Chapter

The Importance of Biofilms to the Fate and Effects of Microplastics

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Abstract

Microplastics are global pollutants in water media ranging from drinking water to freshwater streams to oceanic pollutant gyres. Besides the obvious appearance involving a scattered presence in the environmental landscape, microplastics are ubiquitous across modern society in products, food, and beginning to have strong economic effects too. Ingestion of microplastics is virtually unavoidable for each of us as we consume food, breathe air, or drink liquids. For example, beer has been found to be contaminated with plastic materials having the dimensions of micro- and nanoparticles. In the environment, the formation of biofilms on microplastics is widely observed and this can significantly alter properties important to environmental and human health. Significant research has been conducted on the role of biofilms in the fate and effect of microplastics on environmental and human health, with a general message to avoid contact with microplastics in the environment until more complete strategies for cleanup are developed.

Keywords: biofilms, fate and effects, microplastics, pathogenic human threats, pollutants, toxicity

1. Introduction

Plastic derived from the Greek *plasticos* refers to synthetic carbonaceous polymers that exhibit the desired degree of physical flexibility required for molding. During the past 60 years, the product of organic polymer production exploded to virtually all nooks and crannies across the globe [1]. In 2020, global plastic production is composed of a few well-known polymers used in a wide range of products having differing compositions and properties. Current plastic polymer production levels exceed 320 million metric tons (Mt). This surpassed production in the previous decade when significant production capacities were idled [2]. Massive plastic pollution in the world's oceans is estimated to exceed 5 trillion pieces of plastic with a mass of 250,000 Mt [3].

Carbon-based commercialized polymeric materials having desirable physical and chemical properties constitute a wide range of applications. Plastics have been part of the broad range of commercial materials entering the global economy since 1950. The mass production of virgin polymers has been estimated at 8300 Mt. for the period from 1950 to 2015 [4]. Global consumption of plastics continues at a rate of roughly 311 Mt. per year with 90% derived from a petroleum origin and has become a major worldwide solid waste problem. Plastic packaging enhancements have changed the composition of solid waste to where the plastic fraction exceeds 10% in 2005 [5]. In the plastic recycle flow, packaging plastics are poorly recycled. The bulk of plastic waste is disposed in landfills and the natural environment which may exceed 12,000 Mt. of plastic waste by 2050 if current production and waste management trends continue unabated [2].

Macroplastics or the polymers from which they are constructed have been recognized as valuable materials composed of repeating units and applicable to many material design requirements [6]. Each repeating unit of a polymer is referred to as the "-mer" with "polymer" denoting a chemical composed of many repeating units. Plastics are unique materials having the benefits of being light weight, versatile, having reasonably long service lives, and attractive cost. Across the land and seas, the accumulation of plastic litter found in natural environments looms as a global issue [7]. Potential negative impacts to wildlife, human health, and the economy offer strong incentives to thoroughly explore our approach to the sustainable use of plastics [8].

2. Plastics in the environment

Easily observed plastic pollution is often referred to as macroplastics which have dimensions greater than 1 mm. Smaller plastic particles are referred as micro- or nanoparticle. The aspects of long-term pollution and human health effects have been issues of social concern in recent times [9]. The wanton dispersal of plastic film bags and drink bottles mar our global landscape, waterways, and oceans/seas. Plastics apparent resistance to degradation elongates their residence time in the environment. Environmental processes can contribute to the debris by activating degradation pathways which lead to the conversion of macroplastics to smaller dimension plastic materials [10]. Plastics can carry with them pollutants such as plasticizers, antioxidants, and other persistent organic pollutants **Table 1** [11–15]. Human health concerns have been focused on the monomeric components, additives, and certain combinations of the chemical employed in the synthesis of a plastic [16].

Characteristic	Behavior
Density	Determines the vertical water column position
Crystallinity	Controls susceptibility to photochemical oxidation
Extent of oxidation	Chemical composition determines the ease of oxidation and weathering
Biodegradability	Contributes to the general structural deterioration of microplastics through biological means
Monomer residual	Potential source of toxicity and small molecule pollutants
Transport properties	Affinity for hydrophobic chemicals and metals
Polymer additives	Highly variable depending on polymer composition and application of polymer
Surface properties	Important to aggregate formation and biofouling

Table 1.
Characteristics influencing microplastic behavior.

