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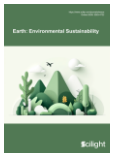

Review

Microplastics: A Potential Vector for Pathogens in Aquatic Ecosystems

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Abstract: This review addresses the critical issue of microplastic (MP) pollution in aquatic environments, with an emphasis on the potential role of MPs as vectors for pathogens. The persistence of MPs, resulting from their strong resistance to degradation, poses major global environmental and public-health challenges. Their inherent stability and large surface area promote pathogen adhesion, rendering MPs a favorable medium for the adsorption and transport of both pollutants and microorganisms. This review first explores the key physicochemical properties of MPs and the decisive factors that influence pathogen adhesion to MP surfaces. It then examines the environmental impacts and associated health risks of MP pollution in marine and freshwater ecosystems, along with its implications for human exposure through the food chain. A critical analysis and discussion of the multiple dimensions of MPs as potential vectors for pathogens highlight the urgent need to implement advanced waste-management strategies and water-treatment technologies. Furthermore, the review emphasizes the necessity of an integrated research approach to elucidate the mechanisms and impacts of MPs as pathogen carriers in aquatic ecosystems.

Keywords: microplastics; pathogens; carrier; adsorption; water

1. Introduction

Microplastics (MPs) pollution of aquatic environments is a significant environmental issue [1]. MPs originate from both the fragmentation of larger plastic debris (>5 mm) and the direct release of primary MPs, such as nurdles used in industrial production. Their resistance to degradation enables them to persist in various aqueous systems. MPs are now recognized as a pervasive and persistent class of pollutants that infiltrate a wide range of environments, including oceans, rivers, soils, sediments, and even the air we breathe. Beyond their established role as physical and chemical contaminants, recent evidence has highlighted their biological dimension and ecological relevance [2]. MPs can act as novel carriers and reservoirs for pathogenic microorganisms, with significant implications for the spread of infectious diseases and antimicrobial resistance. They are prevalent in aquatic ecosystems particularly in marine and freshwater environments where they accumulate in surface waters, sediments, and biota. Their hydrophobic surfaces facilitate the adsorption of organic matter, nutrients, and microorganisms, leading to the formation of diverse biofilms collectively known as the "plastisphere" [3]. These biofilms create favorable microenvironments for the colonization and persistence of pathogenic bacteria, including *Vibrio* spp., *Escherichia coli,* and *Salmonella* spp. [4]. Furthermore, MPs facilitate the long-distance transport of these microbes across aquatic systems, including coastal regions and estuaries, potentially altering pathogen distribution and increasing exposure risks for both marine organisms and humans. In terrestrial ecosystems, the introduction of MPs through sewage sludge, compost, plastic mulching, and atmospheric fallout can significantly impact the soil microbiota and interact with soilborne pathogens. MPs may serve as substrates that facilitate the survival and dissemination of phytopathogens and zoonotic bacteria, potentially affecting crop health and food safety. The increased presence of plastics in agricultural and urban soils may also create microbial selection pressures that favor pathogenic or antimicrobial-resistant strains, particularly under nutrient-rich or anaerobic conditions [5]. Wastewater environments encompassing treatment facilities and urban runoff systems are critical hotspots for interactions between MPs and pathogens. These environments are characterized by elevated concentrations of MPs and diverse microbial communities, including human pathogens and antibiotic-resistant bacteria. In such contexts, MPs can serve as microbial reservoirs that can withstand conventional disinfection processes and facilitate the horizontal transfer of antimicrobial resistance genes (ARGs). The discharge of sludge and effluent further disseminates MPs and associated pathogens into the receiving environment, thereby perpetuating the cycle of human activity, environmental contamination, and associated health risks [6]. The role of MPs as vectors of microbial transmission is an emerging concern at the intersection of environmental science, microbiology, and public health. Their capacity to shield pathogens from environmental stressors, promote dispersal across ecological boundaries, and enhance microbial interactions underscores a complex risk that necessitates further investigation. This review critically evaluates the current understanding of MP-associated pathogens across aquatic, terrestrial, and wastewater systems, with an emphasis on their transmission dynamics, ecological interactions, and potential implications for human and ecological health.

Figure 1 illustrates the intricate trajectory of MPs from their points of origin (sources) to their eventual accumulation (sinks) in the environment. Source regions, shown in red, represent diverse origins of MPs, including urban areas, industrial activities, agricultural runoff, and degradation of vehicle tires. These MPs are conveyed through various pathways, such as air, precipitation, and river systems, and are often facilitated by anthropogenic activities, such as aquaculture and tourism [7]. Sink regions, depicted in green, denote the final deposition sites, such as oceans and soils, where MPs accumulate and interact with biota, potentially causing adverse effects [8]. The ingestion of MPs by aquatic organisms is a well-documented phenomenon that represents a significant pathway for the internalization and biological transport of these particles across trophic levels. Numerous studies have reported MP ingestion across a diverse range of taxa, including zooplankton, mollusks, crustaceans, fish, seabirds, and marine mammals, highlighting their widespread presence in aquatic food webs. This ingestion raises concerns not only about physical and chemical toxicity, but also about the potential role of MPs as vectors for pathogenic microorganisms. Once ingested, MPs may facilitate internal exposure to surface-bound pathogens, thereby altering traditional exposure routes that would otherwise depend solely on contact with contaminated water. Furthermore, this internalization facilitates the trophic transfer of MPs and associated microbes, potentially amplifying pathogen exposure through predator–prey interactions [9–11]. Understanding the extent, pathways, and ecological implications of MP ingestion is therefore essential for assessing their role in the environmental dissemination of pathogens.

