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Microbial hitchhikers of marine plastic debris: human exposure risks at bathing waters and beach environments

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Abstract

Marine plastic debris is well characterized in terms of its ability to negatively impact terrestrial and marine environments, endanger coastal wildlife, and interfere with navigation, tourism and commercial fisheries. However, the impacts of potentially harmful microorganisms and pathogens colonising plastic litter are not well understood. The hard surface of plastics provides an ideal environment for opportunistic microbial colonisers to form biofilms and might offer a protective niche capable of supporting a diversity of different microorganisms, known as the "Plastisphere". This biotope could act as an important vector for the persistence and spread of pathogens, faecal indicator organisms (FIOs) and harmful algal bloom species (HABs) across beach and bathing environments. This review will focus on the existent knowledge and research gaps, and identify the possible consequences of

plastic-associated microbes on human health, the spread of infectious diseases and bathing water quality.

Keywords: marine plastic debris; microplastics; biofilms; pathogens; bathing water quality; public health

1. Introduction

Marine plastic debris is an environmental pollutant of growing concern, with its detrimental effects on aquatic and coastal wildlife already well documented (Hammer et al., 2012; Gregory, 2009; Derraik, 2002). The durable, light weight and inexpensive nature of plastic has made it a ubiquitous choice for many industrial and consumer products (Osborn and Stojkovic, 2014). More than 200 M tonnes of plastic are produced annually worldwide (Ivar do Sul and Costa, 2014), facilitating its entry and accumulation in coastal waters and beach environments. Approximately 4.8 – 12.7 M tonnes of plastic waste entered the ocean from 192 coastal countries in 2010 alone (Jambeck et al., 2015), with global changes in rainfall, wind speed, and more frequent flood and storm events predicted to further increase the amount of stranded and drifting plastics in the coastal zone (Young et al., 2011; Gulev and Grigorieva, 2004; Meier and Wahr, 2002; Goldenberg et al., 2001).

1.1 Size, origin, accumulation and impacts of marine plastic debris

Marine plastic debris includes large, macro particles such as carrier bags, bottles and fishing gear (Eriksen et al., 2014), and now more frequently microplastics and nanoplastics (Driedger et al., 2015; Andrady, 2011). Microplastics, defined generally as plastic particles less than 5 mm in diameter (NOAA, 2009), include "primary" microplastics present in cosmetic care products, clothes fibres, and the industrial discharge of virgin plastic production pellets (Eerkes-Medrano et al., 2015; Wagner et al, 2014; Browne et al., 2011; Cole et al., 2011; Fendall and Sewall, 2009), along with “secondary” microplastics that frequently enter waterways through the breakdown of macro particles by a combination of physical, biological and chemical processes (Ryan et al., 2009; Thompson et al., 2004). The majority of plastic debris entering the oceans are a result of the direct and improper disposal of terrestrial waste and the discard of plastics at sea (Hammer et al., 2012; Barnes et al., 2009). In addition, rivers, tides, wind, heavy rainfall, and storm and sewage discharge facilitate the dispersal of both macro and microplastics within marine and freshwater environments (Wagner et al., 2014; Reisser et al., 2013), with an estimated 5.25 trillion plastic particles weighing approximately 269,000 tonnes currently floating in the sea (Eriksen et al., 2014). However, this number is likely to be much higher, with a recent study by Van Sebille et al. (2015) estimating microplastic abundance (defined here as those plastic particles <200 mm in diameter) to range from 15 to 51 trillion particles, and weighing between 93 to 236 thousand metric tonnes.

The impacts of marine plastic debris go beyond simply posing a threat to marine wildlife (Figure 1). Marine plastics can lead to economic losses by interfering with the shipping and fishing industries, and posing a significant threat to recreational tourism (Pichel et al., 2007; Sheavly and Register, 2007). Beaches polluted with medical and sanitary waste constitute a public health risk, devalue the experience of beachgoers, and can often require costly beach-cleaning efforts (Moore, 2008). With quantities of beach-cast plastic expected to rise due to more severe weather events, coastal areas dependent on tourism are likely to face a number of socio-economic challenges (Mcllgorm et al., 2011).

1.2 Plastic as a rafting material, the formation of biofilms, and the potential for transport of harmful microorganisms

Plastic debris can provide a novel mechanism for the spread of invasive and alien species, in addition to that facilitated by natural substances like rafts of vegetation, wood, or pumice (Bryan et al., 2012; Minchinton, 2006; Jokiel, 1990). A diverse range of organisms has already been found colonising macro-plastics, and in some cases has led to the introduction of non-native species into new habitats (Gregory, 2009; Barnes 2002*a*; Barnes 2002*b*). Until very recently, however, little attention has been paid to the concept of plastic providing a novel means of spatial and temporal transport for microorganisms across marine and coastal environments (Amaral-Zettler et al., 2015; Caruso, 2015). The physical properties of plastic can provide a unique habitat capable of supporting diverse microbial communities (Zettler et al., 2013; Harrison et al., 2011), with the buoyant and persistent nature of plastic possibly contributing to the survival and long-distance transport of those microbial hitchhikers that associate with its surface. The biofilms that colonise this so-called plastisphere could also be a reservoir for pathogenic microbes, faecal indicator organisms (FIOs) and harmful algal bloom (HAB) species. Plastic debris could therefore be acting as a potential vector for the wide-scale dissemination of these organisms (Oberbeckmann et al., 2015; Zettler et al., 2013; Masó et al., 2003).