3. Microplastics

The chemical composition of the major plastics provides some basic understanding of their environmental behavior (**Table 2**) [17]. The physical dimensions of plastic particles are classified by size class which refers to the particle's largest dimension that is important to the design of analytical collection protocols used in sampling microplastics sensitive to particle shape [18, 19]. The term microplastics refers to anthropogenic polymer materials having the dimensions of less than 5 mm (0.2 inch) occurring as

Polymer category	Specific gravity	Water column movement	Degree of crystallinity %
Polyethylene (PE)	0.91–0.94	Float	
Low density LDPE	“	“	45–55
High density HDPE	“	“	70–80
Polypropylene (PP)	0.90–0.92	“	
Atactic PP	“	“	~0
Isotactic PP	“	“	70–80
Polystyrene (expanded) (PS)	0.01–1.05	“	
Seawater	~1.02		
Polystyrene	1.04–1.09	Sink	
Polyvinyl chloride (PVC)	1.16–1.30	“	
Polyamide	1.13–1.15	“	35–45
Polyethylene terephthalate (PET)	1.34–1.39	“	30–40
Polyester resin + glass fibers	>1.35	“	
Cellulose acetate	1.22–1.24	“	

Table 2.
Plastic properties important to the fate and effects of microplastics.

plastic pollution in the environment [20]. Smaller particles referred to as nanoplastics are becoming an issue of growing concern that falls into the size range of 10–1,000 nm [21]. The consensus definition and categorization of plastic debris are yet to be achieved. Uneven size classes are employed for sampling for microplastics to represent random size classes, and even material composition is a matter of debate [22, 23].

3.1 Definition

Microplastic specifications can be found in two broad categories, primary and secondary [24]. Primary microplastics are manufactured particles that are characterized as microbeads, nurdles, and fibers in size dimensions of 5 mm or smaller. Any interception technology must be equipped with appropriately sized filters to remove the particles from contaminated environmental media. Secondary microplastics are formed from larger plastics or macroplastics through the effects of weathering and physical deterioration in the environment. Weathering by photochemical oxidation, UV rays, and wind and wave action leads to the fragmentation of macroplastics to form microplastics. Aquatic plastic debris can be organized by size as mega (>1 m)-, macro (<1 m)-, meso (<2.5 cm)-, micro (<5 mm)-, and nano (<1 μm)-dimensions [25]. A recently proposed size schema separates microplastics in marine environments into the following categories: nano (1–1000 nm)-, micro (1–1000 μm)-, meso (1–10 mm)-, and macroplastics (≥1 cm). Size schemes are proposed to address the sampling problems encountered in the field, but these schemes are lacking since it is difficult to provide a microplastic sample that is spatially representative of a specific environmental space [26–29].

3.2 Composition

Chemical composition and environmental impacts of microplastic samples differ broadly (**Table 2**). Microplastic composition reflects the use and disposal of the most popular macroplastics such as the polyolefins [polypropylene (PP) and polyethylene (PE)], polyvinyl chloride (PVC), polyurethane (PU), polyethylene terephthalate (PET), polystyrene (PS), and polycarbonate (PC). The composition of this list represents a large fraction of plastic use and global plastic production [2]. The high molecular weight of most plastic polymers renders them biochemically inert initially and hence have an inherent low toxicity due to lack of water solubility [30]. Many polymer compositions can contain small concentrations of unpolymerized monomer [31]. Monomers can be toxic and carcinogenic as in the case of styrene or vinyl chloride [32]. Problematic plastics such as PVC, PU, PS, and PC can contain toxic monomers or additives. Additives can include fillers, plasticizers, coloring agents, antimicrobials, flame retardants, and other material property modifiers [33]. These materials represent a source of health risks for humans and other species [34].

3.3 Origin

Microplastics can be produced directly for use as raw materials in the fabrication of larger items. Environmental processes are known to form microplastic particles through mechanical destruction of macroplastic materials such as automobile tires disintegrating during wear and use [35]. As ingredients of abrasive, cleaning, and cosmetic products, microplastics have been manufactured as articles of commerce [36]. Microplastics were found to form during material wear of macroplastics by industrial processes and via physical breakdown of macroplastics [35, 36]. Their abundance and in situ effects of the environment have not been well quantified due in part to the random composition of particles of non-uniform shapes which are difficult to assess by representative samples [37]. The abundance of micro-, meso-, and macroplastics floating in the marine environment has been estimated from aggregated data derived from a host of surveys [38]. An estimate of global plastic pollution identifies at least 5.25 trillion plastic pieces of plastics, and most of its composition is microplastics [39]. Plastic marine debris (PMD) surveys suggested estimates of the total burden could be at least an order of magnitude lower than what has been observed in the environment [40]. A concern for a missing debris component has been interpreted as losses to deep sea and sediment sinks as prominent components to marine plastic fate [41].

3.4 Analytical protocols

An understanding of microplastic pollution requires the use of proper and clear terminology for use in the design of data collection and supporting analytical protocols, enhanced coordination of strategic design for research directions, and most importantly a consensus development of mitigation management practices tailored to the global problem solution [42]. Composition, dimensions, and shape of plastic debris can be defined explicitly to properly design sampling protocols and conduct the requisite analytical determinations (biological, chemical, and physical) using a wide array of techniques ranging from microscopy to different forms of spectroscopy [43]. Physicochemical properties (polymer composition, solid state, solubility) are employed as standards accompanying size, shape, color, and origin for categorical identification [44].