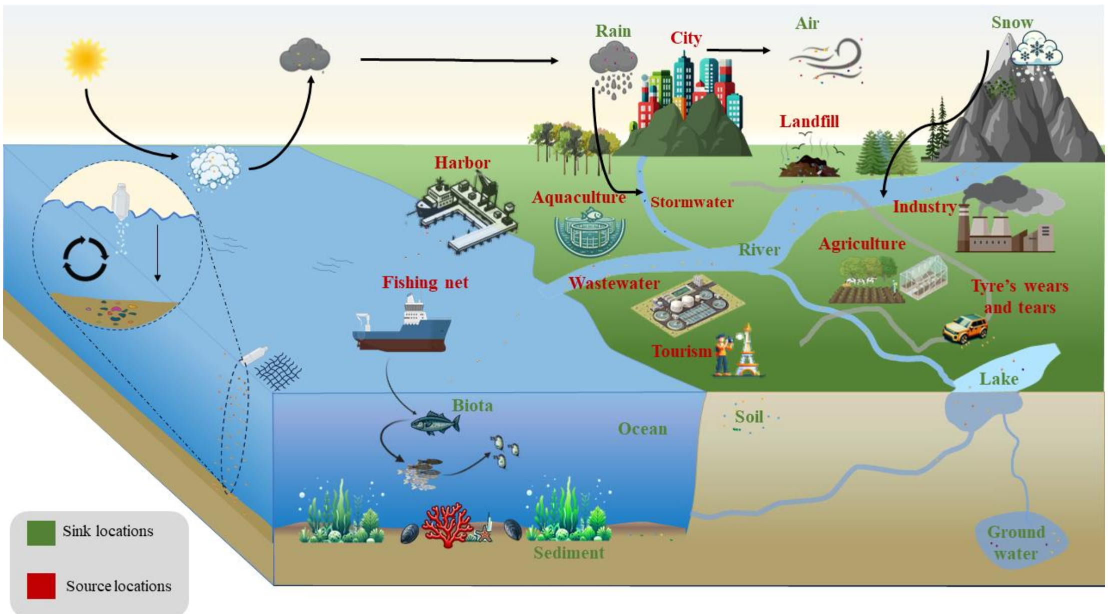

Figure 1. Diverse sources and sinks of microplastics entering aquatic systems.

One significant concern associated with MPs is their capacity to serve as vectors for pathogens, thereby posing risks to both environmental and public health. Due to their extensive surface areas, MPs can adsorb and transport organic pollutants, heavy metals, and pathogens, including bacteria and viruses [12]. The transport of pathogens such as *Vibrio cholerae, Flavobacterium psychrophilum*, *Campylobacter coli*, and *Aeromonas* via MPs creates major challenges for managing disease transmission to aquatic organisms and human populations [13]. Disease outbreaks can occur when aquatic animals ingest MPs carrying pathogenic species. Furthermore, contaminated seafood and water can introduce MPs into the human food chain, with the pathogens they carry potentially affecting the health and well-being of both aquatic and terrestrial organisms [1].

Reported removal efficiencies of MPs in wastewater treatment plants vary considerably depending on treatment configuration and operational conditions. Conventional activated sludge systems typically remove between 70% and 90% of MPs, while tertiary processes such as sand filtration or dissolved air flotation, and advanced membrane bioreactors, can achieve removals higher than 95%. Nevertheless, effluents consistently contain residual MPs, representing millions of particles per cubic meter that may serve as substrates for pathogen attachment [14,15]. Importantly, the removal of MPs must be distinguished from the removal of associated pathogens and antimicrobial resistance genes, since microbial contaminants can persist through treatment or re-enter the environment through sludge application. Addressing MPs as vectors for pathogens, therefore, requires not only the improvement of treatment technologies but also a deeper mechanistic understanding of pathogen–plastic interactions, supported by interdisciplinary collaboration among environmental engineers, microbiologists, and public-health researchers [16].

MPs are now considered as possible vectors of pathogenic microorganisms in aquatic environments; however, the available studies often remain scattered. To date, no single work has brought these findings together in depth, which makes it difficult to see the overall picture. Most of the research has focused on isolated aspects, such as microbial attachment, particle movement, or host exposure, without linking these to the properties of the plastics, the environmental conditions, and the characteristics of the pathogens. In this review, these aspects are unified to provide a clearer understanding of how MPs and pathogens interact, under what conditions, and with what consequences. We also suggested directions for future work that could be integrated and be ecologically relevant, while considering the broader risks for ecosystems and human health. This review followed a systematic approach to ensure transparency and reproducibility in the identification and selection of relevant studies. The Web of Science (Clarivate Analytics) database was used as the primary source because of its comprehensive coverage of peer-reviewed environmental science publications. The search strategy combined keywords such as microplastics, pathogen, bacteria, virus, fungi, plastisphere, biofilm, vector, carrier, and aquatic environment using Boolean operators (“AND”, “OR”). Inclusion criteria were: (i) peer-reviewed original research articles and reviews written in English; (ii) studies explicitly examining the interaction between MPs and pathogenic microorganisms (bacteria, viruses, fungi, or protozoa) in aquatic environments (marine, freshwater, or wastewater); and (iii) studies providing experimental, field, or molecular evidence of adhesion, colonization, or transport of pathogens on microplastic surfaces. Figure 2a shows the analysis of targeted publications from 2019 to 2023, focusing on the interaction between MPs and waterborne pathogens. As depicted in Figure 2b, it was found that 98.5% of the studies pertained to the sustainable development goal of conserving life underwater (SDG 14). In contrast, 1.5% of the studies were related to the goal of ensuring good health and well-being (SDG 3). This distribution demonstrates the significant weight placed on the ecological impacts of MPs in marine and freshwater systems. Together with Figure 1, these results underscore the pervasive nature of MP pollution and the urgent need for a comprehensive understanding of its ecological and health implications.

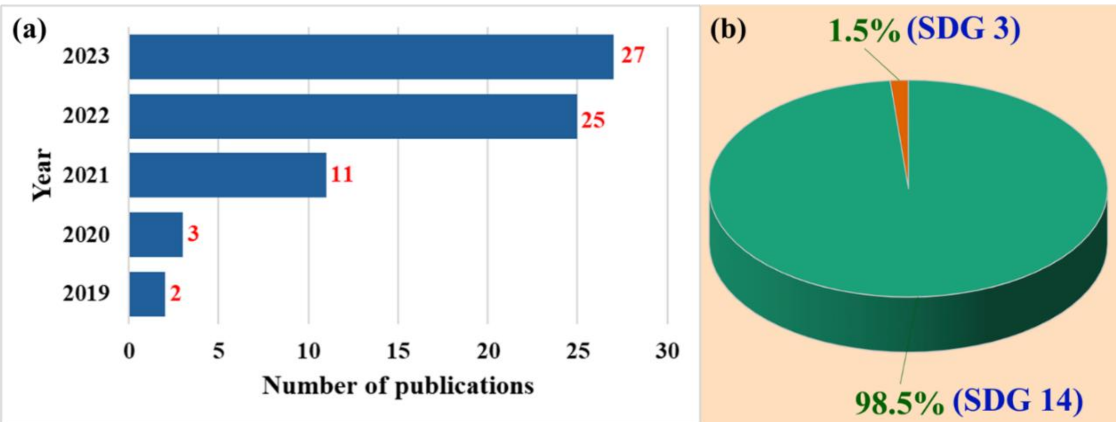

Figure 2. Number of publications from 2019 to 2023 and their relevance to sustainable development goals based on the Web of Science collection database of Clarivate Analytics (**a**,**b**).