1.3 Plastic debris and its unknown impact on beach and bathing environments

A few recent studies have shown evidence for the formation of biofilms by bacteria and FIOs (such as *E. coli*) on plastic water distribution pipes (Yu et al., 2010; Lehtola et al., 2004), and the persistence of potentially harmful pathogens (such as certain strains of *Vibrio* spp.) on plastic debris (McCormick et al., 2014; Zettler et al., 2013), although this is speculative at best. However, the ability of microorganisms to persist on beach-stranded plastic debris and increase dissemination of potentially pathogenic microbes in coastal zones needs urgent addressing to allow regulators and beach managers to make more informed decisions about public safety at bathing environments. Beaches and coastal environments form some of the most ecologically and socio-economically important habitats worldwide (Harley et al., 2006), and ecosystem services in these areas are already facing significant pressure from anthropogenic activities (Quilliam et al., 2015; Schlacher et al., 2007*a*; 2006). In Europe, the quality of bathing water and safety of beaches is governed by the EU Bathing Water Directive (BWD; 2006/7/EC). The BWD sets standards for microbial water quality via the use of FIOs for the assessment of faecal pollution. The BWD also requires the production of a Bathing Water Profile (BWP) for all designated EU bathing waters (Mansilha et al., 2009), which contains details on the nature of possible pollution sources that could have negative impacts on a bather's health (Schernewski et al., 2012). Designations such as the Blue Flag award are also largely driven by the BWD.

Epidemiological studies have reported the relationship between bathing water quality and the occurrence of adverse human health effects such as gastrointestinal (GI) symptoms, respiratory diseases, and eye, nose and throat infections (Wade et al., 2006, Zmirou et al., 2003; Prüss, 1998). Whilst most of these studies have focused on waters impacted by municipal-wastewater effluent, the impacts of other diffuse sources of pollution remain relatively unexplored (Soller et al., 2010). With the potential of plastic providing a possible site for pathogen and FIO attachment, and the subsequent dissemination of these organisms in the marine environment, a better understanding of these processes is required in order to ensure beach safety. Assessing beach and bathing environments for stranded plastic debris and analysing it for associated FIOs and pathogens could provide a better insight into the quality of European bathing waters through the production of a more detailed BWP, as well as enabling plastic debris to qualify as a potential indicator and carrier of FIOs and pathogens that could present a risk to human health. This could further help prevent economic losses associated with beach closures, and enable beaches to maintain their Blue Flag status (Schernewski et al., 2012; Wyer et al., 2010).

Against a backdrop of changing climate, the persistent multi-pollutant effects of plastic debris in coastal environments increases the urgency to understand the risks of human exposure to plastic pollution and inform more sustainable beach management options. The aim of this review is to explore the potential of marine plastics to serve as a mechanism for the persistence and transmission of FIOs and potentially pathogenic or harmful microorganisms, and the pathways of human exposure risk in coastal environments.

2. The Plastisphere: an anthropogenic ecological habitat

Biofilms are formed by the microbial secretion of extracellular polymeric substances (EPS), which include proteins, glycoproteins, and glycolipids (Flemming et al., 2007) that act as a type of architectural scaffolding, forming a matrix around microbes and enabling their attachment to a variety of different biotic and abiotic surfaces (O'Toole et al., 2000). This helps provide a protective environment that enables microorganisms to grow in hostile habitats and facilitates easy dispersal (Hall-Stoodley and Stoodley, 2005). Microorganisms can form biofilms on any artificial or natural surface, including medical equipment (such as catheters, implants, and pacemakers) and copper and plastic pipes of water distribution systems (Costerton et al., 2005; Lehtola et al., 2004). Studies have demonstrated that the surfaces of different types of plastics, such as polyethylene (PE) and polyethylene terephthalate (PET), are rapidly colonised by heterotrophic bacteria when submerged in seawater and that these organisms are able to survive for longer periods than those in the surrounding seawater (Webb et al., 2009; Lobelle and Cunliffe, 2011). Interestingly, these studies also found significant changes in the physiochemical properties of the plastic samples, with Webb et al. (2009) hinting at the existence of plastic-degrading bacteria. There is now an increasing amount of anecdotal evidence that suggests that microbes degrade marine plastic debris (Reisser et al., 2014; Zettler et al., 2013; Webb et al., 2009), although this is not supported by any actual data measurements, e.g. changes in tensile strength or contact angle measurements.