Standardized quantification and analysis procedures designed to analyze microplastics are critical to the design and data collection for comparative research studies [45]. Microplastics have high surface area solids and should be described in consensus terms [46]. The surface area of environmentally sampled microplastics was found to be a very important descriptor along with an accurate parameter to describe plastic size coupled with a description of plastic quantity per spatial area. As widespread contaminants, microplastics can be found in virtually all environmental partitions [47]. Features such as spatial information, contamination sources, fate, and environmental concentration are difficult to assemble and the variety of analytical procedures currently in use hinders a timely and proficient gathering of information [48]. Methods currently used to sample and detect microplastics are under review which is aimed to identify flaws in design and suggest alternatives [49]. Analytical protocols must be designed to include bulk sample collection, particle separation, digestion, identification and quantification, and mitigation of cross-contamination in the form of transportable and consensus tools. This enhanced ability to sample and analyze microplastics enables the use of more representative samples and helps enhance the determination of the sample features mentioned previously. Incorporation of these features provides an enhanced ability to sample and analyze microplastics leading to the utilization of more representative samples attuned to the sample features required for the formulation of standard methods. The inclusion of new and novel analytical methodology can assist the chemical, biological, and physical characterization of samples [50].

3.5 Concerns

Without the proper knowledge of the environmental behavior of microplastics, we are incapable of solving the growing problem of microplastic management as applied to reducing the problem dimensions and human health risk. The necessary knowledge rests on properly designed research efforts and the use of harmonized and consensus analytical tools employed in the data gathering. What parameters for quantifying microplastics are available at a status that permits the comparison of field results acceptable to the general research community?

4. Biofilms

A consortium of microorganisms composed of cells adhering to a surface is called a biofilm [51, 52]. The physical setting for cells to adhere to a surface occurs through the intermediacy of extracellular polymeric substances (EPS) which forms a slimy extracellular matrix **Figure 1** [53]. Microbial cells in the biofilm produce the EPS which are composites of extracellular polysaccharides, proteins, lipids, and DNA [54, 55]. The cellular agglomeration of biofilms forms a three-dimensional structure as a community that offers significant protection against the forces levied by the environment [56].

4.1 Structure

Microbial cells composing a biofilm are distinct from the planktonic cells of the same organism, which are single-cell organisms that are free to float or swim in an aquatic medium [57]. Biofilm structures are formed in response to a variety of different factors enabling biofilm development [58, 59]. Surface recognition is important to specific or nonspecific attachment sites, toxic materials, or antibiotics, and nutritional stress may complicate biofilm growth **Figure 2** [60]. A cell that switches to the biofilm mode of growth undergoes a shift of observable behavior of the bacteria resulting from the interaction of its genotype with the environment that is required of a microbial cell in the transition from planktonic to sessile growth in the regulation genes of the biofilm. A biofilm can mimic a hydrogel, a three-dimensional (3D) network of hydrophilic polymers complex containing a

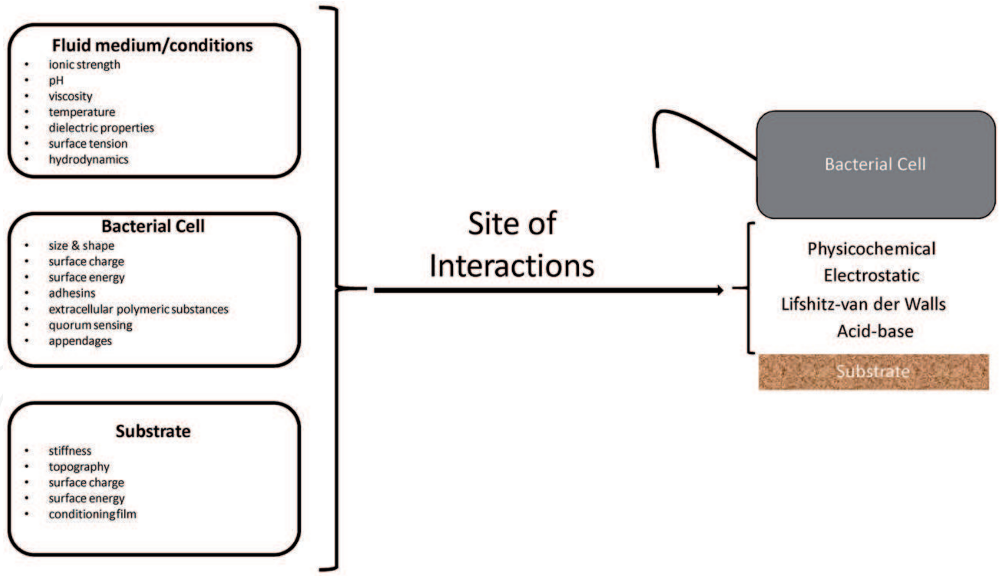

Figure 1.
Site of biofilm interactions.

large quantity of water, which retains its structure through chemical or physical cross-linking polymer chains [61]. Biofilm formation can lead to the formation of a coordinated functional microbial community. The bacteria composing a biofilm can share nutrients due to their proximity in the biofilm and protection from harmful factors of the environment. Biofilms usually begin to form when a free-swimming bacterium attaches to a surface [62].