2. Properties and Factors Influencing Pathogen Adhesion on MPs

MPs exhibit diverse characteristics in terms of their chemical composition and physical structure. These variables influence their environmental behavior, particularly their ability to transport pathogenic microorganisms, which can vary significantly. Owing to their persistent nature, low biodegradability, hydrophobicity, and relatively high surface-to-volume ratio, MPs can act as efficient vectors for transporting pathogens [17]. The biofilm that forms on the surface of MPs has been identified as a nutrient-rich area, facilitating the colonization of opportunistic human pathogens, such as *Vibrio cholerae* [18,19]. Furthermore, MPs serve as long-lasting reservoirs and carriers of fungal pathogens in soil environments, potentially affecting the global spread of fungal infections [5]. MPs are primarily classified as beads, fibers, and fragments based on their shape, each possessing distinct characteristics that influence their interaction with pathogens [20]. Various studies have characterized these particles based on their different physicochemical properties.

2.1. Physical Properties

The physical characteristics of MPs, including their size, shape, and surface roughness, play a crucial role in pathogen adhesion. Irregular and rough surfaces provide additional niches for microbial attachment. Environmental factors such as temperature, pH, and salinity also influence the adhesion process. These factors can affect the survival and metabolic activity of pathogens on MPs, as discussed by Kirstein et al. [21]. Furthermore, another study demonstrated that pathogen adhesion on MPs is significantly affected by temperature and nutrient availability under ambient environmental conditions [22].

MPs exhibit distinct physical characteristics, particularly coloration, which significantly influences microbial colonization on their surfaces. Empirical research has shown that MP color affects both the composition and structure of microbial communities. Specifically, blue MPs are associated with a greater diversity of unique species and exhibit higher functional diversity than transparent and yellow MPs. This suggests a color- or additive-driven selection of microorganisms, indicating that MP color impacts the community structure and functional diversity of microbial assemblages colonizing these plastics in aquaculture environments. Pigments used as additives in plastics may serve as a carbon source for microbial metabolism. However, whether these microbes are pathogenic remains unclear [23]. In another study, both blue and white (light-colored) MPs showed a clear correlation with seven bacterial genera, whereas green, red, and black (dark-colored) MPs did not exhibit a strong correlation with all 20 bacterial genera analyzed. Notably, white MPs were positively correlated with four bacterial genera (*Flavisolibacter, Bacillus, Pseudomonas,* and *Vibrio*) and negatively correlated with *Sphingomonas* [23]. Different studies also highlighted that light-colored MPs are more frequently ingested by fish [24], oysters and mussels [25], and seabirds are more susceptible to eating light-colored MPs likely because of their resemblance to natural food sources [26]. These findings highlight how light-colored MPs can adsorb more pathogenic microorganisms and can be ingested by various organisms, thereby facilitating the transport of pathogen-laden particles into their bodies.

The morphology of MPs is a critical parameter encompassing their shape, size, surface roughness, and porosity serves as a crucial determinant of their potential to function as vectors for pathogen transport in aquatic environments. Irregularly shaped MPs, such as fibers, fragments, and films, typically exhibit a larger specific surface area and more intricate topographies compared to spherical particles, thereby offering increased physical space and microsites for microbial colonization and biofilm formation. Surface roughness and cracks can shield pathogens from environmental stressors, including UV radiation and predation, thereby enhancing their persistence in the environment. Furthermore, smaller MPs, particularly those in the nano and sub-micron range, are more likely to interact with microbial cells due to their high surface area-to-volume ratio and capacity to penetrate biological tissues. Porous structures or weathered MPs further augment the likelihood of pathogen adhesion by providing additional attachment points and microenvironments conducive to microbial survival. Consequently, MP morphology not only affects the extent and strength of pathogen adhesion but also significantly influences the environmental mobility, stability, and eventual fate of these pathogen–MP complexes [27]. Spherical beads, which frequently originate from personal care products, are diminutive and readily ingested by aquatic organisms. This ingestion poses a direct threat to marine life and raises concerns regarding pathogen transmission, because the smooth surfaces of these beads may harbor pathogenic bacteria and facilitate their transport within aquatic systems. Fibers, distinguished by their extensive surface area and elongated structure, are commonly derived from synthetic textiles. Their substantial surface area provides ample space for microbial colonization, including that of pathogens, thereby rendering them effective vectors for pathogen transportation [28]. The interaction between fibers and microbes can result in biofilm formation and the subsequent dissemination of pathogens. Fragments that emerge from the degradation of larger plastics exhibit irregular shapes and diverse surface textures, offering numerous niches for microbial growth and potentially supporting diverse microbial communities, including harmful bacteria [2].

The size and shape of MPs are two additional physical factors influencing their interaction with pathogens. One study found that larger, fiber-shaped particles are more likely to have pathogens adhere to their surfaces. It was also suggested that particles with sharper edges, resulting from the fragmentation of larger plastics into smaller pieces, may facilitate the entry of pathogens or other microorganisms into the human body through contact with tissues such as the skin [29]. However, the opposite effect was also proven in another study, pointing out the smaller a plastic particle is, the better it is for accommodating the biofilm on its surface with 100 μm showing the most available space for microorganisms. It was highlighted that the shape and size of MPs do not play a significant role in the biofilm formation unlike chemical composition [30]. The size of microbes and pathogens was also reported in some studies [3,31,32], where it was mentioned that the microorganisms colonizing these surfaces are generally small, typically ranging from 0.5 to 3 μm in size, which means that even the observed densities of 10^3–10^4 cells mm^{-2} correspond to thousands of individual bacteria attached to the surface of a single MP [33].

2.2. Chemical Properties

The chemical properties of MPs have been shown to significantly influence pathogen adherence to these particles. The type of MPs affects its interactions with microbial entities. According to the data presented in the supplementary table, which identifies the most favorable hosts for pathogens, Figure 3 illustrates the percentage abundance of MP types that potentially harbor pathogenic species across various aquatic environments, including freshwater, seawater, lakes, and estuaries based on the supplementary information. The most frequently detected MPs carrying pathogenic species are polyethylene (PE), followed by polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). Various studies have highlighted the high potential of MPs as hosts for pathogens in comparison to the studied metals. For example, plastics have been found to support significantly larger bacterial populations than copper surfaces. Specifically, research has shown that *Legionella pneumophila* can survive on PVC even at a temperature of 50 °C, a condition under which it is no longer detectable on copper [34]. Similar findings have been observed when comparing plastics, glass, and stainless steel [35]. However, Hou et al. revealed that pathogens exhibit a greater tendency to attach to organic particles than to MPs [22]. The durability and environmental resistance of MPs vary with their type, contributing to their role as potential vectors for pathogens. The surface chemistry of MPs, particularly their hydrophobic nature, plays a crucial role in the adsorption of microorganisms and organic pollutants. A previous study indicated that PE exhibits lower toxicity to organisms than PVC, suggesting that PE is more biodegradable than PVC. The primary reason for this is the higher corrosion rate of PE compared to PVC and PS, which provides organisms with rougher surfaces and more available sites for accumulation [36]. Silva et al. also analyzed the effects of six different types of MPs, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), PP, PS, PET, and PVC, on microbial colonization dynamics. Among the polymers studied, textile PET was notably distinct in supporting a unique microbiota, including the growth of potentially pathogenic genera, such as *Legionella*. This finding underscores the importance of polymer type in determining the ecological niche within the plastisphere, with PET demonstrating a higher propensity to serve as a host for pathogens. Based on previous findings, the behavior of pathogens is related not only to the type of MPs, but also to the type of pathogens themselves [37]. Factors such as environmental conditions and the age of MPs influence biofilm formation and enhance pathogen carriage capability. Additionally, the integration of additives into plastics can alter microbe-MP interactions and affect microbial communities and pathogen behavior [38].

