PLASTISPHERE

The Ecosystem of Plastics

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Plastisphere

The plastisphere provides a unique man-made habitat for organisms and microbial communities. Investigating the interactions and functions of these organisms helps us understand how fouling communities can settle on these novel platforms and be moved beyond their natural ranges as well as their contribution to nutrient cycling and biogeochemical processes. This book examines the plastisphere and reveals a secret world of microbes that have adapted to live on plastic surfaces. It explains the ecological effects of plastic pollution, human health concerns, microbial ecology, and mitigation techniques and advocates sustainable solutions. Readers will dive into this enthralling ecosystem rich with microscopic life and explore its mysteries in this thought-provoking book.

Features:

- Presents recent insights into the fundamentals of the plastisphere, with a specific focus on environmental interactions.
- Introduces the work of global experts and their ongoing studies, creative approaches, and new discoveries.
- Highlights the macro and molecular interactions of environmental domains with the plastisphere.
- Explores the notion of bioinvasion that can threaten the health and productivity of our ecosystems.
- Includes detailed multidisciplinary data on the behavior of plastic materials and environmental microbiome.
- Explains the main factors causing ecosystems to evolve and to live in human-made plastic environments.
- Helps readers from various backgrounds to gain a thorough understanding of the topic of the plastisphere.

This book is an insightful reference for researchers, academics, students, and professionals in Environmental Science, Microbiology, Environmental Engineering, Oceanography, and Material Science.

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Dhammika N. Magana-Arachchi, Tharindi Bandara, and Shashini Gunathilaka

18.1 INTRODUCTION

Scientists have identified microplastics (MPs) in all environments they have studied in the last decade, from the deepest ocean depths to the highest remote mountain peaks, tropical regions, and polar areas. These MPs are generously found in the air, soils, food, digestive tracts, and also in lungs (Ghosh et al., 2023). MPs are widespread and could be categorized as the most ubiquitous contaminator of the earth (Magana-Arachchi and Wanigatunge, 2023).

MPs' persistent nature creates a novel habitat for microbial colonization, which leads to biofilm formation. Biofilms are complex aggregates of microorganisms sheathed in a self-produced matrix that facilitates their adherence to surfaces and protects them from environmental stressors. This environment on MPs attracts a range of microorganisms, including pathogenic microbes and bacteria that carry antibiotic-resistance genes (ARGs). The biofilm matrix on MPs helps infective microbes to survive in water. This increases the chance that the microbes will interact with other living things. Second, the proximity of diverse microbes within the biofilm facilitates horizontal gene transfer (HGT) and allows bacteria to exchange genetic material, including ARGs. This interaction within the biofilm can accelerate the spread of antibiotic resistance. The plastisphere, an ecosystem of plastic debris suspended in water surfaces with living microorganisms, could be considered a vector for infectious bacteria and antibiotic-resistant gene transmission in several ways. Hence, this chapter explores the interrelation between microorganisms, biofilm formation, and MPs within the plastisphere, highlighting the plastisphere's potential to act as a vector for developing ARGs and transmitting antibiotic-resistant bacteria (ARB).

18.2 THE PLASTISPHERE CONCEPT

The environmental pollution caused by man-made polymers has been a significant concern for many years. Plastics are made out of synthetic or semi-synthetic organic material, and about 60% of this plastic is disposed of in landfills or recycled, while the rest is in the environment (Muñoz Meneses et al., 2022). Large plastic waste is the primary source of MPs, which are small particles that measure 5 mm or less. MPs are categorized into two groups based on their original sizes. Plastic microbeads, industrially produced particles, and powders (<5 mm diameter) are considered primary MPs, and in contrast, large plastic fragments break down through physical, biological, and chemical processes into smaller fragments, known as secondary MPs.

MPs exhibit various shapes, including foils, foams, fibres, pellets, fragments, and microbeads. Plastics are characterized by chemical diversity. Materials such as polyamide (PA), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) have higher densities than water, so their settlement rates in sediments are increasing. Conversely, plastics like polystyrene (PS), high-density

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polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyurethane (PUR) have lower densities and tend to float predominantly on water (Du et al., 2022).

In 2013, Zettler and his team defined the plastisphere as a microbial community found on plastic waste in aquatic ecosystems (Zettler et al., 2013). Since the 1970s, when scientists first observed bacteria and diatoms growing on plastic debris in the Sargasso Sea, it has become clear that plastic in the ocean quickly becomes home to various microorganisms and small animals (Didier et al., 2017). Certain microbes, such as members of the fungal phylum Chytridiomycota and bacterial phyla Bacteroidetes, Proteobacteria, and Cyanobacteria, are highly prevalent in the plastisphere. It still needs to be determined if certain types of microbes only live on specific kinds of plastics (Du et al., 2022). Further, the plastisphere community has exhibited significant metabolic pathways compared to the sea-water-free living microbes. It remains to be seen if different sorts of plastic attract and support diverse communities of microbes and small creatures. Plastispheres are significant in harbouring and disseminating pathogenic microorganisms and ARB. Hence, understanding and monitoring the plastisphere is essential for assessing its potential risks to aquatic ecosystems and human health.

