PAPER

Interactions Between Microorganisms and Marine Microplastics: A Call for Research

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ABSTRACT

Synthetic thermoplastics constitute the majority by percentage of anthropogenic debris entering the Earth's oceans. Microplastics (≤5-mm fragments) are rapidly emerging pollutants in marine ecosystems that may transport potentially toxic chemicals into macrobial food webs. This commentary evaluates our knowledge concerning the interactions between marine organisms and microplastics and identifies the lack of microbial research into microplastic contamination as a significant knowledge gap. Microorganisms (bacteria, archaea, and picoeukaryotes) in coastal sediments represent a key category of life with reference to understanding and mitigating the potential adverse effects of microplastics due to their role as drivers of the global functioning of the marine biosphere and as putative mediators of the biodegradation of plastic-associated additives, contaminants, or even the plastics themselves. As such, research into the formation, structure, and activities of microplastic-associated microbial biofilms is essential in order to underpin management decisions aimed at safeguarding the ecological integrity of our seas and oceans.

Keywords: microplastics, microorganisms, marine, sediment, biodegradation

Introduction

We live in the Plastic Age, with industrialized nations now reliant on synthetic polymers in most aspects of our lives. The worldwide demand for plastics is estimated to have annually increased by 10% since the 1950s, with their total mass of production reaching 245 million tons in 2006 (Andrady and Neal, 2009; PlasticsEurope, 2008). Given this 600-fold increase in predicted consumption during the past 60 years, synthetic thermoplastics (e.g., polyethylene) comprise the most abundant and rapidly growing component of anthropogenic debris entering the Earth's oceans (Derraik, 2002; Moore, 2008; Barnes et al., 2009; Law et al., 2010). The increasing significance of this debris as a descriptor of the ecological integrity of marine ecosystems is recognized in environmental treaties across the globe, including the multilateral European Marine Strategy Framework Directive (Cheshire et al., 2009; Galgani et al., 2010; GESAMP, 2010).

Plastic waste is globally distributed across both surface waters and sediments within the marine environment, reflecting the widespread use of polymer products and their ability to resist physical and biological degradation for centuries (Galgani et al., 2000; Moore et al., 2001; Katsanevakis and Katsarou, 2004; Sudhakar et al., 2007a, 2007b; Andrady and Neal, 2009). The environmental fate of this waste is controlled by human activities and hydrogeological factors (e.g., littering, accidental disposal, and oceanic circulation), with an excess of 200,000 plastic fragments having been discovered within a square kilometer of water in the North Atlantic Subtropical Gyre (Galgani et al., 2000; Katsanevakis and Katsarou, 2004; Morishige et al., 2007; Law et al., 2010). Since the majority of synthetic polymers sink in seawater, sediments function as sinks for the accumulation of plastic debris (Moore, 2008; Barnes et al., 2009). For example, up to 47.4 kg/km^2 of anthropogenic debris have been discovered in the Eastern Mediterranean seabed, over half of which was comprised by plastic (Koutsodendris et al., 2008). In comparison, 5.1 kg/km^2 of floating plastics have been described in the North Pacific Central Gyre (Moore et al., 2001; Ryan et al., 2009).

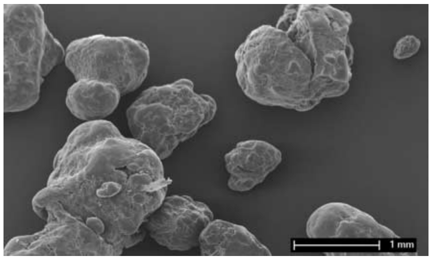
The ubiquity and persistence of synthetic polymers are promoting global public concern about the impacts of plastic pollution on marine wildlife. These impacts are most apparent when considering the risks of entanglement in and ingestion of readily visible (≥5 mm) fragments of plastic by higher organisms, such as birds and fish (Laist, 1987; Derraik, 2002; Moore, 2008; Gregory, 2009). Other impacts of plastic waste on marine animals include the transport of invasive species and alterations in the structure of macrobial communities in the seabed (Barnes, 2002; Katsanevakis et al., 2007; Gregory, 2009).

Within the last decade, increasing attention has been directed toward the proliferation and potential environmental impacts of microplastics (≤5-mm fragments) in marine ecosystems (Figure 1) (Thompson et al., 2004; Arthur et al., 2009; Barnes et al., 2009). However, we only possess an elementary understanding of the interactions of this debris with higher organisms (Barnes et al., 2009). In addition, although microorganisms (bacteria, archaea, and picoeukaryotes) mediate functions that sustain life in our oceans and could facilitate the breakdown of microplastic-associated chemical compounds or even of the debris itself, little research has been directed toward assessing the interactions between microplastics and microbial communities in marine ecosystems.