Colonization of a surface requires a significant transition from the free-living planktonic existence in the bulk aquatic phase to a surface-attached state. A biofilm life cycle is portrayed in **Figure 2** [63]. This process is initiated by the reversible adhesion of a few single cells to a surface leading to a reversible attachment where weakly attached cells are sloughed to the bulk medium, or irreversible attachment where interactions of the cells and a surface are reinforced [64]. Irreversibly attached cells at a surface continue to agglomerate to form microcolonies through cellular division and can proceed to form a mature biofilm when the conditions support growth [65]. As the biofilm matures, factors that will prevent sustainable growth can be triggered by limited nutrients supply or lowered oxygen concentrations may reverse biofilm formation through the dispersal of cells from the biofilm to the bulk aquatic phase. Released cells may attach to a new surface [66]. For single-cell adhesion, three factors leading to single-cell adhesion require attention: the chemical and physical composition of the aquatic environment, the solid surface, and the transitioning microbiota [67].

4.2 Characteristics

Microorganisms form from attached phase growth structures (biofilms) or multicellular microbial communities by transitioning from planktonic (freely-swimming) biota to components of a complex, surface-attached community (**Figure 1**). These communities of adhering microorganisms in the form of biofilms provide protection to the microbes participating in its development. The process begins with planktonic microorganism encountering a surface where some adsorb followed by surface release to final attachment by the secretion of exopolysaccharides which act as an adhesive for the growing biofilm (**Figure 2**) [68]. Switching from a planktonic existence to an attached-life state (sessile) requires a complex

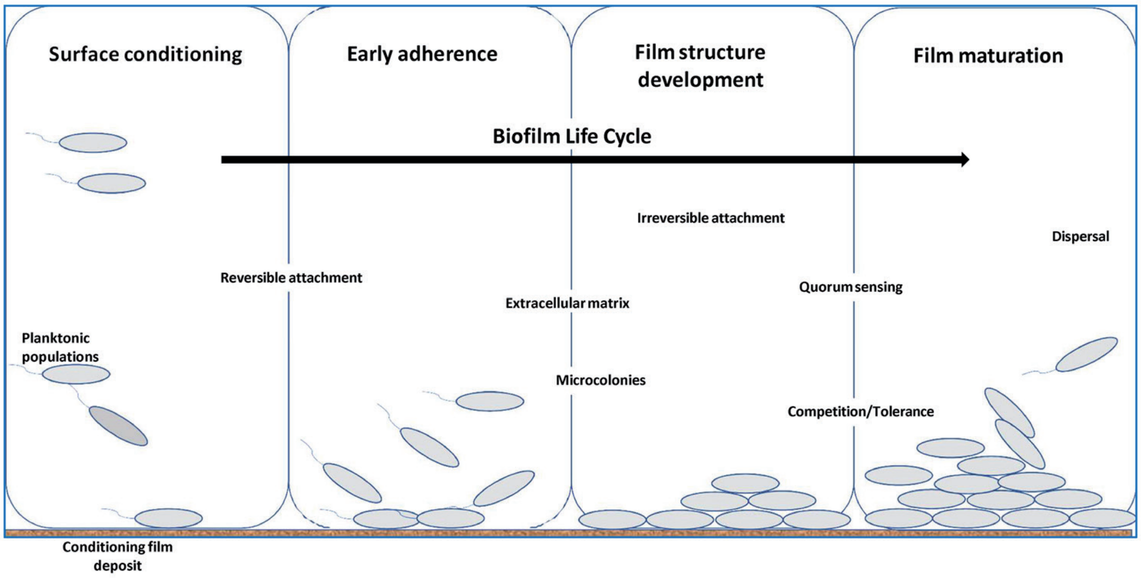

Figure 2.
Biofilm life cycle.

process composed of several factors derived from biological, chemical, and physical properties of the environment, the surface, and the bacterial cell (**Figure 2**) [69]. Initial weak, reversible interactions between a bacterium and a surface lead to irreversible adhesion. New phenotypic characteristics are exhibited by the bacteria of a biofilm in response to environmental signals. Initial cell-polymer surface interactions, biofilm maturation, and the return to the planktonic mode of growth have regulatory circuits and genetic elements controlling these diverse functions. Studies have been conducted to explore the genetic basis of biofilm development with the development of new insights. Compositionally, these films have been found to be a single microbial species or multiple microbial species with attachment to a range of biotic and abiotic surfaces [70]. Mixed-species biofilms are generally encountered in most environments. With proper nutrient and carbon substrate provided, biofilms can grow to massive sizes. A biofilm can achieve large film structures that may be sensitive to physical forces such as agitation. Such energy regimes can lead to biofilm detachment. An example of biofilm attachment and utility can be found in the wastewater treatment sector where large polypropylene disks are rotated through industrial or agriculture wastewater and then exposed to the atmosphere to treat pollutants through the intermediacy of cultured biofilms attached to the rotating polypropylene disk.