The detailed dataset used to generate Figure 3 is provided in the Supplementary Information. This table compiles, for each reviewed study, the sampling year, water matrix (freshwater, marine, estuarine, or wastewater), polymer type, particle size, morphology (shape), identified pathogenic taxa, and the corresponding reference. The proportions shown in Figure 3 were calculated based on the relative frequency of studies reporting pathogen detection for each polymer type within the compiled dataset.

MPs can carry various surface charges due to different functional groups like –COOH, $–NH_2$, and $–SO_3H$ on their surfaces [33]. Research has indicated that the distribution and movement of MPs within different plant tissues are influenced by the surface charge of the plastic, with negatively charged particles demonstrating greater mobility [39]. Consequently, surface charge plays a critical role in adhesion mechanisms, where initial electrostatic attractions contribute to stable attachment, modulated by the ionic composition of the aquatic environment. The effect of surface charge on colonization is highly context-dependent. In freshwater systems with low ionic strength, positively charged MPs such as $PS–NH_2$ strongly promote bacterial adhesion through electrostatic attraction to negatively charged cell walls [40]. By contrast, under marine or higher ionic strength conditions, negatively charged MPs such as PS–COOH are more readily colonized. In these environments, counter-ions compress the electrical double layer, reducing electrostatic repulsion and allowing bacteria to overcome the interaction barrier [41]. Thus, whether negatively or positively charged MPs favor adhesion depends strongly on the surrounding ionic composition, pH, and the bacterial lineage involved [42,43]. Further research demonstrated that MPs with a higher surface charge (zeta potential) tend to inhibit bacterial growth more effectively. Negatively charged MPs, in particular, show enhanced antibacterial activity in seawater, especially against Gram-positive bacteria such as *Bacillus subtilis*. This enhanced inhibition is likely attributable to the strong interactions between the highly charged MPs and thick peptidoglycan layers, a key component of the bacterial cell wall, in gram-positive bacteria. Additionally, the ionic conditions in seawater may amplify these interactions, enhancing the stability and aggregation of MPs, and further promoting bacterial inhibition [44].

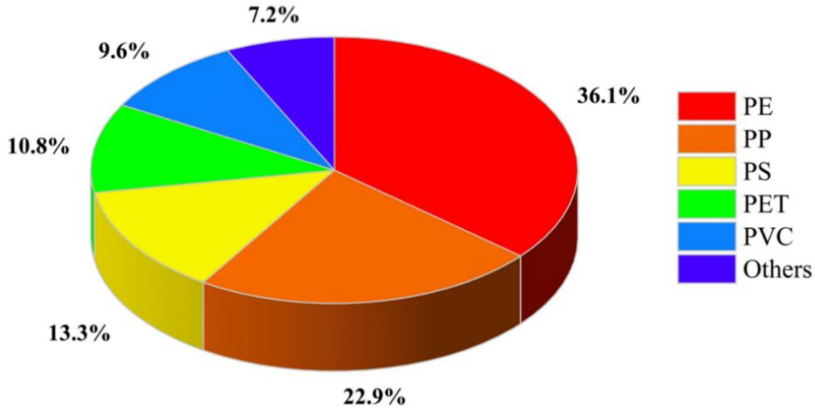

Figure 3. Proportion of microplastic types harboring pathogens across various environmental water matrices, including river water, lake water, seawater, estuaries, and wastewater, as summarized from the datasets provided in the Supporting Information.

Hydrophobicity is another key determinant of microbial interactions with MPs. Hydrophobic MPs serve as optimal substrates for microbial cells, facilitating colonization, adhesion, and biofilm formation. A decrease in MP hydrophobicity can increase surface roughness, thereby promoting greater biofilm accumulation [45]. These biofilms, which are composed of microorganisms within an extracellular matrix, provide a stable environment conducive to pathogen survival and proliferation, potentially enhancing virulence and resistance [30,46]. He et al. identified an indirect mechanism whereby the hydrophobic nature of MPs fosters a more favorable environment for microbial attachment. This study demonstrated that the high hydrophobicity of MPs renders them an ideal substrate for organic matter adherence, which subsequently enhances the conditions for microorganisms to attach and establish colonies on the surface [47]. In a computational modeling study, results indicated that bacteria are less likely to adhere to surfaces bearing rigid hydrophobic chemical groups, as observed in poly(meth)acrylates with hydrocarbon side chains. In these polymers, hydrophobic components are coupled with hydrophilic ester groups, producing rigid amphiphilic structures [48]. A comparative study examining the effects of physicochemical properties such as hydrophobicity, surface charge, roughness, and hardness of PE, PET, PP, and PVC on microbial adhesion established that surface roughness plays a predominant role. PE and PVC exhibited higher microbial adhesion than PVC and PET in both short- and long-term exposure, with the order being PE > PVC > PP > PET [49].

To assess the impact of surface charge on microbial interactions, the reported zeta potential values for common microplastic polymers, including PE, PP, PS, PET, and PVC, consistently fall within a moderately negative range under environmentally relevant conditions (pH ~7, ionic strength 1–10 mM). Specifically, PE and PP typically exhibit zeta potentials ranging from −20 to −35 mV [50], PS is slightly more negative (−25 to −40 mV), while PET and PVC display somewhat less negative values (−10 to −30 mV) [51]. Interaction energy modeling based on DLVO theory across these polymers yields comparable energy barriers (≈3–20 kT), with overlapping minima and maxima, indicating similar electrostatic repulsion and aggregation tendencies [52]. These findings suggest that intrinsic surface charge differences among virgin plastic types are relatively minor and are unlikely to be the dominant factor influencing pathogen attachment.