This commentary assesses our knowledge concerning the potential ecological impacts of microplastics on marine organisms in order to identify avenues for novel microbial research. First, our understanding concerning the interactions between microplastics and higher organisms is evaluated. Second, a brief appraisal of the role of microorganisms as drivers of the functioning of marine ecosystems is provided. Third, published studies into microbial-plastic interactions are explored with the aim of identifying key opportunities for future research. Given the role of the sediment environment as a sink for plastic pollution, emphasis is given to microbial-plastic interactions in the seabed.

FIGURE 1

Scanning electron microscope image of polyethylene microfragments.



The Emergence and Potential Impacts of Microplastics

Although the accumulation of small fragments of plastics in the marine environment has been recognized since the 1970s, research into their sources, distribution, fate, and ecological impacts has only gained momentum during the last decade, following the identification of microplastics as a distinct category of anthropogenic debris (Carpenter et al., 1972; Carpenter and Smith, 1972; Colton et al., 1974; Morris and Hamilton, 1974; Thompson et al., 2004; Arthur et al., 2009). Since then, it has become evident that microplastics are entering marine habitats at a global scale, either as a result of the photo-oxidative, hydrolytic, and mechanical breakdown of larger plastics or as components of industrial and domestic waste (Thompson et al., 2004; Koutny et al., 2006; Ng and Obbard, 2006; Browne et al., 2007; Moore, 2008; Barnes et al., 2009; Corcoran et al., 2009; Fendall and Sewell, 2009). Therefore, microplastics are likely to constitute the numerically most abundant type of plastic debris in marine ecosystems, particularly in coastal environments (Barnes et al., 2009; Corcoran et al., 2009; Browne et al., 2010). For example, at least two billion microscopic fragments of plastic have been estimated to have entered Californian coastal waters over 3 days, merely via two rivers (Moore et al., 2005). Moreover, at an intertidal site near a ship-wrecking yard in India, microplastics have been discovered in the sediment at a concentration of 81 parts per million (Reddy et al., 2006).

While microplastics may represent a physical hazard to marine animals as in the case of larger plastic fragments (e.g., via ingestion), their prevalence, high bioavailability and surface area-to-volume ratio have promoted significant additional concern over the ability of this type of debris to function as a substrate for the accumulation on and transport of plastic additives and persistent organic pollutants (e.g., polycyclic aromatic hydrocarbons and polychlorinated biphenyls) (Mato et al., 2001; Masó et al., 2003; Rios et al., 2007; Teuten et al., 2007; Karapanagioti and Klontza, 2008; Teuten et al., 2009; Colabuono et al., 2010). The selective ingestion and subsequent bioaccumulation of microplastics has been demonstrated for suspension- and deposit-feeding invertebrates at the base of marine food webs, and there is partial evidence for the transport of these fragments to higher trophic levels (Eriksson and Burton, 2003; Thompson et al., 2004; Teuten et al., 2007; Browne et al., 2008; Graham and Thompson, 2009; Teuten et al., 2009). It has been estimated that the presence of a single microgram of phenanthrene-contaminated polyethylene in a gram of sediment significantly increased the body burden of this priority contaminant for the lugworm *Arenicola marina* (Teuten et al., 2007). The desorption of plastic-associated contaminants in the gut has also been demonstrated for seabirds (Teuten et al., 2009). As such, microplastics may constitute a threat to the functioning of marine ecosystems, which parallels that of engineered nanomaterials (Zhu et al., 2006; Blickey and McClellan-Green, 2008; Koehler et al., 2008).

In the following sections, the significance of microorganisms in the maintenance of the ecological integrity of the marine environment and in potential interactions with synthetic microplastics is further illustrated. For a comprehensive discussion of how microorganisms drive the biogeochemistry of marine ecosystems, the reader is referred to reviews by Arrigo (2005), Azam and Malfatti (2007), Karl (2007), Falkowski et al. (2008), and Strom (2008).