Successional changes in bacterial colonisation of artificial surfaces including glass, stainless steel and polycarbonate sheets have been demonstrated in seawater, with early-stage colonisation often marked by higher species richness (Jones et al., 2006; Jackson et al., 2001). *Alphaproteobacteria* was found to be the most dominant group of colonising bacteria on acryl, glass, steel and polycarbonate substrata, with *Gammaproteobacteria* mainly occurring during the early colonisation stages in the first 9 hours, indicating that initial colonisation might be substrate-specific (Lee et al., 2008; Jones et al., 2006). *Gammaproteobacteria* are an ecologically diverse group of Gram-negative bacteria that contain a number of potentially pathogenic strains of *Salmonella* spp. and *Vibrio* spp. that might be harmful to human health. Since certain strains of *Vibrio* spp. are recognised to readily colonise plastics, the potential of pathogenic species of *Vibrio*, including for example *Vibrio cholerae* that causes cholera, to colonise plastic requires urgent investigation, particularly in light of prescient knowledge that plastic debris can easily be dispersed in the marine environment (Zettler et al., 2013).

Reports of biofilms on plastic waste in the environment are limited (summarised in Table 1). Biofilm formation on plastic debris was first reported in 1972 in the Sargasso Sea, where bacterial communities were found colonising floating microplastic particles (Carpenter et al., 1972; Carpenter and Smith, 1972). Zettler et al. (2013) conducted the first high-throughput sequencing study of its kind, which characterised the composition of microbial communities colonising six micro and macro pieces of PE and polypropylene (PP) collected from geographically distinct open ocean areas of the North Atlantic Subtropical Gyre. The plastisphere community consisted of a morphologically diverse range of microbes that comprise a dense mix of eukaryotic and prokaryotic cells, such as diatoms, coccolithophores, dinoflagellates, fungi and bacteria (Zettler et al., 2013). However, how representative these results are in relation to the wider plastisphere communities remains unclear, since these were generated from just six plastic fragments collected from only one environment

Amaral-Zettler et al. (2015) provide a more comprehensive study of the bacterial communities found on plastic debris collected from two different environments, the North Pacific and North Atlantic subtropical gyres, using DNA sequencing techniques. Their findings, although lacking taxonomic details, highlight significant differences between bacteria found in the water column and those attached to plastic debris, along with differences in plastisphere-communities collected from the two different ocean basins (Amaral-Zettler et al., 2015). Polymer type appeared less important in determining bacterial colonisation, with significant differences only occurring between polystyrene and PE, or polystyrene and polypropylene (Amaral-Zettler et al., 2015). This finding lies in accordance with that made by Carson et al. (2013), who highlight the possible influence of size, type and surface roughness of marine plastic debris on the diversity and abundance of the colonising microbial taxa, with polystyrene exhibiting higher bacterial abundance. Another study conducted by Reisser et al. (2014) on plastic particles collected in Australian waters yielded similar results as those from Zettler et al. (2013). However, it should be noted that both the Carson et al. (2013) and Reisser et al. (2014) studies are based solely on morphological data, with only Zettler et al. (2013) and Amaral-Zettler et al. (2015) employing sequencing techniques.

Microbial assemblages associated with marine plastics are also distinctly different from those of the surrounding seawater (Amaral-Zettler et al., 2015; Harrison et al., 2014; McCormick et al., 2014; Oberbeckmann et al., 2014; Zettler et al., 2013). PET drinking water bottles attached to buoys in the North Sea, UK, showed clear differences in the composition of the plastisphere community compared to microbial communities of seawater and those attached to plankton and debris (Oberbeckmann et al., 2014). The study also illustrated temporal differences in microbial community composition colonising the plastic bottles, revealing a higher abundance of photosynthetic brown algae and cyanobacteria during the summer months compared to a dominance of heterotrophic bacteria and photosynthetic diatoms during the winter (Oberbeckmann et al., 2014).

In a study by Harrison et al. (2014) employing a laboratory-based microcosm setup containing sterile artificial seawater and inoculated with low-density polyethylene (LDPE) microplastics, colonisation of plastics by morphologically distinct prokaryotic cells, predominantly bacteria, occurred over time. Further molecular analysis revealed significant differences between the bacterial communities found attached to the LDPE microplastics and those within the sediment (Harrison et al., 2014). This finding corroborates that of McCormick et al. (2014) who demonstrate significant differences in microbial communities found on microplastics in an urban Chicago River compared to those of the surrounding water column and suspended organic matter. Harrison et al. (2014) also highlight significant time-dependent variation in the structural community of the LDPE bacterial community. Initial observations showed the existence of sediment type-specific communities present on microplastics, with shifts towards "LDPE-associated" bacterial communities occurring at days 7 and 14 of the experiment, indicating a possible adaptation and change in community structure of these bacteria to microplastic waste (Harrison et al., 2014). The tendency of microplastics to attract a bacterial community that differs from that of the surrounding environment is further supported by a study conducted in a freshwater system, where bacterial communities on plastic litter from the Chicago River and Chicago's Lake Michigan beaches differed significantly from those colonising organic substances such as leaves and cardboard (Hoellein et al., 2014). The prevailing evidence appears to indicate that plastisphere communities are distinctly different from those found colonising other substrates or within the same environment but not associated with the plastic debris, indicating the possibility of specific adaptation to this man-made habitat. Plastic could therefore provide a new ecological niche or biotope, which, owing to its longevity in the environment, could help facilitate the persistence and transport of microorganisms across oceans and into new geographic areas (De Tender et al., 2015). Further research is needed in order to establish whether this novel transport mechanism could lead to the spread and prolonged persistence of disease-causing organisms in marine environments.