18.3 THE MICROPLASTICS IN BIOTA

Microorganisms tend to inhabit the surfaces of MPs. The interaction between microorganisms and MPs is influenced by several surface properties of the MPs, including size, shape, roughness, and hydrophobicity. The interaction is primarily driven by hydrophobic and electrostatic forces, further modulated by environmental factors such as temperature, pH, and ionic strength.

For bacteria, initial attachment to MPs is driven by electrostatic forces. MPs can serve as conducive substrates for microbial colonization. It provides essential nutrients, such as metal ions like zinc, iron, and copper, by adsorption from the surroundings. Various microorganisms, including bacteria such as *Aeromonas*, *Rhodococcus*, *Pseudomonas*, *Enterobacter*, *Halomonas*, *Mycobacterium*, *Photobacterium*, and *Shigella*, as well as fungi, have been discovered on MP surfaces (Gkoutselis et al., 2021; Parsaeimehr et al., 2023). The composition and characteristics of MPs, biodegradability, and varying hydrophobicity levels influence microbial colonization. It indicates a degree of selectivity (Sooriyakumar et al., 2022). Proteobacteria, Bacteroidota, and Actinobacteria were the most abundant phyla in beach sand MPs (Vidal-Verdú et al., 2022).

Some evidence indicates that viruses can adhere to plastic surfaces. Studies have shown that SARS-CoV-2, the virus responsible for COVID-19, can adhere to PP surfaces and remain viable for over 72 hours (Ashokkumar et al., 2023). It is longer than on materials like copper or cardboard. Viruses can adhere to naked PP plastic surfaces through non-ionic forces (Ashokkumar et al., 2023). In certain instances, adhesion to plastic surfaces leads to viral inactivation, as observed with Poliovirus 1 when stored in a hydrophobic PP container in groundwater. Therefore, the fate of viruses interacting with MPs depends on the specific type of plastic and the nature of the virus (Gassilloud and Gantzer, 2005). While the coexistence of bacterial colonies and viruses on MPs seems plausible, experimental confirmation of this phenomenon has yet to be achieved.

Studies have shown that MPs could carry more potential pathogenic microbes and ARB than the natural substrate. In 2019, Miao and colleagues investigated biofilm growth on several substrates under laboratory conditions; cobblestone, wood, polyethylene (PE), and PVC were compared. Among those, the natural substrate had a lower species abundance. In contrast, the MP substrate had a higher species abundance. Table 18.1 lists a diverse array of microorganisms found in different substrates.

18.4 MICROPLASTIC-ASSOCIATED BIOFILM FORMATION

MPs are susceptible to colonization by microorganisms when they come into contact with water, leading to the formation of biofilms. Naturally, biofilm development involves a complex three-phase process: attachment, maturation, and detachment. Temperature, light/dark conditions, oxygen levels,

TABLE 18.1
Comparison of Microbial Communities on Different Substrates

Location	Natural/Plastic Substrate	Microbial Community		References
		Non-Pathogenic	Potential Pathogenic	
China	Wood –cultured under the laboratory condition	Deltaproteobacteria, Verrucomicrobiae, Anaerolineae, Cytophagia, Oscillatoriophycideae, Phycisphaerae, Planctomycelia, Synechococcophycideae, Chloracidobacteria	Alphaproteobacteria, Betaproteobacteria, Gammaproteobacteria, Flavobacteria	Miao et al. (2019)
China	Glass – cultured under the laboratory condition	Rhodobacterales, Planctomycetales	Frankiales, Micrococcales, Rhizobiales, Sphingomonadales, Burkholderiales, Cytophagales, Sphingobacteriales	Ogonowski et al. (2018)
United Kingdom	Coastal sand – collected from site	Verrucomicrobia, Deltaproteobacteria	Bacteroidetes, Proteobacteria, Actinobacteria, Gammaproteobacteria	Gobet et al. (2012)
China	Leaf –collected from site	*Pseudomonas oryzae*, *Pseudomonas benzenivorans*, *Pseudomonas graminis*, *Pseudomonas peli*	*Pantoea vagans*, *Pantoea agglomerans*	Wu et al. (2019)
China	Cobblestone – cultured under the laboratory condition	Cytophagia, Oscillatoriophycideae, Planctomycelia, Synechococcophycideae, Chloracidobacteria	Alphaproteobacteria, Betaproteobacteria, Gammaproteobacteria, Flavobacteria	Miao et al. (2019)
Kandy lake, Sri Lanka	Microplastic – collected from lake waters in an urban city	*Acinetobacter baumannii*, *Herbaspirillum huttiense*	*Serratia marcescens*, *Stenotrophomonas maltophilia*, *Bacillus anthracis*	Welagedara et al. (2023)
China	Microplastics – collected from water in urban area	Denococcus-Thermus Acidobacteria, Nitospirae, Actinobacteria	Proteobacteria	Huang et al. (2021)
China	Microplastics – collected from site	*Pseudomonas chlororaphis*, *Pseudomonas rhizosphaerae*, *Pseudomonas denitrificans*	*Pantoea agglomerans*, *Leclercia adecarboxylata*	Wu et al. (2019)
China	Microplastic – cultured under the laboratory condition	*Aquabacterium* sp. *Loktanella* sp.	*Hyphomonas* sp. *Hydrogenophaga* sp.	Ogonowski et al. (2018)

and nutrient availability can influence biofilm formation. The hydrophobicity and texture of attaching surfaces also contribute to biofilm formation. Microorganisms colonize particles with rough surfaces more readily than smooth surfaces (Rajcoomar et al., 2024). They are exposed to various physical and chemical factors that may influence biofilm development in different conditions.

