of polymers (Andrady, 2011). The most-used polymer types (i.e., PE and PP) have high molecular weights and are non-biodegradable (Shah et al., 2008). However, once in the marine environment, they start to suffer photo-oxidative degradation by UV solar radiation, followed by thermal and/or chemical degradation. This renders plastics susceptible to further microbial action (i.e., biodegradation) (Shah et al., 2008; Andrady, 2011). The light-induced oxidation is orders of magnitude higher than other types of degradation (Andrady, 2011). Any significant extent of degradation inevitably weakens the plastic, and the material become brittle enough to fall apart into powdery fragments (Andrady, 2011) when subjected to sea motion. This process essentially occurs forever (Barnes et al., 2009), including on the molecular level (Andrady, 2011).

Reports of plastics have spread rapidly in terms of geography, marine habitat and biota influenced (Barnes et al., 2009; Ryan et al., 2009). It was hypothesised that microplastics accumulate in the centres of subtropical gyres, but their means of movement and transport in the sea are largely unknown (Hidalgo-Ruz et al., 2012), especially along the vertical axis. Environmental microplastics are available to every level of the food web, from primary producers (Oliveira et al., 2012) to higher trophic-level organisms (Wright et al., 2013). Individuals who ingest microplastics may suffer physical harm, such as internal abrasion and blockage. Impacts at the population-level are also possible, but largely unknown (Wright et al., 2013). Plastic pellets are also used as oviposition sites by insects, such as *Halobates micans* and *H. sericeus*, which can affect their abundance and dispersion (Majer et al., 2012; Goldstein et al., 2012). In the western Atlantic, 24% of the pellets ($N > 1000$) had eggs attached to their surface, most with viable embryos. In the North Pacific Ocean, the numbers of adults, juveniles and eggs (*H. sericeus*) were significantly correlated with microplastic abundance. Although it is still risky to conclude the magnitude of this problem (i.e., transport of fouling species), it is fair to consider plastics as potential vectors that transport species to previously unknown mobility levels (Barnes et al., 2009).

As predicted (e.g., Carpenter et al., 1972), microplastic pollution became widespread with significant implications for ecosystems and organisms in a variety of forms. Supporting evidence has been published in peer-reviewed journals from the 1971 benchmark paper by Buchanan (1971) to the present. In this context, the present work aims to sort, critically analyse, and synthesise the recent literature regarding microplastics at sea, as well as highlight the risks to and effects on the marine biota. The Arthur et al. (2009) definition of microplastics was adopted (fragments and primary-sourced plastics that are smaller than 5 mm) as the main criteria for discerning a specific size class of plastic pollution. A periodic critical assessment of this issue is essential, especially because the problem is mounting and will persist for centuries, even if pollution is immediately stopped (Barnes et al., 2009).

2. Results

Results from the scientific literature were classified according to the main focus of each work: (1) the presence of microplastics in plankton samples; (2) the presence of microplastics in sandy and muddy sediments; (3) the ingestion of microplastics by vertebrates and invertebrates; (4) microplastics' interactions with chemical pollutants (see the supplementary content in Tables S1, S2, S3, S4 and S5). Papers in each category were analysed for their most relevant findings to improve and advance discussions on microplastics at sea.

One hundred and one documents from various sources fulfilled the review criteria (Table 1). Two works were included in more than one category: Carpenter et al. (1972) and Thompson et al. (2004). Fourteen literature reviews, from 2008 to 2013, on microplastics in the marine environment were also consulted. Research related to the development of new sampling or laboratory methods and/or analytical procedures, the (bio)degradation of plastics and other relevant issues were used when appropriated. Approximately 80% of the articles were published in the last 15 years, and more than 60% of the articles were published in the last 5 years.

2.1. Plankton samples and floating microplastics

The notion of using surface plankton samples to diagnose pelagic areas in relation to the presence and amount of floating

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