There is also a growing commercial interest in plastic biodegradation, with current research focussing on identifying the types of microorganisms capable of degrading plastics (Loredo-Treviño et al., 2012). Numerous studies have shown several different species of marine bacteria with the capacity to degrade hydrocarbons. Species of hydrocarbon-degrading bacteria belonging to over 20 genera and distributed across some of the major bacterial Classes (*Alpha*-, *Beta*- and *Gammaproteobacteria*; *Actinomycetes*; *Flexibacter-Cytophaga- Bacteroides*), have been isolated and described (Yakimov et al., 2007; Head et al., 2006; Head and Swannell, 1999; Floodgate, 1995). These organisms are strongly enriched for during an oil spill at sea and play an important role in the biodegradation of oil (Gutierrez et al., 2014; Gertler et al., 2012). To our knowledge, the marine environment is the only place where we find bacteria with the ability to utilize hydrocarbons almost exclusively as a sole source of carbon and energy. Considering that plastic is composed of hydrocarbons, these types of bacteria could have important implications with respect to their role in degrading plastic debris. There are reports of changes in the surface topography of plastic samples colonised by microorganisms, and microbial cells have been identified within pits and grooves, suggesting possible microbial degradation of plastic surfaces (Reisser et al., 2014; Zettler et al., 2013; Webb et al., 2009), again however lacking any real evidence. Only a handful of studies have investigated biodegradation through actual measurement. A recent study by Nauendorf et al. (2016) examining mass loss, changes in surface wettability and surface chemical composition of biodegradable plastic bags and PE recovered from sediments from the Western Baltic Sea, found no signs of biodegradation after 98 days. However, Yoshida et al. (2016), have recently discovered the existence of a new bacterium, *Ideonella sakaiensis* 201-F6, which is able to completely degrade PET within six weeks. The mechanics of biodegradation of marine plastic debris, and the underlying processes that influence this behaviour, are areas that clearly need much further investigation to fully exploit the implications this can have on the environment.

Current research relating to plastisphere communities often fails to consider the likely impacts of associated chemical co-pollutants present on plastics that may also play a role in determining the community structure of the attached biofilm. Plastic debris, including microplastics, contain numerous organic contaminants such as, for example, polychlorinated biphenyls (PCBs), petroleum hydrocarbons and bisphenol A, which are either added during the plastic manufacturing process or absorbed from the surrounding environment (Koelmans et al., 2016; Teuten et al., 2009). Plastic debris is therefore a known vector of such chemical pollutants (Cole et al., 2011). Studies have already demonstrated the negative impacts associated with such additives on wildlife, humans and the environment (Van der Meulen et al., 2014; Teuten et al., 2009), with a large amount of these chemicals known to desorb when the plastic is ingested by marine species and eventually bioaccumulate in the food chain (Engler, 2012). Future research should consider the combined biotic and chemical load present on plastic debris and the consequent role microbial hitchhikers play in either mitigating this problem by biodegradation or aggravating it through increased biofilm binding. This could also help in trying to establish a more accurate risk assessment of plastic debris by taking into consideration both the effects of potentially harmful plastic-associated microbes as well as chemical co-pollutants.

3. Plastic dispersal: Dissemination of pathogenic and harmful microbes

The introduction of invasive species into new habitats through colonisation of natural substances, such as wood, dead plants and pumice (Bryan et al., 2012; Minchinton, 2006; Van Duzer, 2004), and the ability of intertidal species to travel great distances offshore on floating rafts of seaweed (Ingólfsson, 2000) are well described. An increase in anthropogenic waste, in particular plastic litter, provides another mechanism for facilitating the dispersal of non-native species in marine environments (Gregory, 2009; Jokiel, 1990). The buoyancy and durability of plastic makes it an ideal alternate substratum for a variety of colonisers, with plastic often shown to have a higher diversity of species compared to other floating substrates, though this is likely to be dependent on the location and experimental sampling time (Bravo et al., 2011). The non-biodegradable nature of plastic increases its longevity in the marine environment, which in turn significantly increases its potential for wide-scale dispersal of alien and invasive species (Barnes 2002a,b; Winston et al., 1997; Jokiel, 1990; Gregory, 1978). Increased survival and long-distance transport of native benthic invertebrates has been observed following their attachment to marine plastic debris (Barnes and Milner, 2005), with one study reporting the introduction of pathogens into a coral reef ecosystem through drifting plastic litter (Goldstein et al., 2014). Colonisation of a single piece of plastic by at least ten different species of marine animals (including Bryozoans, Porifera, Annelida, Cnidaria, and Mollusca) has also been reported at remote locations such as the Southern Ocean, an area that has a relatively low input of anthropogenic litter (Barnes and Fraser, 2003). The size of the encrusting invertebrate colonies indicated that this particular piece of plastic had been afloat for at least a year, illustrating the potential for plastic-colonising organisms to survive and adapt at sea for many months, and potentially years (Barnes and Fraser, 2003). This provides important evidence that microbial hitchhikers on marine plastic debris could be widely disseminated, with the increasing amounts of global marine plastic providing ample opportunities for the transport of species into new habitats (De Tender et al., 2015).