Recent findings indicate that microorganisms attached to MPs can be transported and dispersed over significant distances. Biofilm-forming bacteria have physiological features that facilitate biofilm formation, including flagella, fimbriae, and pili. Gram-negative and Gram-positive bacteria can form biofilms. However, MP surfaces' most frequently reported biofilm-forming families include Pseudomonadaceae, Moraxellaceae, Enterobacteriaceae, and Comamonadaceae (Cholewińska et al., 2022).

18.4.1 Role of Extracellular Matrix

The Lifshitz–van der Waals forces and electrostatic interactions potentially occur between the cell surface and the substrate at the first bacterial adhesion phase (Carniello et al., 2018). They act to strengthen adhesion via adhesion receptors. In the subsequent irreversible adhesion stage, bacteria produce extracellular polymers, lipopolysaccharides (LPS), or proteins that lead to the proliferation of the initial adherent cells and the enlargement of microcolonies. Bacterial cells are connected through extracellular polymeric substances (EPSs), consisting of polysaccharides, proteins, nucleic acids, surfactants, lipids, and water, with the exact composition depending on the bacterial species. EPS mainly supports the formation and functioning of biofilms. Such as forming a protective barrier that enables tolerance to bactericidal factors, avoidance of host immune responses and predator attacks, bacterial cell aggregation, increased density, and mutual recognition with the transfer of genetic material (Rajcoomar et al., 2024). Nutrient supply to cells within the biofilm is facilitated by the formation of numerous tubules within the structure, allowing fluid flow around the microcolonies. This system delivers essential nutrients and oxygen while removing unnecessary metabolic products (Tu et al., 2020).

18.4.2 Quorum-Sensing

The expression of quorum-sensing genes by bacteria accumulated on surfaces, including MPs, facilitates further cell-to-cell adhesion, maturation, and dispersion of biofilms. This process increases bacterial resistance (Nath et al., 2023). Quorum sensing involves the production of different signalling molecules known as autoinducers. Bacteria produce these molecules in proportion to their population density. As the concentration of these molecules increases, they regulate gene expression, coordinating communal activities such as biofilm formation. On MPs, quorum sensing triggers the production of EPSs, which form the biofilm matrix. That enables bacteria to adhere firmly to the surface and each other (Zhao et al., 2020). This biofilm environment protects from environmental stressors, antibiotics, and the immune responses of host organisms, enhancing bacterial survival and persistence.

18.4.3 MP Surface Chemistry on Biofilm Formation

Several physical and chemical properties of the plastic substrates, including polymer type, surface characteristics, and particle sizes, influence the formation of biofilms on MPs. For instance, PVC and PE promote more bacterial adhesion compared to PP and PET due to their larger specific surface area and roughness (Cai et al., 2019). The surface properties of MPs, such as hydrophobicity, significantly affect bacterial colonization. Surface roughness has been identified as a significant factor influencing cell attachment. Furthermore, the number of attached cells increases with roughness (Joo et al., 2021). Differences in bacterial attachment and community composition on MPs depend on surface hydrophobicity (Zhao et al., 2024). Additionally, surface charges and sizes of MPs also influence microbial attachment and biofilm formation (Moyal et al., 2023). This biofilm formation can also lead to the partial degradation of MPs, enhancing the release of leachates and toxic substances into the environment (Nath et al., 2023).

Several studies have reported that biofilm formation can increase the density of MPs, thereby affecting their environmental transport (Kaiser et al., 2017; Semcesen and Wells, 2021). The growth of biofilms on MPs alters their density, affecting their mobility in the environment, whether in water or soil. The biofilm formation can elevate particle density, enhancing sinking behaviour in aquatic environments (Semcesen and Wells, 2021). The sinking velocity of PS MPs increases significantly after biofilm formation, with an 81% increase in marine water and a 16% increase in estuarine water (Kaiser et al., 2017).

18.4.4 MP Biophysical Forces on Biofilm Formation

Microorganisms are attracted to MP surfaces via hydrophilic interactions, electrostatic interactions, or Van der Waals forces facilitated by functional groups expressed in the ecocorona due to the sorption of biological materials into plastics (Chen et al., 2022; Galloway et al., 2017; Zhang et al., 2022). Microbial cells may adhere to surfaces through both specific and non-specific interactions. Hydrophobic interactions are typically the strongest among all long-range non-covalent interactions in biological systems (Fu et al., 2021).

Upon contacting surfaces, cell attachment occurs in two phases. The initial attachment is reversible and occurs rapidly. It involves hydrodynamic and electrostatic interactions. During this period, the adhesive force between bacteria and surfaces increases quickly. The second phase of attachment is irreversible, occurs over several hours, and involves van der Waals interactions between the hydrophobic regions of the outer cell wall and the surface (Tuson and Weibel, 2013). Most bacteria exhibit a negative surface charge, particularly in the stationary phase of their cell development stage. That influences their interactions with surfaces. This negative charge leads to better interactions with positively charged surfaces, and it has been shown that aliphatic plastics attract unique microorganisms compared to other plastics (Martínez-Campos Gutiérrez, 2022).