The wettability data, as measured by the static water contact angle, indicate that PE and PP exhibit high hydrophobicity, with angles ranging from 95° to 110°. PS is slightly less hydrophobic, with angles between approximately 88° and 100°, whereas PET and PVC are moderately hydrophilic, displaying lower angles of approximately 70° to 85° [30,53]. Although variability exists among polymer classes, multiple studies have reported overlapping ranges with no statistically significant differences under neutral pH and natural ionic strength conditions ($p > 0.05$). Collectively, the evidence from zeta potential and contact angle measurements suggests that the pristine physicochemical surface properties of different plastic types vary only slightly. Factors such as weathering, surface oxidation, and biofilm development are therefore likely to play decisive roles in influencing pathogen adhesion and colonization under real environmental conditions.

The surface roughness of various polymer types has been quantified utilizing Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM), which facilitate the measurement of root-mean-square roughness (Rq) at the nanometer scale. Reported AFM data indicate that PE and polyvinyl chloride (PVC) surfaces generally exhibit higher roughness values (Rq ≈ 40–80 nm) than PP and PET (Rq ≈ 20–50 nm), suggesting a somewhat more irregular topography [53]. However, several studies have demonstrated that these differences often fall within overlapping ranges and are not statistically significant under identical preparation and imaging conditions ($p > 0.05$) [30]. Consequently, pristine surface roughness alone is not considered a predominant factor influencing pathogen adhesion.

Notably, the mechanical characteristics of the polymer substrate appear to exert a particularly strong influence. Softer, more compliant plastics such as PE and PVC have been documented to facilitate greater bacterial adhesion and biofilm development than harder, more rigid polymers such as PP and PET [54,55]. This phenomenon is partially attributed to the modulation of bacterial quorum sensing, as reduced mechanical stress at the colony periphery on softer surfaces may enhance the expression of genes involved in quorum sensing and extracellular polymeric substance (EPS) production [55]. Taken together, these observations indicate that while surface roughness contributes to microtopography, the stiffness and viscoelasticity of polymers may play a more decisive role in governing bacterial colonization dynamics.

Apart from the previously discussed physical and chemical properties of MPs the crystallinity of the polymer structures, whether crystalline or amorphous, can significantly influence microbial adherence to their surfaces. A study has indicated that MPs, such as PS and PVC are predominantly amorphous and characterized by more random polymer chains. In contrast, PE and PP are considered semi-crystalline polymers that possess both ordered and disordered regions [56]. Crystallinity influences both sorption of small organic molecules and the hydrophobicity of microplastic surfaces, but its implications for pathogen adhesion are more nuanced. In crystalline polymers, the highly ordered structure offers less free space for chemical adsorption, while amorphous polymers provide more disorder and surface sites for sorption [57]. Higher crystallinity is also associated with increased hydrophobicity, as seen in PE, PP, and PA, which exhibit higher organic carbon–water partition coefficients (Koc) compared to more amorphous plastics such as PC, PS, and PVC [58]. This hydrophobicity can favor adhesion of microorganisms with hydrophobic cell envelopes, such as *Vibrio* spp., by lowering interfacial free energy. Conversely, reduced crystallinity caused by weathering or UV exposure introduces surface disorder and roughness, which promote adsorption of organic macromolecules (proteins, polysaccharides, lipids). These conditioning layers act as anchoring points, lowering the free energy of adhesion and facilitating microbial colonization [59,60]. Therefore, while sorption studies demonstrate that lower crystallinity enhances adsorption of organic pollutants, direct extrapolation to pathogen adhesion is not valid without considering interface science. Pathogen colonization depends not only on crystallinity and hydrophobicity but also on the presence of conditioning films, extracellular polymeric substances, ionic strength, and environmental aging. Recognizing these interacting factors reconciles seemingly contradictory findings in the literature and highlights the need for comparative experimental studies that directly measure pathogen–MP interactions [57]. An *in situ* study demonstrated that nylon MPs, when subjected to weathering and UV exposure, undergo changes in crystallinity. Reduced crystallinity, along with increased surface roughness and weathering, fosters microenvironments conducive to microbial colonization, including pathogens such as *Vibrio, Escherichia coli*, and *Pseudomonas* spp. The roughened surface and biofilm matrix enhanced their adhesion to MPs by providing anchoring points. However, other studies have revealed that the higher hydrophobicity of polymer surfaces, potentially due to increased crystallinity, improves the adhesion of specific pathogens to hydrophobic cell walls. Therefore, crystallinity, which directly affects hydrophobicity, cannot be considered the sole factor influencing the adherence of pathogens. In addition to crystallinity, other external factors such as ultraviolet (UV) light exposure and aging can influence adherence [61]. Overall, inconsistencies across studies can be reconciled by recognizing that intrinsic MP properties (charge, crystallinity, hydrophobicity) interact with extrinsic conditions such as ionic strength, salinity, pH, organic matter, and aging. Future studies that directly measure pathogen adhesion under controlled conditions are needed to clarify these mechanisms and resolve contradictory findings. The entire process of pathogen adherence results from complex biophysicochemical interactions between microbial surfaces and MPs, as illustrated in Figure 4.

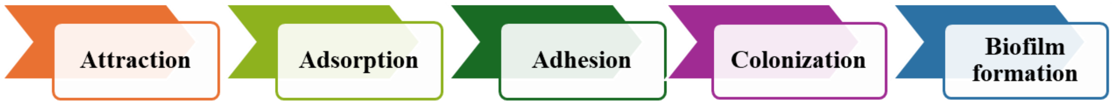

Figure 4. Schematic representation of the sequential stages involved in the adherence of pathogens to microplastic surfaces, illustrating the formation mechanism.

The adherence of pathogens to various types of MPs is governed by fundamental principles, including quantitative parameters such as contact angles, free energy of adhesion, and total energy of interaction. These factors arise from the close interactions between MPs and microorganisms and are critical in determining the suitability of a solid support for a specific pathogen. Regardless of the type of pathogen or MP, these physical factors are critical. Accurate calculation and thorough analysis of these factors can significantly enhance the scientific basis for the selection of specific MPs for pathogens. Microbial adhesion to solid supports, including MPs, is explained by the extended Derjaguin, Landau, Verwey, Overbeek (XDLVO) theory. This theory encompasses attractive Lifshitz van der Waals (LW), electrostatic double layer (EL), and short-range Lewis acid–base (AB) interactions between microorganisms and substrata. The XDLVO approach offers a more precise quantification of the interaction energy, thereby improving the prediction of pathogen adhesion to MPs [62]. Figure 5 provides a comprehensive overview of the physical and chemical factors and interactions that influence pathogen adhesion to various MPs, encapsulating the key points discussed in this section.