Relatively little is known about the growth and dispersal dynamics of potentially pathogenic and harmful microorganisms colonising the plastisphere, and the increased risk of human exposure from this poorly understood vector. Plastic-associated microbes from the Chicago River, a freshwater environment, were found to contain taxa of potential pathogens and plastic decomposers, although these were less diverse than those of the surrounding water column and suspended organic matter (McCormick et al., 2014). The authors found a high abundance (7.4%) of the family Campylobacteraceae colonising microplastics released from a nearby sewage treatment plant, certain taxa of which are known to cause human GI infections (McCormick et al., 2014). This suggests the potential of microplastics to be colonised by waste-water associated microbes that could have a negative impact on human health and might contribute towards the transport of disease-causing organisms in the environment. However, entrance of these plastic particles into marine systems would likely increase die-off of the associated freshwater microbes attached to plastics, and hence the potential for wider dispersal of these possibly pathogenic microorganisms remains unclear. *Aeromonas*, *Acrobacter* and *Pseudomonas* were also found in higher abundance on microplastics, all of which could contain possible pathogenic strains (McCormick et al., 2014). Other studies also indicate the ability of plastic debris to be colonised by potential pathogens, with LDPE-associated bacterial colonies found in coastal sediments dominated by *Arcobacter* and *Colwellia* spp., amounting to 84-93% of sequences (Harrison et al., 2014), and possibly pathogenic species of *Vibrio* found to dominate one of the PP samples in the Zettler et al. (2013) study, where they covered nearly 24% of the plastic surface. Whilst this illustrates the potential of plastic debris to be colonised by potentially harmful microbes, how representative this pathogenic *Vibrio* is with respect to the wider plastisphere communities remains unknown since this was found on just one of the six collected plastic fragments. Several *Vibrio* species, such as *V. cholerae* the causal agent of cholera and *V. fluvialis* that can cause bloody diarrhoea and gastroenteritis, are known human pathogens, so their potential to colonise marine plastic litter presents an yet unexplored pathway for dispersal. Therefore, plastic debris could represent a vehicle for the transport of these disease-causing organisms, particularly due to the ability of plastics to persist for significantly longer periods of time compared to other natural substances such as wood and feathers, and their widespread global distribution across marine and terrestrial environments (Caruso, 2015; Zettler et al., 2013).

Drifting plastic debris can also be colonised by HAB species, such as *Ostreopsis* sp. and *Coolia* sp., in addition to resting cysts of unknown dinoflagellates, and temporary cysts and vegetative cells of *Alexandrium taylori* (Masó et al., 2003). Experiments using *A. taylori* cultured in plastic flasks showed the tendency of temporary cysts to attach to plastic surfaces (Masó et al., 2003), providing an important insight towards understanding the global increase in HABs due to their dispersion via anthropogenic means. There is presently very little information on the role of plastic litter in the dispersion of HAB species, particularly in comparison to other natural debris (Carson et al., 2013), and further studies are needed to better understand this. Furthermore, more emphasis should be placed on characterising plastic-associated eukaryotic microbes using sequencing techniques, which represents another substantial knowledge gap needed to fully understand the diverse and complex nature of the plastisphere communities.

4. Implications for bathing water quality: human health and beach management

FIOs such as *E. coli* and intestinal enterococci are widely used to monitor the quality of bathing waters and beach environments. These microorganisms mainly inhabit the mammalian gut, but can be delivered to the wider aquatic environment from numerous diffuse and point sources including sewage discharge, agricultural storm run-off, and sewer overflows (Oliver et al., 2015; Kay et al., 2008; Oliver et al., 2005). The rate of FIO delivery to receiving waters will vary according to land-use and seasonal climatic conditions, e.g. patterns of localised storm events. The survival of FIOs in sand and water at beach environments is well documented (Halliday et al., 2015; Heaney et al., 2014), with Bonilla et al. (2007) demonstrating significantly higher levels of bacteria in dry (2- to 23-fold) and wet (30- to 460-fold) sand compared to seawater. The harbouring of FIOs and potential human pathogens by certain species of freshwater macroalgae and beach-cast wrack (seaweed) have also been reported (Quilliam et al., 2014; Imamura et al., 2011; Ishii et al., 2006). Van der Meulen et al. (2014) found 150 different bacterial species colonising microplastics found in the Interreg region, including those associated with causing diseases in humans such as *E. coli* and *Pseudomonas anguilliseptica*.