18.4.5 Temporal Dynamics of Plastisphere

The temporal dynamics of the plastisphere depend on several factors, including colonization patterns, microbial succession, and changes in community composition. These factors influence the abundance and diversity of ARBs and ARGs associated with MPs. Furthermore, factors such as nutrient availability, temperature fluctuations, and exposure to antimicrobial compounds also play a significant role.

18.4.5.1 Seasonal Variations

Long-term monitoring studies have revealed fluctuations in ARG abundance over time, with seasonal variations and anthropogenic activities, that impact microbial communities and their resistance profiles (Yang et al., 2021). In temperate regions, microbial colonization may peak during the warmer months when environmental conditions favour microbial growth and activity. Conversely, microbial biomass and diversity may decline during colder periods because it reduces metabolic rates and nutrient availability (Zhang et al., 2022). Certain conditions may promote the proliferation of ARB and ARGs, while others may lead to their decay or removal from the plastisphere environment (Lenaker et al., 2019).

18.4.5.2 Anthropogenic Activities

Anthropogenic activities, such as urbanization, agricultural runoff, and industrial pollution, can also influence the temporal dynamics of the plastisphere by introducing additional stressors and pollutants into aquatic ecosystems (Ng et al., 2018). High levels of organic matter and nutrients from wastewater effluent can stimulate microbial growth on MP surfaces, which may lead to shifts in community composition and the enrichment of ARBs and ARGs (Sooriyakumar et al., 2022).

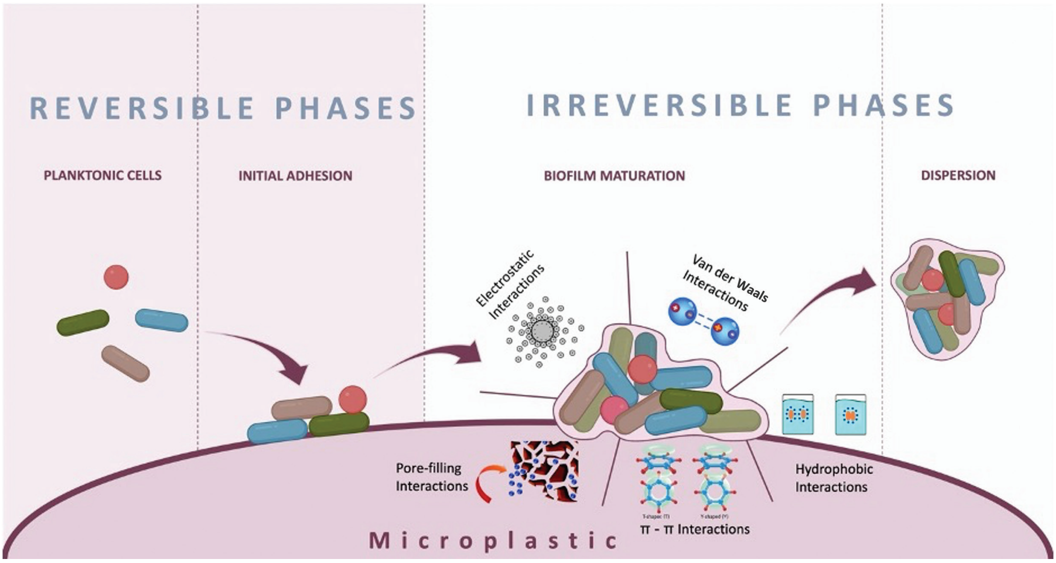

FIGURE 18.1 The formation of the plastisphere on microplastic surfaces through microbial colonization and biofilm formation.

18.4.5.3 Presence of Pharmaceuticals

The presence of pharmaceuticals on MPs can further modulate the temporal dynamics of the plastisphere by utilizing selective pressures on microbial communities. Antibiotics and other antimicrobial agents may promote the proliferation of ARBs, which leads to the accumulation of ARGs over time (D'agata and Mitchell, 2008). Fluctuations in pharmaceutical concentrations or exposure to environmental stressors may drive changes in microbial community structure and resistance phenotypes. Environmental stressors such as nutrient depletion, UV radiation, and fluctuations in salinity may inhibit microbial growth and reduce the abundance of ARB and ARGs in the plastisphere. These stressors can disrupt microbial communities, leading to composition shifts and ARG loss over time (Yang et al., 2021).

Microbial turnover rates, biofilm detachment, and sedimentation processes could influence the fate and persistence of ARGs in the plastisphere. Some ARGs may persist on MP surfaces for extended periods, while others undergo degradation or transformation through microbial metabolism and environmental factors (Nguyen et al., 2023). Understanding these dynamics is essential for elucidating the long-term implications of MP pollution on antimicrobial resistance (AMR) in aquatic environments (Figure 18.1).

18.5 ROLE OF MP AS A VECTOR FOR PATHOGENS

MPs are recognized as facilitators for the emergence of human diseases (Loiseau and Sorci, 2022). The biofilms formed on MPs have unique features compared to those on natural materials such as rocks and wood. Hence, the relative proportions of pathogenic bacteria such as *Chlamydiae and Pseudomonadota* were higher in biofilms formed on MPs than in biofilms formed on natural substrates (Wu et al., 2019). The global records on the presence of pathogenic microbes on plastics collected from oceans are increasing, and according to researchers, *Vibrios* are plentiful in the plastisphere, though only some are pathogenic (Bowley et al., 2021). Furthermore, according to Bowley et al. (2021), with rising plastic waste in oceans, *Vibrio* and other pathogens may get transported and transmitted into potential hosts, causing disease outbreaks.