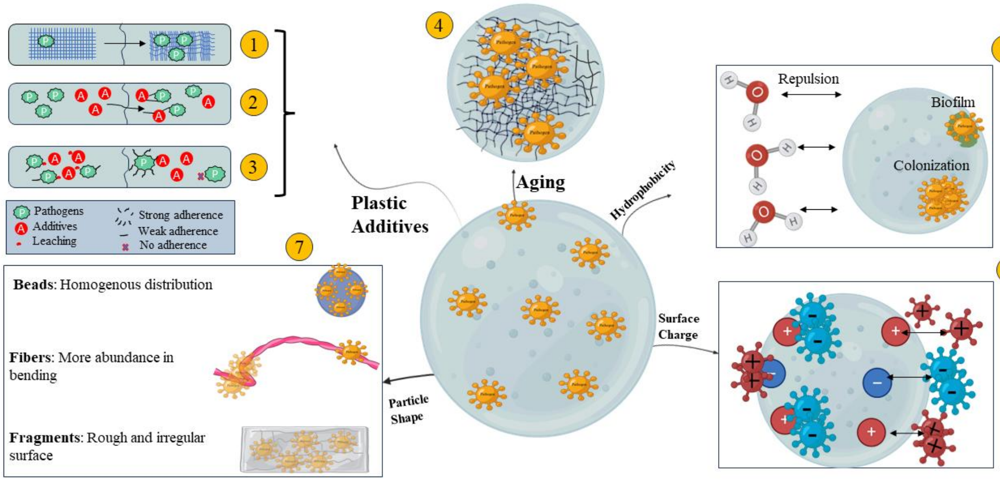

Figure 5. Interactions and Influences on Pathogen Adhesion to Microplastics: (**1**) Additives alter polymer morphology, impacting pathogen adhesion; (**2**) Chemical interactions between additives and pathogens determine adhesion; (**3**) Increase/decrease of pathogen adhesion affected by additives leachate; (**4**) Aging increases pathogen adhesion via surface cracks; (**5**) MPs repel water, facilitating pathogen colonization; (**6**) Surface charge influences pathogen attachment; and (**7**) MPs' shape impacts pathogen adhesion.

3. Sustainability Relevance, Environmental Impact and Health Risks

The potential role of MPs as vectors for pathogenic microorganisms presents a complex challenge for sustainable development. This issue intersects with several United Nations Sustainable Development Goals (SDGs), including clean water and sanitation (SDG 6), reduction of infectious disease burden (SDG 3), responsible production and consumption (SDG 12), climate action (SDG 13), and protection of marine life (SDG 14). The persistence and mobility of MPs in aquatic ecosystems, combined with their ability to transport pathogens, may heighten risks to human and ecosystem health, particularly in regions that lack adequate wastewater treatment or plastic management infrastructure. Mitigating these risks is essential for building resilient environmental systems and achieving long-term sustainability [63].

Recent studies have revealed that MPs in marine and freshwater environments can harbor opportunistic and potentially harmful microorganisms, including bacteria and viruses, which were previously confined to specific niches or hosts. The majority of pathogenic species detected in various environmental water matrices are bacteria (90%), compared to viruses, fungi, and protozoa [64].

MPs have been identified as carriers of bacteria that are capable of causing severe diseases. Notably, bacteria such as *Neisseria* spp., which can lead to meningitis, and *Providencia rettgeri*, associated with travelers' diarrhea, urinary tract infections, and eye infections, have been detected in MPs derived from discarded plastic food packaging. When ingested by aquatic organisms, these pathogens have the potential to ascend the food chain, ultimately reaching apical predators and humans, thereby posing significant health risks [65].

The role of MPs in viral transmission is an emerging concern. Research has identified the presence of human pathogens such as Norovirus and SARS-CoV-2 on MPs in various environments, including residential and healthcare settings. These findings suggest that MPs may serve as reservoirs for viruses, potentially facilitating their transmission across different environments and species [66].

Aquatic organisms, ranging from plankton to larger fish and marine mammals, ingest MPs either directly or through the consumption of contaminated prey. This ingestion can result in physical harm, such as gastrointestinal blockage and physiological stress. Furthermore, pathogens associated with MPs can cause infections in these organisms, thereby disrupting aquatic ecosystems and reducing biodiversity. Pathogens and chemicals adhered to MPs can bioaccumulate in the tissues of organisms and biomagnify in the food chain. This process not only affects wildlife health but also poses risks to human health, particularly through the consumption of contaminated fish and shellfish [67].

To accurately assess and quantify the ecotoxicological impact of the plastisphere, it is imperative that MPs utilized in experimental settings closely resemble those found in other aquatic environments. Biofilm formation and the subsequent chemical partitioning remain largely unexplored [68]. Consequently, addressing the ecological and health risks associated with MP pollution requires comprehensive research to elucidate the extent of pathogen transfer from MPs to humans and the long-term effects of such exposure. Strategic interventions should include the enhancement of waste management practices to prevent MP pollution and the improvement of filtration techniques in water treatment facilities to mitigate potential health risks [69].

Figure 6 illustrates potential transmission pathways of pathogens adsorbed onto MPs from treated wastewater into marine ecosystems, eventually reaching humans through seafood consumption. Risk assessment should be interpreted along a continuum of evidence: (i) molecular detection of microbial DNA or RNA on MPs; (ii) confirmation of viability through culture-based or viability-PCR assays, (iii) experimental infection studies that demonstrate pathogenicity; and (iv) realistic dose–response scenarios through exposure routes such as shellfish consumption, recreational water use, or incidental ingestion of treated water. Within this framework, bacteria such as *Vibrio*, *Escherichia coli*, and *Salmonella*, viruses such as Norovirus and SARS-CoV-2, and fungi such as *Candida* and *Aspergillus* differ in their likelihood of persistence and transmission on MPs. Viral pathways of exposure often represent the highest risk because of their low infectious dose. This hierarchical approach provides a more realistic evaluation of potential human health risks associated with MP-borne pathogens.