Beaches and bathing waters attract millions of tourists, swimmers, volunteers, and beach-goers each year and are a significant point of contact between humans and potential sources of pollution. Swimming is one of the most popular recreational activities (Wade et al., 2006), and epidemiological evidence shows a relationship between poor water quality and the occurrence of GI illnesses

(Wade et al., 2010). Recreational water sports that are associated with varying degrees of potential water ingestion/contact, such as fishing, boating, wading and kayaking, are another emerging risk factor contributing towards possible GI illness (Dorevitch et al., 2011). However, beachgoers usually spend more time on the beach and strandline than in the water, with young children engaged in playing in the sand at the water's edge, and adults and the elderly often found sunbathing (Heaney et al., 2012). Beach sands are known to harbour both FIOs and human pathogens in localised 'hotspots', often in concentrations much higher than those found in bathing waters (Sabino et al., 2014; Bonilla et al., 2007). A few studies have demonstrated the occurrence of GI symptoms and diarrhoea in people exposed to sand via digging, building sandcastles and burying their bodies in sand at beaches with potential FIO contamination from nearby sewage treatment plants, with children found to have a higher susceptibility for contracting such illnesses (Heaney et al., 2012; Heaney et al., 2009).

With plastics now widely present in sediments and beach sands (Van Cauwenberghe et al., 2015; Imhof et al., 2013), and representing a potential unknown reservoir of FIOs and pathogens, a series of emerging research questions relating to plastics as a vector for wider public health risks need critical investigation. Furthermore, increasing amounts of floating plastic debris in bathing waters could also contribute to negative health impacts on bathers and recreational water users, owing to the yet underexplored potential of plastic litter to harbour and transmit diseases. The abundance of stranded and drifting plastic debris (both macro and micro particles) along beaches and coastal areas is expected to increase with projected increases in sea level, wind speed, wave height, and altered rainfall conditions (Browne et al., 2015; Young et al., 2011; Gulev and Grigorieva, 2004; Meier and Wahr, 2002). This is likely to lead to even greater human exposure to washed-up plastic debris. The majority of studies on marine plastic debris have focused on its occurrence in coastal waters and open ocean areas such as gyres. Limited research, however, has been performed to investigate stranded beach plastics at designated bathing waters or other public beaches (Table 2). Of these limited studies, the majority have investigated abundance and distribution of plastic debris, with a variety of citizen science-based studies further complementing these assessments (Hoellein et al., 2015; Eastman et al., 2014). Links between the colonisation of stranded plastic litter with human pathogens and FIOs, and the impact this could have on beachgoers and their health, have not yet been established, despite the likelihood of public exposure to beach-cast plastic waste being much higher compared to litter in the open ocean. Strandlines are also marked by large quantities of beach-cast wrack and plastics, both of which could contain potential human pathogens (Quilliam et al., 2014). Faecal loading from animals, such as gulls, waterfowl and dogs, significantly contributes towards elevated FIO abundance on beaches and in recreational waters (Edge and Hill, 2007; Wither et al., 2005; Lévesque et al., 2000). This could further facilitate the colonisation of beach-cast plastic litter with FIOs and potential pathogens, which could then be prone to dispersal by wind, an incoming tide, or other means.

The ingestion of colonised plastic debris (particularly microplastics) by fish and marine birds that mistake it as food represents another potential pathway for disease-carrying plastic particles to enter the food chain and be dispersed to other environments (Oberbeckmann et al., 2015). Recent evidence has demonstrated that deposit-feeders, such as mussels and shrimps, can ingest microplastics (Li et al., 2015; Van Cauwenberghe et al., 2015; Setälä et al., 2014; Browne et al., 2008), highlighting the potential for the transfer of microplastics from one trophic level to another. Therefore, as microplastics and stranded plastic debris are so prevalent on beaches, surface waters, marine sediments and in the water column, it is important that we develop a better understanding of the fate of plastics colonised by FIOs and pathogens, and their potential to become incorporated into the food chain and to persist in the gut of animals. Clearly, this could have far-reaching consequences for human health, commercial fisheries and the environment (Lattin et al., 2004; Thompson et al., 2004; Moore et al., 2001).

Furthermore, microplastics from cosmetic care products and fibres in clothing are not effectively removed by Waste Water Treatment Plants (WWTPs) and accumulate in the environment (McCormick et al., 2014), with 250% more microplastics found in coastal WWTP disposal sites compared to reference sites in the United Kingdom (Browne et al., 2011). Microplastics entering aquatic systems from WWTPs have been in close contact with human faeces, hence facilitating their potential to be colonised by FIOs and a range of human faecal pathogens (Oberbeckmann et al., 2015). The potential for sewage-exposed microplastics to harbour possible pathogens has only recently been explored, with McCormick et al. (2014) reporting high levels of members of Campylobacteraceae colonising microplastics downstream of a WWTP. This reinforces the need for further work to understand the mechanisms by which microorganisms, especially pathogens, in sewage "hitchhike" on microplastic particles and find their way onto beaches and surrounding bathing environments. At present there is very limited information available to assess whether the presence of microbial pathogens and FIOs on plastic debris represents a real risk to human health, and it is therefore currently not yet possible to establish a complete risk assessment on the multi-scale effects of plastic debris (Van der Meulen et al., 2014). Targeted research in these areas could have significant societal impact, perhaps most notably by advancing beach management protocols and providing improved evidence to informing EU BWPs for increased public protection.