A study by Siddiqui et al. (2024) revealed the presence of bacteria, including pathogenic *Vibrio* species, namely *V. campbelli*, *V. alginolyticus*, and *V. coralliilyticus*, with high abundance and viruses Herpesvirales, Caudovirales, and Poxviridae groups with low in numbers on floating plastic surfaces collected from the two sites of the Mediterranean seas. For the first time, in the marine plastisphere, the researchers recorded the White Spot Syndrome virus (WSSV), a causative agent for epidemics in the aquaculture industry (Siddiqui et al., 2024).

Metagenomic sequencing studies of residential bacterial communities on MPs revealed pathogenic bacteria in urban wastewater samples. Studies have demonstrated that microbes attached to MPs are the bacterial communities in the surrounding waters. The pathogens *Arcobacter cryaerophilus*, *Aeromonas salmonicida*, *Vibrio areninigrae*, and *Vibrio navarrensis* were the dominant bacterial communities, causing gastroenteritis and wound infections in humans (Loiseau and Sorci, 2022). In wastewater, MPs are a carrier for these pathogenic bacteria (Lai et al., 2022). Proteobacteria were the leading bacteria on the MPs collected from freshwater systems. Among numerous *Proteobacteria*, *Escherichia coli*, and *Shigella* are noteworthy for causing diarrhoea and fever. Moreover, observations confirm the occurrence of potentially pathogenic *Faecalibacterium*, *Enterococcus*, *Enterobacter*, *Campylobacteraceae*, *Rumunicoccus*, *Romboutsia*, and *Burkholderia* on the surfaces of MPs (Murphy et al., 2018). Hence, MPs are not only carriers of pathogenic microbes but can be considered enriching infectious strains through HGT (Bowley et al., 2021), as described elsewhere in the chapter. Furthermore, it is not only humans but other species that are also affected by the MPs with pathogenic bacteria. Many aquaculture and fishery reports demonstrate how these infectious organisms on MPs cause diseases.

18.6 THE MICROPLASTICS AND ANTIBIOTIC RESISTANCE CONNECTION

High density and close physical contact of MPs with biofilms increase the transfer of ARGs within bacteria and their ability to persist in the environment. The biofilms act as sinks for contaminants, including heavy metals and antibiotics. Recent studies have reported the role of different plastic types in biofilm formation and their impact on ARG composition. For example, PET plastic-associated biofilms have been found to significantly influence the composition of ARGs (Ventura et al., 2024). The specific characteristics of PET, including its surface properties and polymer structure, create a distinct environment that affects microbial colonization and the types of ARGs present. During the COVID-19 epidemic, personal protective equipment (PPE), including gloves, facemasks, and protective suits, has accumulated in the natural environment. Among those, as facemasks became mandatory, inappropriately dumped facemasks accumulated in waste and provided substrates for microorganisms, including potential pathogens.

18.6.1 Antibiotic-Resistance Genes Identified in Microplastics

The most common ARGs identified in MPs confer resistance to multiple critical classes of antibiotics. These include tetracycline, sulfonamide, aminoglycoside, β-lactam, MLSB, and vancomycin (Itzhari et al., 2024). Among MP samples, the most abundant ARGs from the drift line zone that confer resistance to tetracycline are tetW, tetG, and tetM for sulfonamide, sul1 and sul2 and aminoglycoside, aaC3-VI. The β-lactam responsible genes include blaKPC and blaTEM_1, and for macrolide, lincosamide, and streptogramin B (MLSB), it is mphA (Merline and Dhinagaran, 2023). These antibiotic classes are among the most widely administered globally and have been used to treat bacterial infections for over half a century. The presence of blaKPC, blaCTX-M, and tetM in MPs is particularly concerning because these genes are associated with multidrug resistance and may be linked to other antimicrobial-resistance genes (Merline and Dhinagaran, 2023).

Examples of commonly detected ARB are included in Table 18.2.

These genes are often found on bacterial plasmids, mobile genetic elements (MGEs) that can be easily transferred between bacteria, facilitating the rapid spread of resistance (Lerminiaux and

TABLE 18.2
Antibiotic-Resistance Genes Associated with the Plastisphere in Various Ecosystems