Microorganisms and the Marine Biosphere

Microorganisms are incredibly abundant in marine ecosystems and may reach up to hundreds of millions of bacterial cells in a gram of wet marine sediment (Amann et al., 1995; Sievert et al., 1999). The metabolically active fraction of these cells underpins the functioning of marine food webs by catalyzing redox reactions that control primary productivity and the cycling of nutrients (including nitrogen, phosphorus, and sulphur) in the oceans (López-Urrutia et al., 2006; Hamasaki et al., 2007; Falkowski et al., 2008; Gasol et al., 2008). As such, the entire marine carbon cycle is tightly coupled to elemental cycles that are exclusively mediated by microorganisms (Arrigo, 2005; Madsen, 2008).

Marine sediments provide habitats for microbial growth that are fundamentally different from those in the water column (Falk et al., 2007). Horizontal and vertical gradients of physical and geochemical parameters (e.g., pH, oxygen, organic carbon, nutrients, and light) are thought to structure the local composition and activities of microbial communities in the seafloor at the scale of millimeters (Edlund et al., 2008; Köster et al., 2008; Wu et al., 2008). The responsiveness of these communities to variation in habitat physicochemistry and the availability of growth substrata render the composition and metabolic activities of microbial assemblages within the seafloor potentially vulnerable to perturbation. Moreover, most of the biogeochemical transformations mediated by marine microorganisms occur in coastal sediments, which are at greater risk of exposure to human activities (including the disposal of synthetic plastics) than off-shore sites (Walsh, 1991; Moore, 2008; Wu et al., 2008).

Given the high metabolic potential of microbial communities in the seafloor, coastal habitats represent an untapped resource of microbial taxa that may contribute to the biodegradation of plastics and plastic-associated compounds (Wu et al., 2008). In order to guide both environmental and applied research into the responses of microorganisms to marine microplastics, it is pertinent to consider existing research into microbial-plastic interactions.

Interactions Between Plastics and Microorganisms

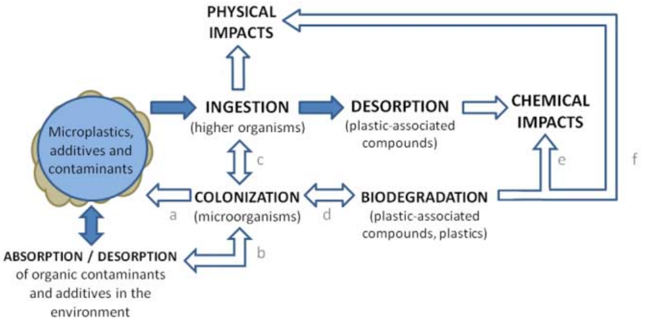
Microbial assemblages in marine sediments may catalyze metabolic reactions that contribute to the absorption, desorption and breakdown of microplastic-associated compounds or even the breakdown of the debris itself. Moreover, microplastics may function as sites for the colonization of microorganisms 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 2.

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 (Carpenter et al., 1972; Carpenter and Smith, 1972; Morris and Hamilton, 1974). In fact, evidence for the ecological impacts of plastic debris on microorganisms in these environments is largely restricted to demonstrations of the colonization of and survival on polymer surfaces by bacteria and algae in seawater (Masó et al., 2003; Webb et al., 2009; Dang et al., 2008; Tatchou-Nyamsi-König et al., 2008, 2009). Detailed accounts of our understanding concerning the prerequisites and mechanisms underlying the microbial biodegradation of plastics have been provided by Chiellini et al. (2003), Gu (2003), Kawai et al. (2004), Koutny et al. (2006), Lucas et al. (2008), Shah et al. (2008), and Eubeler et al. (2010).

The biodegradability of synthetic polymers is thought to depend on the type and chemical properties of the plastic, the environment (e.g., seasonality and the availability of oxygen) and metabolic interactions within plastic-associated biofilms (Bonhomme et al., 2003; Gilan et al., 2004; Artham et al., 2009). Although research into the biotransformation of plastics has focused on microorganisms from terrestrial habitats (e.g., Chiellini et al., 2003; Arkatkar et al., 2009), a limited

FIGURE 2

A schematic 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.



number of experiments have characterized the capacity of microbial assemblages in the water column to utilize synthetic polymers as a resource for growth (Table 1). Only two studies have examined the potential for sediment microorganisms in marine ecosystems to biodegrade plastic debris (Kumar et al., 2007; Balasubramanian et al., 2010). 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 the plastic, exploit plastic-associated chemicals, or both (Koutny et al., 2006; Lucas et al., 2008; Eubeler et al., 2010).