4.3 Plastic colonization and plastisphere communities

Plastic's role in freshwater and marine systems is poorly understood from many perspectives especially microbiology. Microscopic scrutiny and next-generation sequencing of PMD from locations in the North Atlantic were used to characterize attached microbial communities. A microbial community having a high degree of diversity was identified as the "Plastisphere" from the pitting of the debris surface which suggested bacterial shapes engaged in the utilization of the polymer by enzymatic means [71]. Opportunistic pathogens were observed as specific members of the genus *Vibrio* [72, 73]. Attached plastisphere communities were found to be distinct from surrounding surface water, suggesting that PMD could be a novel ecological habitat in the open ocean. Most natural floating marine substrates have shorter half-lives than PMD which is enhanced by a hydrophobic surface that assists microbial colonization and biofilm formation. The adhesion of individual bacteria to a surface-initiated biofilm formation is supported by a collection of factors arising from initial adhesion to the growth of a mature biofilm [74].

Bacteria communicate with one another using chemical signal molecules [75]. This process, termed quorum sensing, allows bacteria to monitor the environment to adjust community behavior at a population-wide scale in response to community changes in the number and species present [76]. The information conveyed by these molecules works to synchronize activities for a wide group of cells. This cell-to-cell communication is used by bacteria to coordinate population density-dependent changes in behavior. Quorum sensing involves the production of and response to diffusible or secreted signals, which can vary substantially across different types of bacteria and important to the first stage of encounter between a bacterium and a solid surface [77].

Initial bacterial adhesion to a surface, bacterial mass transport, the role of substratum surface properties in initial adhesion and the transition from reversible to irreversible adhesion have been analyzed through a physiochemical lens to yield great insight. Surface thermodynamics and Derjaguin Landau Verwey Overbeek analyses can describe bacterial support using smooth, inert colloidal particles to estimate bacterial cells. A depiction of initial bacterial adhesion to surface-programmed biofilm growth was found to have four major stages: bacterial mass transport towards a surface, reversible bacterial adhesion, conversion to irreversible adhesion, cell wall deformation, and associated developing properties [78]. The production of EPS can be surface-programmed [79]. Initial bacterial adhesion to surfaces and biofilm growth at the solid surface is driven by aspects of physico-chemistry [80].

Bacterial adhesion is important to the fate and transport of plastics in aquatic environments. There has been no systematic investigation of bacterial adhesion to different types of plastics. A limited evaluation of short-term and long-term adhesion for different types of bacteria and four types of plastics, polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC), was conducted [81]. The target physicochemical factors of surface charge, hydrophobicity/hydrophilicity, roughness, and plastic hardness were characterized. Surface hardness of the plastics was identified as a major factor dominating the adhesion of bacteria onto plastic surfaces in contrast to the other factors [82]. There were significant differences in bacterial cell adhesion for the types of plastics. The different plastic types influenced the bacterial adhesion due to intrinsic surface properties in both short- and long-term studies [83]. Generally, surface roughness, topography, surface free energy, surface charge, electrostatic interactions, and surface hydrophobicity are anticipated to be important to the process of biofilm attachment [84].

5. Environmental effects and fate

A complex network of interactions existing among the physical, chemical, and biological aspects of microplastics in an aquatic environment is shown in **Figure 3** [85]. The microplastic interfaces with pollutant chemicals and biofilms. In this system the plastic surface can be composed of pollutant chemical, biofilm, or biofilm contaminated with pollutant. With time the interactions of microorganisms and microplastics modify pollutant characteristics establishing how and why cells attach to plastic particles. The complexity of the relationship between plastic particles and microorganism attachment relies on factors influencing community development of biofilm and physical characteristics of microplastic particles.