Source	Major MP Polymer Type	ARGs	Possible Microbes/ Microbial Communities	References
Recirculating aquaculture system	PET	*tetG*, *qnrS*, *sul1*, *sul2*, *ermF*	Proteobacteria *Mycobacterium* sp. *Marinobactor* sp. *Pseudophaeobactor* sp. *Alcanivorax* sp.	Lu et al. (2019)
Sewage	PE, PVC	*tetA-02*, *bla*, *tetW*	*Clostridum* sp. *Mycobacterium* sp. *Neisseria* sp. *Legionella* sp. *Arcobactor* sp.	Wang et al. (2021)
Sediments/soil of mangroves	PHA, PET, PE, PFP, PP, PS, PF	*bcrA*, *macB*, *rpoB2*, *vanR*	*Acinetobacter baumannii* *Enterococcus faecium* *Haemophilus influenzae* *Helicobacter pylori* *Klebsiella pneumoniae* *Neisseria gonorrhoeae* *Pseudomonas aeruginosa*	Sun et al. (2021)
Tap water/ground water	PE, PET, PP, PA	*sul1*, *tetA*	*Klebsiella pneumonia* *E. coli* *Enterobacter cloacae* *Pseudomonas aeruginosa*	Bergeron et al. (2017), Gambino et al. (2022)
Synthetic wastewater/ membrane-filtered seawater	PS	*tetA, tetB, tetC, tetX, tetO, tetQ, acrB, blaKPC, blaCTX-M, tetM, mdtE,* and *acrB_1* *mexB, mexD, intI1,* and *intI* *107 ARGs*	*Escherichia coli* *Enterococcus* sp.	Dasí et al. (2024), Zhao et al. (2020)
Wastewater treatment plant	PS	*Antibiotic-resistant plasmid RP4*	*Raoultella ornithinolytica* *Stenotrophomonas maltophilia* Heterotrophic *Novosphingobium* Filamentous *Flectobacillus*	Pham et al. (2021)
Lake water/river water	PE, PVC, PET, PP, PB	*Sul1, sul2, i-tetA, i-TetC, iTetO, i-sul1 e-tetA, e-bla*	*Flavobacterium* sp. *Rhodoferax* sp. *Pseudomonas* sp. *Janthinobacterium* sp.	Perveen et al. (2022)
Sewage	PE, PVC	*tet,bla*	*Proteobacteria* sp. *Mycobacterium* sp. *Neisseria* sp. *Arcobacter* sp.	Wang et al. (2021)

Abbreviations: PET, polyethylene terephthalate; PE, polyethylene; PVC, polyvinyl chloride; PHA, polyhydroxyalkanoate; PFP, plant fibre plastic; PP, polypropylene; PS, polystyrene; PF, phenol formaldehyde; PA, polyamide; PB, polybutylene.

Cameron, 2019). Therefore, MPs could be described as co-selective agents for AMR (Stevenson et al., 2024). The genetic linkage of antibiotic resistance and virulence genes on multidrug-resistant plasmids can facilitate the co-selection of AMR genes. In biofilms, ARGs can spread to pathogenic bacteria via HGT through conjugation (plasmid-borne ARGs), transformation (free extracellular ARGs), or transduction (phage-transported ARGs) (Tao et al., 2022). The distribution and transfer mechanisms of ARGs within biofilms remain unclear.

Flavobacterium spp. and *Chryseobacterium* spp. frequently carry ARGs on MPs (Merline and Dhinagaran, 2023; Tuvo et al., 2023). There is a significant correlation between MP concentration and the integron integrase class-1 gene, an MGE that promotes ARG transfer (Pham et al., 2021). According to a study, the conjugation rates of ARGs were more significant in the plastisphere than in control wastewater communities (Stevenson et al., 2024) and also higher than in planktonic communities.

Considering transformation, the presence of PS nanoplastics significantly increased the transformation frequency of *E. coli* (Stevenson et al., 2024). Furthermore, transformation frequency was significantly greater in the plastisphere than in free-living and natural particle controls (Stevenson et al., 2024). The increased transformation rate observed in the plastisphere is associated with several factors. These factors include bacterial density, EPS content (such as extracellular DNA (eDNA)), and the expression of genes related to biofilm formation or DNA uptake, such as flagella motility and bacterial adhesion (Stevenson et al., 2024).

The uptake frequency of plasmids in bacterial communities was twice as high in MP biofilms compared to free-living bacteria. The reported HGT on MPs could lead to many MGEs with a diverse ARG composition (Stevenson et al., 2024). Arias-Andres et al. (2018) observed that mobile elements carrying resistance genes could develop faster in biofilms than in planktonic bacterial communities. It additionally provided evidence that MPs could accelerate gene exchange between the biofilms of attached communities and the surrounding water environments (Arias-Andres et al., 2018).

Non-biodegradable MPs like PET have a higher ARG binding capacity than biodegradable MPs such as polyhydroxyalkanoates (PHAs) (Sun et al., 2021). *Pseudomonas* spp. with multidrug or glycopeptide-resistance genes was found on PET and PHA. The *Desulfovibrio* spp. resistant to macrolide–lincosamide–streptogramin was mainly isolated on PET (Tuvo et al., 2023). The environmental ageing of MPs, caused by mechanical abrasion, solar radiation, and biodegradation, enhances their ability to bind ARG-carrying bacteria or free-floating genetic materials. UV-C radiation exposure for 5–20 days increases the pore size and total volume of MPs, and it promotes ARG binding, biofilm formation, and gene exchange (Tuvo et al., 2023). However, releasing chemical compounds from MPs can alter microorganism membrane permeability, facilitating ARG transfer. Additives or pollutants on MPs, such as copper and zinc, may also favour ARG binding (Trevisan et al., 2022). These pollutants and polycyclic aromatic hydrocarbons apply selective pressure on ARG transfer through co-selection or cross-selection (Tuvo et al., 2023).