5. Conclusion

The negative impacts of marine plastic debris are widespread, but not yet fully understood. Marine and freshwater plastic debris is constantly being modified by the chemical and physical environment; therefore, biofilm communities colonising plastics need to be dynamic with an ability to adapt to their changing environment. The potential for complex interactions between plastic waste and microorganisms of human health significance are currently poorly understood, yet a number of emerging studies indicate the ability of potential pathogens to attach to plastic debris and possibly be transported to new environments. However, further work is essential in order to determine the implications this has in terms of disease transmission and whether this linkage significantly impacts human health. Promoting increased knowledge of both the role and importance of plastic surfaces in facilitating the survival and transfer of pathogens, particularly with respect to plastisphere-pathogen associations, currently represents an emerging research agenda in the wider field of health-related water microbiology. Quantifying the spatial and temporal shifts in human exposure pathways to pathogens that might occur from macro to micro plastic debris, and the changing magnitude of risks this presents to human health, will be challenging. However, the nature of threat associated with this novel transport mechanism capable of transferring microorganisms across large geographic ranges also introduces new regulatory challenges associated with the environmental and socio-economic protection of bathing waters and waters of significant recreational interest.

Understanding the ecology of the plastisphere community will further inform regulators and environment mangers of the risks from particular types and sizes of plastics, and the effects of environmental stressors such as temperature and exposure to higher UV radiation on the survival of plastic-colonising pathogens and harmful microorganisms. Future research should entail studying microbial interactions with plastic debris at all sites of its accumulation including soils, sediments, beaches, rivers, open oceans and the deep sea in order to allow a more comprehensive assessment of plastic-associated communities and its potential negative impacts on the environment and public health. Advances in plastisphere ecology will also contribute towards our knowledge of biodegradation of plastic and its adsorbed pollutants, and could provide useful information for future remediation strategies.

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Table 1: Studies investigating aquatic plastic debris and biofilm formation

Area sampled	Size of plastic	Microbial issue investigated	Reference
Open ocean	Micro (0.25-05.cm)	Colonisation of plastic particles by diatoms & hydroids	Carpenter and Smith, 1972
Open ocean	Macro (15x10cm)	Variation of biofilm community on High density polyethylene(HDPE), Low density polyethylene (LDPE) & PP coupons with season & polymer type	Artham et al., 2009
Open ocean	Macro & Micro	Characterization of microbial plastisphere community	Zettler et al., 2013
Open ocean	Macro & Micro (<5mm)	Abundance, diversity & variation of microbial community	Carson et al., 2013
Open ocean	Macro & possibly Micro (<2cm)	Characterization of microorganisms colonising plastic debris; relationship between size of plastic & number of observed taxa	Goldstein et al., 2014
Open ocean	Macro (PET bottles)	Seasonal & spatial differences in biofilm diversity	Oberbeckmann et al., 2014
Open ocean & coastal waters	Macro & Micro (<5mm)	Differences in composition of plastisphere community with respect to biogeographic origin & polymer type	Amaral-Zettler et al., 2015
Coastal waters	Micro (0.1-2mm)	Bacterial colonisation of polystyrene particles	Carpenter et al., 1972
Coastal waters	Macro	Potential of floating plastics to disperse toxic algal species	Masó et al., 2003
Coastal waters	Macro (30x30cm)	Bacterial colonisation of polyvinylchloride by *Rhodobacterales*	Dang et al., 2008
Coastal waters	Macro (PE plastic food bags)	Early stages of microbial biofilm formation on marine plastics	Lobelle and Cunliffe., 2011

Coastal waters	Macro	Biofilm formation on polystyrene particles by bacteria & diatoms	Briand et al., 2012
Coastal & ocean waters	Macro & Micro	Characterization of microorganisms colonising plastic debris	Reisser et al., 2014
Beach sediments	Micro (<5mm)	Bacterial colonisation of LDPE microplastics from three different sediment types	Harrison et al., 2014
Marine sediments	Macro (PE bags & biodegradable bags)	Colonisation & degradation of PE & biodegradable plastic bags by microbes in oxic & anoxic marine sediments	Nauendorf et al., 2016
Seafloor	Macro (>25mm) & Micro (<5mm)	Comparison of plastisphere community to bacterial community of beach microplastics, sediment & surrounding seawater	De Tender et al., 2015
Laboratory experiment using seawater	Macro (PET bottle pieces)	Biofilm formation & attachment of marine bacteria to PET surfaces	Webb et al., 2009
Urban river	Micro	Assessment of microplastic abundance in urban river & composition of bacterial biofilms on plastics	McCormick et al., 2014

Table 2: Studies conducted on plastic debris from public bathing water beaches (excluding citizen science volunteer data studies).