Opportunities for Future Research

This commentary has highlighted several potential avenues for novel research into the interactions between marine microorganisms and synthetic microplastics:

1. *Fundamental research into the ecological responses of microorganisms to the deposition of microplastics and plastic-associated chemicals into our seas and oceans*

   In order to facilitate the management of microplastic pollution, our efforts must be focused on understanding how the deposition of this debris into sediment habitats affects those taxa and life stages that are most likely to be exposed to microplastics and which mediate ecosystem services that sustain marine life (Arthur et al., 2009; Galgani et al., 2010). While we are beginning to address these questions with reference to invertebrate species at the base of macrobial food webs, it is pertinent to recognize that microorganisms underpin the functioning of marine ecosystems by driving primary productivity and elemental cycling (Madsen, 2005; Falkowski et al., 2008). This control of ecosystem functioning by microbial interactions, coupled to advances in molecular methodologies, has encouraged interest in the utilization of prokaryotes and microbial eukaryotes as sensitive indicators of ecosystem health (Paerl et al., 2003; Cao et al., 2006; Chiu et al., 2008; Marshall et al., 2008; Mojtahid et al., 2008; Tett et al., 2008). In this respect, research into the potential for the deposition of microplastics into the marine environment to impact on microbially mediated biogeochemical processes is of significant interest.
2. *Wider research into the colonization and biodegradation of synthetic polymers by microorganisms*

   There is a fundamental lack of information concerning the potential for microplastics in marine ecosystems to function as hotspots for the attachment of microbial assemblages originating from the wider environment. Furthermore, our understanding concerning the biodegradation of plastics and plastic-associated compounds is constrained by the fact that most research into this topic has been based on the utilization of culture-based methodologies or unidentified microbial assemblages (Table 1). Only 1% or fewer of all bacterial taxa are thought to be cultivable in the laboratory (Amann et al., 1995). Therefore it is likely that most marine microorganisms potentially participating in the degradation of plastic debris and plastic-associated chemicals remain undiscovered and could be characterized by culture-independent molecular analyses. Since culture-independent methods (e.g., microscopy, gene sequencing and

TABLE 1

Examples of existing research into the biodegradation of synthetic plastics by pelagic microorganisms.

Microbial Taxa	Plastic Type	Environment	Exposure	Comments	References
Pseudomonas sp. B2	Polycarbonate film containing bisphenol A (BPA)	Marine	*In situ* and *in vitro*	9% loss of mass over 12 months, leaching of BPA	Artham and Doble (2009)
Unidentified consortium	Polycarbonate, polyethylene and polypropylene coupons	Marine	*In situ*	Degradation dependent on plastic type and season	Artham et al. (2009)
Unidentified consortium	Polyethylene film containing pro-oxidant additives	Freshwater	*In situ*	Degradation dependent on degree of polymer oxidation	Chiellini et al. (2007)
Unidentified consortium	Polyethylene films with and without starch additive	Marine	*In situ* and *in vitro*	Little or no evidence for degradation over 20 months	Rutkowska et al. (2002a)
Unidentified consortium	Polyurethane sheets	Marine	*In situ* and *in vitro*	Degradation dependent on polymeric cross-linking	Rutkowska et al. (2002b)
Bacillus cereus, B. sphericus, Vibrio furnisii, Brevundimonas vesicularis	Nylon pellets	Marine	*In vitro*	Degradation varied across microbial taxa (highest for *B. cereus*)	Sudhakar et al. (2007a)
Pseudomonas spp., *Clostridium* spp., unidentified anaerobic, hetetrophic and iron-reducing bacteria, fungi	Polyethyelene and polypropylene sheets	Marine	*In situ*	Degradation dependent on study site, plastic type and season	Sudhakar et al. (2007b)
B. cereus subgroup A, *B. sphericus* GC subgroup IV	Polyethylene sheets	Marine	*In vitro*	Degradation dependent on type of polyethylene	Sudhakar et al. (2008)

community fingerprinting) are also pivotal in the monitoring of marine environmental change, the applications of microbial ecology in improving our ability to understand the potential adverse effects of global microplastic pollution are bound to offer significant opportunities for future research (Osborn et al., 2000; Daims et al., 2005; Röling and Head, 2005).

3. *Research in order to determine spatio-temporal patterns in the taxonomic composition and functional potential of plastic-colonizing microbial assemblages in different types of sediment and in contact with higher organisms*

These investigations must be combined with attempts to characterize the potential for the *in situ* biotransformation of microplastic-associated additives, contaminants, and the polymers themselves. Together with a combination of traditional and molecular microbiological tools, an experimental approach to unraveling microbial-microplastic interactions will be essential to the translation of primary research into management measures aimed at the safeguarding of marine life.

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