MPs may transport pathogens and ARGs in the aquatic environment (Gaylarde et al., 2023). In marine aquacultures, ARB on MP surfaces is 100–5,000 times higher than in the surrounding water (Zhang et al., 2020). MPs may not solely serve as vehicles for microbial pathogens; they could enrich pathogenic strains that have acquired pathogenicity islands (PAIs) and other antimicrobial properties through HGT (Bowley et al., 2021).

18.6.2 Plastispheres as Hotspots for AMR in Soil

In parallel, recent research has highlighted that plastispheres, which form on MPs in soil environments, are critical hotspots for AMR. These plastispheres show a significantly higher abundance of ARGs compared to the surrounding soils. Long-term exposure to plastic mulch applications in Chinese soils has led to an increase in antibiotic resistance. The researchers discovered the presence of ARGs and thousands of MGEs, including integrons, insertions, and plasmids (Wu et al., 2019).

These findings illustrate the significant environmental and health risks posed by the interaction of MPs with pathogenic and ARBs. In the terrestrial environment, plastisphere communities comprised 12.4 times more potential pathogens than ambient soil (Stevenson et al., 2024). In the agricultural soil, environmental factors like manure addition, elevated soil temperatures, and increased moisture levels provide a nutrient-rich environment and a protective biofilm structure; within plastispheres, it creates an ideal setting for the proliferation and exchange of ARGs through HGT. All of which have been shown to significantly enhance ARG concentrations within plastispheres. These findings underscore the role of plastispheres as reservoirs of ARGs, which poses a substantial risk to soil health and ecosystem balance (Zhu et al., 2021). Doxycycline (DOX), when combined with manure, significantly enhances biofilm formation on MPs within the soil plastisphere, with low doses of DOX increasing biofilm concentration and the correlation between ARGs and biofilm development while also boosting the abundance of potential pathogens on MPs and promoting biofilm production of MP-associated strains (Liu et al., 2023).

18.6.3 The Co-occurrence of Heavy Metals and Antibiotics in Microplastics

Due to their hydrophobic nature, MPs provide extensive surfaces for the adsorption of hydrophobic pollutants, altering their bioavailability and chemical properties. Current research indicates that concentrations of heavy metals and organic contaminants on MP surfaces can be up to 10^6 times higher than in the surrounding environment (Campanale et al., 2020). Creating combined toxicity as chemicals adhered to MP biofilms could be released during natural weathering processes. The heavy metals, antibiotics, and other xenobiotics make MPs potential carriers of pollution and multidrug resistance in humans.

There is a higher prevalence of metal resistance and multidrug-resistance genes in bacteria isolated from MPs than in free-living strains (Piergiacomo et al., 2023) and these contaminated particles can enter humans indirectly. People may consume seafood such as crustaceans, bivalves, fish, or sea salt containing MPs that transmit antibiotic-resistant pathogens and metal-driven multi-resistances. Approximately 80% of fish have been found to contain MPs in their stomachs, which can cause tissue necrosis, inflammation, cell necrosis, cytotoxic complications, and oxidative stress in humans.

In one study, PVC MPs pre-adsorbed with copper and/or tetracycline were incubated in an artificially activated sludge system (Stevenson et al., 2024). The antimicrobials selectively enriched ARGs in the plastisphere and surrounding sludge. Additionally, exposure to PVC leachate significantly increases the relative abundance of ARGs and virulence genes in a marine bacterial community (Vlaanderen et al., 2023). The hydrocarbonoclastic bacteria, capable of producing plastic-degrading enzymes, have been previously documented in the plastisphere (Delacuvellerie et al., 2019). The adsorption of oxytetracycline to biodegradable MPs is enhanced in the presence of a biofilm, compared to virgin MPs (Sun et al., 2021).

MPs can be vectors for harmful microorganisms, often closely associated with other microbes and sorbed contaminants, including metals. This can lead to MPs functioning as a microcosm for more effective gene exchange between bacteria, potentially facilitating the spread of antibiotic resistance (Bowley et al., 2021). Differences in microbial community composition on plastic buried at various depths suggest that environmental conditions and dominant redox processes control plastic colonization. Organisms with metabolic flexibility are found throughout changing redox conditions of the plastisphere (Dodhia et al., 2023). The variability in microbial communities on plastics may be attributed to thicker biofilm development on plastics in the water column compared to those in the sediment and selective sorption of iron and manganese oxides and minor metals. These metals and minerals can serve as templates for microbial attachment and catalysts for further reactions, influencing the composition of the biofilm (Dong et al., 2022) (Figure 18.2).