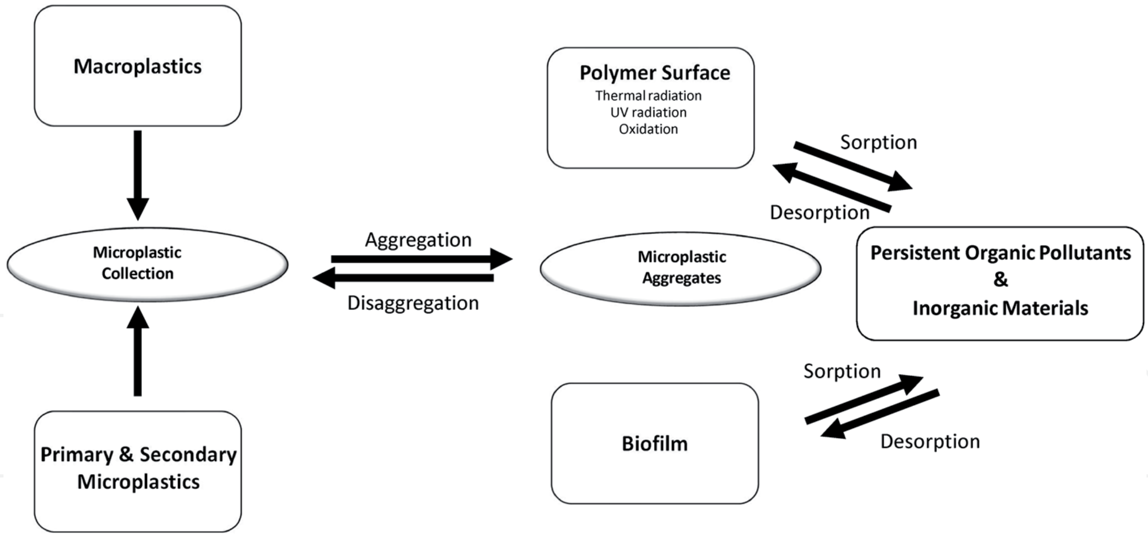

Figure 3.
Microplastic formation and environmental degradation.

5.1 Sorption

Plastics contaminating aquatic environments have been shown to hold various pollutant chemicals arising from the plastic manufacture and environmental pollution. Understanding of sorption and desorption of chemicals by plastics is pivotal to the evaluation of plastics, and their role is important to the environmental dynamics of these chemicals and as a vector of pollution and human health concerns [86]. The chemicals can be of inorganic and organic composition. Environmental microplastic pollution is an assembly of effects found in freshwater and marine conditions relating the complex interrelationship of physical processes, pollutant chemicals, and biota in the formation of biofilms. Sorption of chemicals and microbes to microplastic surfaces involves sorption of chemicals and biota directly to the plastic surface that may or may not be covered with other pollutant chemicals or biofilm. Direct sorption of chemicals to the plastic or biofilm covered plastic surface may exhibit different effects.

The sorption of neutral chemicals to solids from a water phase requires partitioning of freely floating or partially dissolved organic chemical moieties from an aqueous phase to a plastic surface [87, 88]. Factors affecting the partitioning process are the magnitude of the sorption coefficient, temperature, pH, and other coexisting organic and inorganic constituents present in the water phase [89]. The environmental partitioning process is seldom if ever at equilibrium and non-equilibrium conditions describe the general status of environmental conditions. Stagnant or quiescent conditions in the environment may come the closest to equilibrium partitioning conditions. Non-equilibrium conditions in environmental aquatic systems arise from turbulent conditions ranging from flows through broken or incomplete flow paths found in freshwater streams, sea wave action, and wind and turbulent weather-related phenomena. Sorption properties are also related to phenomena such as the chemical/physical properties of the solid, the extent of physical degradation, biodegradation, and agglomerating processes such as biofouling [90].

Sorption is a physical process of the environment where chemicals are transferred from a fluid phase such as water and air to a solid phase [91]. The term “sorption” collectively refers to both absorption and adsorption which are components of the sorption process. Molecular penetration of a chemical and association within a solid phase matrix defines absorption [92]. Whereas, adsorption refers to a process where molecules are confined at the interface between fluid and solid phases as an adherent physical form [93]. Sorption is directly related to properties of the solid, a chemical, and the surface-to-volume ratio of the solid which for microplastic particles is quite large [94]. Apart from surface area, plastics exhibit a range of properties and dimensions, implying the relevance of absorption and adsorption to understanding the importance to the understanding of microplastics' fate and effect. Physisorption or physical sorption occurs from noncovalent intermolecular interactions such as van der Waals interactions. The interaction forces of solids and chemicals though the noncovalent interactions and their combinations and physisorption are usually reversible. Generally, the sorption of materials and chemicals to environmental solids is by physisorption.

5.2 Chemicals

Microplastics can sorb and accumulate both organic and inorganic contaminants detrimental to humans and ecosystem life when released to organisms that may ingest them [95]. Sorption is a major determinant for bioavailability and contributes to the effects of combined exposure to chemicals and microplastics related to the toxicity and bioaccumulation in humans and ecosystem flora. Neutral charged areas of the microplastic surface offer attractive settings for deposition of chemicals due to attractive hydrophobic forces. This is in contrast with hydrophilic or charged compounds that are attracted to the negative-charged areas on the microplastic surface through electrostatic interactions and aquatic media characteristics [94, 96]. Organic chemicals associated with microplastic debris are typically in the semi-volatile or non-volatile categories such as polychlorinated biphenyls and some organic pesticides [97, 98]. Inorganic chemical species are generally ionic. Fuel chemicals and other higher-boiling constituents can be found in the microplastic debris [88, 99–103]. Weathering can be significantly changed the composition containing volatile compounds.