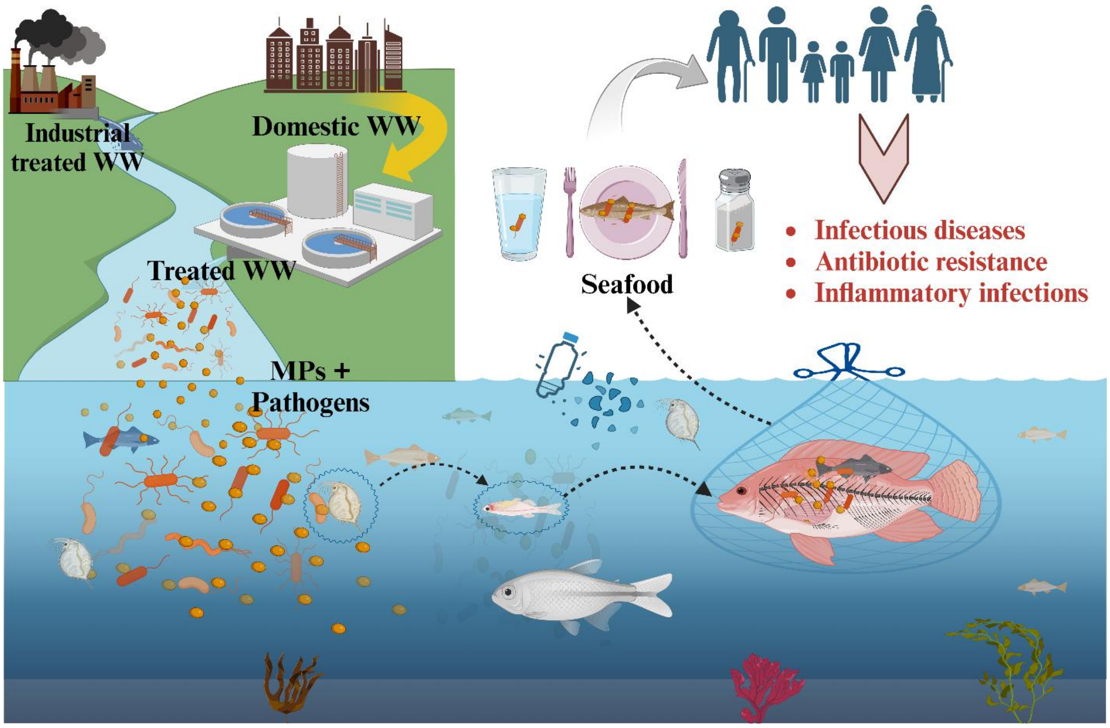

Figure 6. Pathways of Microplastic and Pathogen Transfer from Pollution Sources to Ecological and Human Health Impacts.

4. Conclusions

This review article examined the potential of MPs as vectors for pathogen transmission across various environments. It highlighted several key factors, including the physical and chemical characteristics of MPs that facilitate pathogen adherence. Among the physical properties, surface roughness, particle size, shape, and color influence this process. MPs with greater surface roughness offer more favorable sites for microbial attachment and colonization. In addition, smaller particles, particularly fibers, demonstrate a higher capacity for pathogen adsorption due to their larger surface-to-volume ratio. Furthermore, the reviewed studies indicate that light-coloured particles, especially light blue and white, are more conducive to pathogen growth than darker colours, potentially due to additives in the pigments that enhance the surface's suitability for pathogen proliferation. These light-colored particles are more frequently ingested by marine biota and pose a greater threat to aquatic ecosystems. In addition to their physical attributes, the chemical properties of MPs also play a crucial role. For example, polyvinyl chloride, polyethylene, and polyethylene terephthalate have been identified as more favorable hosts for pathogenic growth, likely due to their specific chemical compositions. Positively charged particles enhance bacterial adhesion owing to their affinity for negatively charged bacteria, in contrast to negatively charged particles, which repel pathogens. Hydrophobic MPs create a favorable environment for pathogen adhesion by facilitating the accumulation of organic matter, which supports biofilm formation. These hydrophobic surfaces render MPs more attractive to microbes, providing an optimal substrate for microbial colonization, thereby enhancing pathogen survival and potential virulence. MPs serve as vectors for harmful pathogens, including bacteria such as *Neisseria* and *Providencia*, and viruses such as Norovirus and SARS-CoV-2, facilitating their dissemination through aquatic ecosystems and the food chain to humans. Effective waste management, advanced water filtration, and further research on pathogen-MP interactions are essential for mitigating the health and ecological risks associated with MP pollution.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2511031611433689/EESUS-2508000293-Supplementary-material1.pdf

Author Contributions

B.N.: data collection, writing and editing; S.N.: data collection, writing and editing; J.M.: data collection, writing and editing; R.P.: review and editing; R.K.D.: writing, review and editing, S.K.B.: review, editing and supervision. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable

Informed Consent Statement

Not applicable

Data Availability Statement

The data supporting this review have been included as the Supplementary Information.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Abbreviation

MP	Microplastic
MPs	Microplastics
WW	Wastewater
PE	Polyethylene
PP	Polypropylene
PS	polystyrene
PET	Polyethylene terephthalate
PVC	Polyvinyl chloride
HDPE	High density polyethylene
LDPE	Low density polyethylene