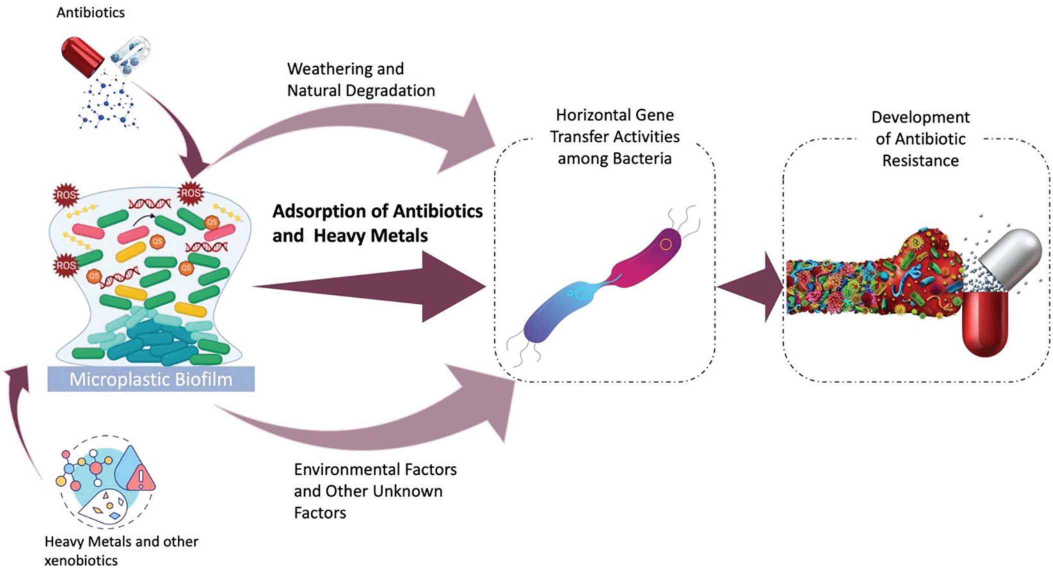

FIGURE 18.2 The interconnection between microplastic biofilm formation and the development and environmental transmission of antibiotic resistance.

18.7 MITIGATION OF ENVIRONMENTAL HEALTH RISKS

Mitigating the environmental health risks of pharmaceuticals adsorbed on MPs and the spread of ARB in natural environments require an interdisciplinary approach. The risks involve comprehensive strategies to manage pollution and control the transport of MPs over large areas. Effective mitigation strategies must address the complex interactions between pharmaceuticals, MPs, and microbial communities (Caban and Stepnowski, 2021).

18.7.1 Source Reduction and Proper Disposal of Pharmaceuticals

The release of pharmaceuticals at the source is the one major factor in concluding pharmaceutical pollution in the environment (Larsen et al., 2004). Minimizing unnecessary pharmaceutical use and promoting proper disposal of unused or expired medications could be practised as preventive measures to reduce pollution.

18.7.2 Implementation of Wastewater Treatment Technologies

Wastewater treatment plants (WWTPs) are supposed to be able to remove pharmaceuticals and MPs from effluent streams before they are discharged into aquatic ecosystems. Progressive treatment technologies include ozonation, activated carbon adsorption, membrane filtration, and UV disinfection (Khasawneh and Palaniandy, 2021).

However, conventional WWTPs may not be adequately equipped to effectively remove pharmaceuticals and MPs, as these compounds can persist through treatment and enter receiving waters at relevant concentrations. To address this challenge, upgrades and optimization of existing treatment facilities are needed, as well as the development of novel treatment technologies specifically designed to target pharmaceuticals and MPs.

18.7.3 Development of Environmentally Friendly Alternatives to Conventional Plastics

Reducing the accumulation of MP in aquatic habitats requires a shift toward using environmentally friendly alternatives to conventional plastics. Biodegradable polymers, plant-based plastics, and other sustainable materials offer potential solutions for reducing plastic pollution (Song et al., 2009). However, it is essential to ensure that alternative materials are environmentally sustainable and do not pose unintended consequences, such as increased resource consumption or habitat disruption.

18.7.4 Promotion of Responsible Antibiotic Use Practices

The proliferation of ARB and ARG in aquatic environments is mainly due to improper healthcare, agriculture, and aquaculture antibiotic practices. Antibiotic overuse contributes to the emergence and spread of antibiotic resistance, creating selective pressures that promote the survival of resistant bacterial strains (Chokshi et al., 2019).

Public health campaigns, antibiotic awareness programs, and regulatory measures can help promote appropriate antibiotic prescribing practices and minimize unnecessary antibiotic use. In agricultural and aquaculture settings, alternative disease management strategies, such as vaccination, biosecurity measures, and probiotic supplements, can reduce the reliance on antibiotics and mitigate the risk of AMR in food production systems (Adorka et al., 2013).

18.7.5 Continued Research and Monitoring

Continued research and monitoring are essential for improving our understanding of pharmaceuticals, ARGs, and ARBs about MPs, transport, and ecological impacts on the environment. Long-term monitoring programs with field data can track changes in pollutant concentrations, microbial community dynamics, and antibiotic resistance patterns over time, providing a valuable understanding of the effectiveness of mitigation measures. Interdisciplinary research collaborations are needed to address knowledge gaps and develop innovative solutions.

18.8 CONCLUSION

MPs contribute to ecosystems by providing substrates for colonizing microbes in natural environments. This chapter highlights that PS can act as a vector for ARB, thereby causing the emergence and spread of human diseases. The adsorption of antibiotics on MPs facilitates the persistence and spread of ARG, which enhances the frequency of plasmid transfer among PS-associated bacteria with the help of unique features of biofilm formation around them. MP shows substantial abundance and potential pathogen diversity compared to biofilm formed around natural materials such as rocks and wood. These unique features resulted from higher relative proportions of chemical and physical characteristics of MPs. These findings underscore that PS acts as living vectors, facilitating the movement and persistence of pathogenic bacteria within ecosystems and across communities, thus posing substantial risks to human health.

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