Sorption evaluations can identify the chemicals with higher affinity to microplastics under a variety of environmental conditions. Bench scale sorption studies permit the evaluation of the mass balance for a specific chemical or chemical mixtures. The distribution of chemicals in an environment contaminated with microplastics can be estimated from experimentally determined sorption capacities. Toxicity parallels sorption data, but greater sorption to microplastics does not necessarily lead to higher toxicity or bioaccumulation of a pollutant chemical.

5.3 Buoyancy and aggregation

Biofilm formation at the surface of microplastics may lead to density changes of particles that alter the specific gravity for the mass of microplastic debris [104]. Mineral detritus when incorporated in microplastic debris will increase the density which leads to sinking. Biofilm distribution and bioavailability are expected to be adjusted in response to the buoyancy of microplastics [105]. Biofouling causes changes in the buoyancy of microplastics and, with increasing specific gravity, leads to descension in the water column to a depth of comparable density. Microplastic sampling in the water column can lead to an underestimation of quantities since turbulence leads to vertical mixing.

Aggregate debris formation can be enhanced by biofilm formation on microplastic surfaces commonly expected in situations where diverse bacterial communities colonize the microplastic surfaces. Aggregation has been confirmed by experiment as a factor leading to the apparent removal of microplastics from the surface layer of the marine ecosystems [106].

Microplastics aggregate rapidly with biogenic particles found in the marine environment [107]. The incorporation of organic material is accelerated through gross aggregate formation. It is anticipated that natural aggregation dynamics will influence particle size distribution and the export rates of organic matter which may mirror the similar processes of freshwater and marine ecosystems.

5.4 Plastic biodegradation

Significant abiotic and biotic conditions exist to show that plastics are vulnerable to these forces found in the environment. Plastic weathering contributes to structural defects and size reduction but incomplete decay. Chemical and physical degradation processes contribute to the overall weathering process. Plastics are composed of a wide variety of chemical structure features that degrade in a spectrum of kinetics under biotic and abiotic conditions. Biodegradation of plastics under aerobic conditions forms new products during the degradation path leading potentially to mineralization forming process end-products such as CO_2, H_2O, or CH_4 depending on the terminal electron acceptor [108]. Oxygen is the terminal electron acceptor for the aerobic degradation process. Aerobic conditions lead to the formation of CO_2 and H_2O in addition to the cellular biomass of microorganisms during the degradation of the plastic forms. When sulfidogenic conditions are encountered, plastic biodegradation can lead to the formation of CO_2 and H_2O. Polymer degradation accomplished under anaerobic conditions produces organic acids, H_2O, CO_2, and CH_4. The aerobic process has been found to be more efficient than anaerobic conditions. The anaerobic process produces less energy due to the absence of O_2, serving the electron acceptor, which is more efficient in comparison to CO_2 and SO_4^{-2} [109]. The exposed surface of plastics is where the initial effects of biodegradation are encountered. The biodegradation rate is directly related to the composition of the plastic. The increase of microbial-colonized surface area leads to faster biodegradation rates assuming all other environmental conditions to be equal [110]. Microorganisms can break organic chemicals into simpler chemical forms through biochemical transformation. Plastic biodegradation is a process in which any change in the polymer structure occurs through the structure altering action of microbial enzymes leading to plastic property changes in the form of molecular weight reduction, mechanical strength changes, and surface properties. A more complete understanding of plastic daughter products of environmental degradation is required to more thoroughly understand the effectiveness of environmental plastic degradation.

5.4.1 Human health and pathogenicity

A wide spectrum of pathogenic microorganisms exists and some form biofilms with microplastics in aquatic environments [111]. Freshwater ecosystem analysis has the formation of biofilms on microplastic substrates by a selected grouping of human pathogens utilizing high-throughput sequencing of 16S rRNA that had distinctive community structures [112]. Opportunistic human pathogens such as *Pseudomonas monteillii*, *Pseudomonas mendocina*, and a plant pathogen *Pseudomonas syringae* were detected forming a microplastic biofilm. The opportunistic pathogens were enriched in a biofilm, and the microplastic biofilm exhibited a unique microbial community structure. Distinctive antibiotic resistance genes were detected in the microplastic biofilm. It appears that microplastic surfaces are novel microbial niches and may serve as a vector for antibiotic resistance genetic traits and pathogens in freshwater bodies, engendering environmental risk and exerting adverse impacts on human health [113].