Area sampled	Size of plastic	Issue investigated	Reference
Beach sediments	Pellets (0.1-0.5cm)	Potential of PP plastic pellets to transport toxic chemicals	Mato et al., 2001
Beach sediments	Macro & micro (1-15 mm)	Abundance of small plastic debris on Hawaiian beaches	McDermid and McMullen, 2004
Beach, estuarine and subtidal sediments	Micro	Abundance and extent of microplastic pollution	Thompson et al., 2004
Coastal beach sediments and seawater	Micro (>1.6µm)	Presence and abundance of microplastics	Ng and Obbard, 2006
Beach shorelines	Macro (> 1mm) & micro (< 1mm)	Influence of wind on spatial patterns of plastic debris	Browne et al., 2010
Beach	Virgin pellets, small (< 20mm) & micro (<20mm)	Size & distribution of plastic fragments on Brazilian beach	Costa et al., 2010
Beach shoreline sediments	Micro (<1 mm)	Spatial distribution of microplastics along six different continents	Browne et al., 2011
Beach sediments	Micro (<5 mm)	Bacterial colonization of low-density polyethylene (LDPE) microplastics from 3 different sediment types	Harrison et al., 2014
Beach shoreline and coastal waters (70-100m)	Macro	Distribution of anthropogenic litter in freshwater system & microbial interactions	Hoellein et al., 2014
Beach	Macro	Predicting short-term quantities of plastic debris washing ashore on beaches using a particle tracking model (PTM) & webcam monitoring	Kako et al., 2014
Beach	Macro	Colonisation of plastic litter by *E. coli* and *Vibrio* spp.	Quilliam et al., 2014

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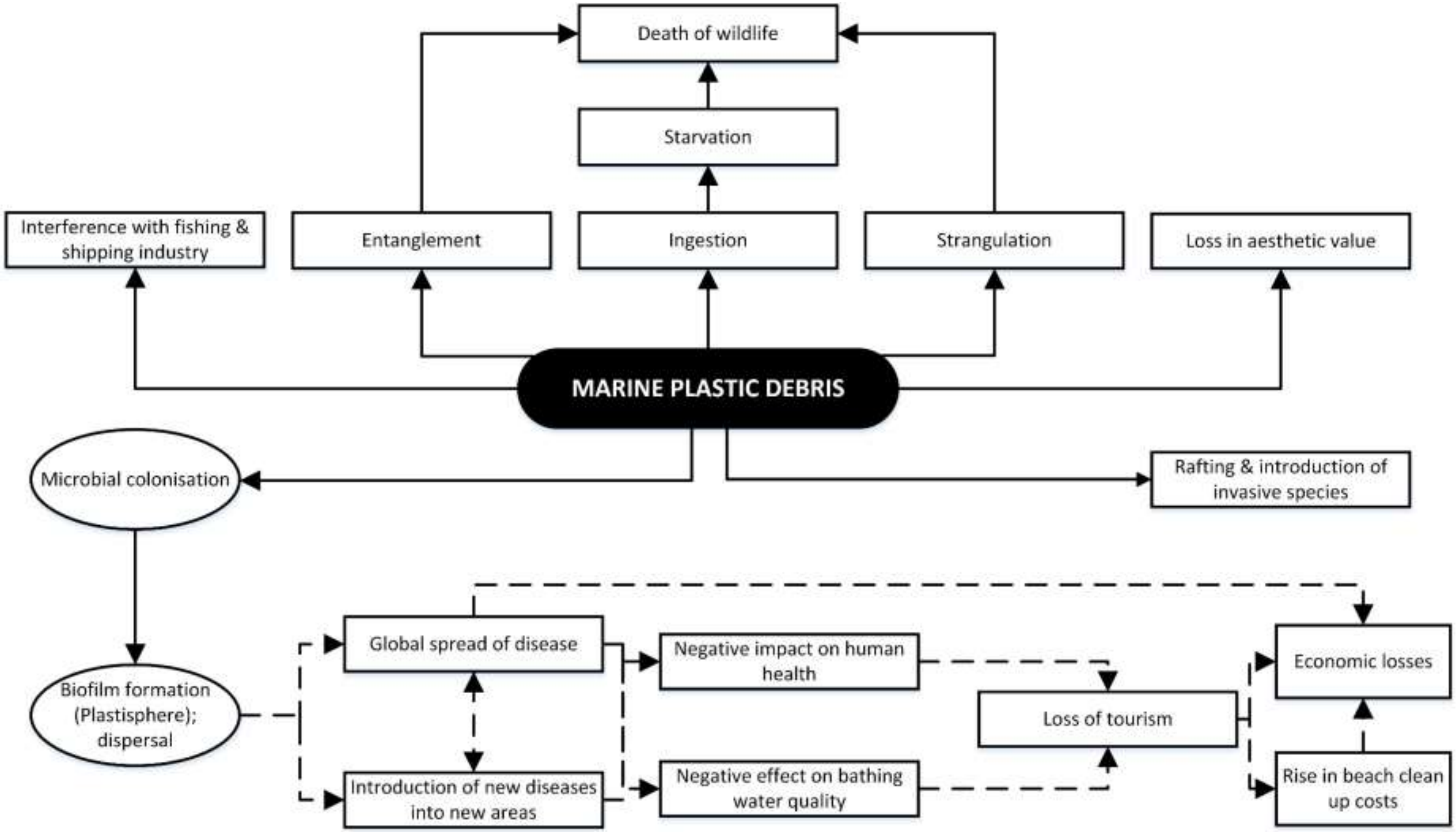

Figure 1: Impacts and interactions of marine plastic debris. Solid black arrows indicate known effects; dotted black arrows indicate the yet unexplored effects/interactions as mediated by marine plastic debris.