Vibrios are Gram-negative-curved bacilli naturally occuring in marine, estuarine, and freshwater systems [114]. A group of factors has been shown to drive certain microorganisms' virulence in *in vivo* studies, and some are fitness factors in the environment [115]. Factors associated with virulence, nutrient acquisition, competition, survival in unfavorable biotic and abiotic conditions, and attachment and colonization were found to be in the group [116]. As human and animal pathogens, it is important to understand virulence factors, attachment factors, regulatory factors, and antimicrobial resistance factors, which have been characterized for their importance to the organism's fitness apart from its external environment. Virulence and fitness factors were designated and characterized for the three main human pathogens *Vibrio cholerae*, *V. parahaemolyticus*, and *Vibrio vulnificus*.

Bacterial fitness depends on the ability to colonize and grow in hosts, avoid immunological inhibition, and be transmitted to a new host [117]. Established virulence factors can be considered fitness factors, as these factors render the organisms more fit under specific circumstances. Mobile components such as pathogenicity islands carry genes that strengthen the fitness of *Vibrios* even when not producing a toxic effect in a host [118]. Elevated mutation rates can also facilitate evolution of bacteria, making it possible to survive under a wide array of environmental conditions [119].

The three-dimensional complex communities of microbes found in biofilms form on both organic and inorganic substrates that render bacteria more protected from environmental stressors [112]. Biofilms have been demonstrated and characterized for *V. vulnificus*, *V. parahaemolyticus*, *V. cholerae*, *V. fischeri*, *V. harveyi*, and *V. anguillarum* [120].

Pathogen fitness factors and virulence factors produce similar effects in different environments [121]. In unfavorable environments, microbial survival requires factors supporting attachment and colonization such as polysaccharide synthesis, secretion, colonization, motility, toxicity, and genetic regulation. Accompanying these factors may be additive and synergistic effects important to active colonization of biotic and abiotic substrates.

6. Conclusions

The global society's concern over microplastics is directly related to its persistence and potential adverse effects on aquatic biota. In aquatic environments, microorganisms can colonize surfaces by forming adherent biofilms. Biofilm's role in the fate and effects of microplastic has not been completely delineated since active research is aimed to fill copious information gaps. The physical interactions of plastic surfaces and their microbial colonizers is becoming more functionally integrated in the understanding of the effects of microplastic weathering, vertical transport in the water column, and processes of sorption and contaminant release [122]. Biofilm-plastic interactions are recognized for their influence on the fate and effects of microplastics through modification of a particle's physical and chemical properties.

The use of proper and clear terminology for the design of data collection and supporting analytical protocols is necessary for the collection of representative data which is important to the strategic design of research directions based on consensus data development [42]. The necessary analytical determinations (biological, chemical, and physical) developed from a wide array of current and developing technologies offer answers to questions concerning the details of microplastics in the environment. Spatial information, contamination sources, fate, and environmental concentrations are necessary to a timely and proficient gathering of information [48]. New and novel analytical methodology designed to assist the chemical, biological, and physical characterization of samples is welcomed [50].

An understanding of surface biofouling of submerged surfaces is important to decipher surface colonization processes relative to of the behavior of plastic in the environment [123–126]. An enhanced understanding of biofilm formation on submerged surfaces is required to develop a more complete pictures of microbial colonization and the basic processes involved in biofilm formations. Biofilm-plastic interactions important to hydrodynamic processes, such as vertical transport, require the use of environmentally representative biofilm.

The effect of biofilm formation and its connection to the kinetics of chemical partitioning required additional scrutiny [127, 128]. The complexity of surfaces available to sorption processes needs attention to discover the relative importance of the multiple surface adsorption of organic and inorganic pollutant chemicals. The importance of surface topography to the sorption process requires further research. Mechanisms to explain toxic chemical transport by microplastics employing established biofilm contaminated with heavy metals and organic chemicals will be very helpful.

Microbial effects specific to the ability of biofilm-forming microorganisms on a microplastic surface in contact with aqueous media are important to the development of biofilms and their control. Human pathogens such as strains of *Vibrio* spp. have been isolated in formed biofilm on microplastics. The pathogen-populated biofilms must be scrutinized for their possible role in the transmission of materials that could be lethal [129].

Studies are available suggesting that biofilms on microplastics do not present a threat over biofilms on naturally occurring surfaces [130, 131]. The pathogenic populated biofilms are viewed as having no new adverse effect on human food supplies. Since we are still an early state of learning with the environmental effects of microplastics, it is incumbent that we continue to scrutinize biofilm effects and their relation to human health and the health of aquatic ecosystems [132].

This chapter has focused on the question of a role for bacterial biofilms to the environmental effects attributable to microplastics. The importance of biofilms to plastics and their degradation is becoming more completely revealed through continuing focused research effort. The alacrity with which biofilms form on plastic in the environment is functionally connected to ambient conditions and the weather effects to which the plastic has been subjected. Microplastics and adherent biofilms provide potential vector mechanisms to assist the transport of pollutant chemicals and pathogens to a wide area of the aquatic environment.

Conflict of interest

No conflict of interest is known or expected.

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