References

1. Nayebi, B.; Khurana, P.; Pulicharla, R.; et al. Preservation, storage, and sample preparation methods for freshwater microplastics—A comprehensive review. *Environ. Sci. Adv.* **2023**, *2*, 1060–1081. https://doi.org/10.1039/D3VA00043E.
2. Pham, D.N.; Clark, L.; Li, M. Microplastics as hubs enriching antibiotic-resistant bacteria and pathogens in municipal activated sludge. *J. Hazard. Mater. Lett.* **2021**, *2*, 100014. https://doi.org/10.1016/j.hazl.2021.100014.
3. Mishra, S.; Swain, S.; Sahoo, M.; et al. Microbial Colonization and Degradation of Microplastics in Aquatic Ecosystem: A Review. *Geomicrobiol. J.* **2022**, *39*, 259–269. https://doi.org/10.1080/01490451.2021.1983670.
4. Song, J.; Beule, L.; Jongmans-Hochschulz, E.; et al. The travelling particles: Community dynamics of biofilms on microplastics transferred along a salinity gradient. *ISME Commun.* **2022**, *2*, 35. https://doi.org/10.1038/s43705-022-00117-4.
5. Gkoutselis, G.; Rohrbach, S.; Harjes, J.; et al. Microplastics accumulate fungal pathogens in terrestrial ecosystems. *Sci. Rep.* **2021**, *11*, 13214. https://doi.org/10.1038/s41598-021-92405-7.
6. Mathew, J.; Pulicharla, R.; Rezai, P.; et al. Microplastics in wastewaters: Pretreatment to detection trail. *J. Water Process Eng.* **2024**, *64*, 105702. https://doi.org/10.1016/j.jwpe.2024.105702.
7. Chen, Y.-N.; Rani, A.; Chiang, C.-Y.; et al. Monitoring, control and assessment of microplastics in bioenvironmental systems. *Environ. Technol. Innov.* **2023**, *32*, 103250. https://doi.org/10.1016/j.eti.2023.103250.
8. Lamichhane, G.; Acharya, A.; Marahatha, R.; et al. Microplastics in environment: Global concern, challenges, and controlling measures. *Int. J. Environ. Sci. Technol.* **2023**, *20*, 4673–4694. https://doi.org/10.1007/s13762-022-04261-1.
9. Athey, S.N.; Albotra, S.D.; Gordon, C.A.; et al. Trophic transfer of microplastics in an estuarine food chain and the effects of a sorbed legacy pollutant. *Limnol. Oceanogr. Lett.* **2020**, *5*, 154–162. https://doi.org/10.1002/lol2.10130.
10. Hurley, R.R.; Woodward, J.C.; Rothwell, J.J. Ingestion of Microplastics by Freshwater Tubifex Worms. *Environ. Sci. Technol.* **2017**, *51*, 12844–12851. https://doi.org/10.1021/acs.est.7b03567.
11. Hamilton, B.; Rochman, C.; Hoellein, T.; et al. Prevalence of microplastics and anthropogenic debris within a deep-sea food web. *Mar. Ecol. Prog. Ser.* **2021**, *675*, 23–33. https://doi.org/10.3354/meps13846.
12. Joo, S.H.; Liang, Y.; Kim, M.; et al. Microplastics with adsorbed contaminants: Mechanisms and Treatment. *Environ. Chall.* **2021**, *3*, 100042. https://doi.org/10.1016/j.envc.2021.100042.
13. Zhang, Q.; He, Y.; Cheng, R.; et al. Recent advances in toxicological research and potential health impact of microplastics and nanoplastics in vivo. *Environ. Sci. Pollut. Res.* **2022**, *29*, 40415–40448. https://doi.org/10.1007/s11356-022-19745-3.
14. Rice, J.; Westerhoff, P. Spatial and Temporal Variation in De Facto Wastewater Reuse in Drinking Water Systems across the USA. *Environ. Sci. Technol.* **2015**, *49*, 982–989. https://doi.org/10.1021/es5048057.
15. Negrete Velasco, A.; Ramseier Gentile, S.; Zimmermann, S.; et al. Contamination and Removal Efficiency of Microplastics and Synthetic Fibres in a Conventional Drinking Water Treatment Plant. *Front. Water* **2022**, *4*, 835451.
16. Vercauteren, M.; Semmouri, I.; Van Acker, E.; et al. Toward a Better Understanding of the Contribution of Wastewater Treatment Plants to Microplastic Pollution in Receiving Waterways. *Environ. Toxicol. Chem.* **2023**, *42*, 642–654.
17. Murphy, L.; Germaine, K.; Dowling, D.N.; et al. Association of Potential Human Pathogens with Microplastics in Freshwater Systems. In *Springer Water, Proceedings of the 2nd International Conference on Microplastic Pollution in the Mediterranean Sea, Capri, Italy, 15–18 September 2019*; Cocca, M., Di Pace, E., Errico, M.E., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 112–120. https://doi.org/10.1007/978-3-030-45909-3_19.
18. Wu, X.; Pan, J.; Li, M.; et al. Selective enrichment of bacterial pathogens by microplastic biofilm. *Water Res.* **2019**, *165*, 114979. https://doi.org/10.1016/j.watres.2019.114979.
19. Naik, R.K.; Naik, M.M.; D'Costa, P.M.; et al. Microplastics in ballast water as an emerging source and vector for harmful chemicals, antibiotics, metals, bacterial pathogens and HAB species: A potential risk to the marine environment and human health. *Mar. Pollut. Bull.* **2019**, *149*, 110525. https://doi.org/10.1016/j.marpolbul.2019.110525.
20. Junaid, M.; Siddiqui, J.A.; Sadaf, M.; et al. Enrichment and dissemination of bacterial pathogens by microplastics in the aquatic environment. *Sci. Total Environ.* **2022**, *830*, 154720. https://doi.org/10.1016/j.scitotenv.2022.154720.
21. BugBitten Terrestrial Pathogens and Microplastics: Hitchhiker's Guide to the Ocean. Available online: https://blogs.biomedcentral.com/bugbitten/2022/09/09/terrestrial-pathogens-and-microplastics/ (accessed on 15 October 2023).

22. Hou, D.; Hong, M.; Wang, Y.; et al. Assessing the Risks of Potential Bacterial Pathogens Attaching to Different Microplastics during the Summer-Autumn Period in a Mariculture Cage. *Microorganisms* **2021**, *9*, 1909.
23. Zhang, X.; Xia, X.; Dai, M.; et al. Microplastic pollution and its relationship with the bacterial community in coastal sediments near Guangdong Province, South China. *Sci. Total Environ.* **2021**, *760*, 144091.
24. Browne, M.A.; Dissanayake, A.; Galloway, T.S.; et al. Ingested Microscopic Plastic Translocates to the Circulatory System of the Mussel, *Mytilus edulis* (L.). *Environ. Sci. Technol.* **2008**, *42*, 5026–5031. https://doi.org/10.1021/es800249a.
25. Li, H.X.; Ma, L.S.; Lin, L.; et al. Microplastics in oysters Saccostrea cucullata along the Pearl River Estuary, China. *Environ. Pollut.* **2018**, *236*, 619–625. https://doi.org/10.1016/j.envpol.2018.01.083.
26. Tata, T.; Belabed, B.E.; Bououdina, M.; et al. Occurrence and characterization of surface sediment microplastics and litter from North African coasts of Mediterranean Sea: Preliminary research and first evidence. *Sci. Total Environ.* **2020**, *713*, 136664. https://doi.org/10.1016/j.scitotenv.2020.136664.
27. Zhong, H.; Wu, M.; Sonne, C.; et al. The hidden risk of microplastic-associated pathogens in aquatic environments. *Eco Environ. Health* **2023**, *2*, 142. https://doi.org/10.1016/j.eehl.2023.07.004.
28. Jeong, E.; Lee, J.-Y.; Redwan, M. Animal exposure to microplastics and health effects: A review. *Emerg. Contam.* **2024**, *10*, 100369. https://doi.org/10.1016/j.emcon.2024.100369.
29. Yang, W.; Li, Y.; Boraschi, D. Association between Microorganisms and Microplastics: How Does It Change the Host–Pathogen Interaction and Subsequent Immune Response? *Int. J. Mol. Sci.* **2023**, *24*, 4065.
30. Rummel, C.D.; Jahnke, A.; Gorokhova, E.; et al. Impacts of Biofilm Formation on the Fate and Potential Effects of Microplastic in the Aquatic Environment. *Environ. Sci. Technol. Lett.* **2017**, *4*, 258–267.
31. Liu, P.; Dai, J.; Bie, C.; et al. Bioaccessibility of Microplastic-Associated Antibiotics in Freshwater Organisms: Highlighting the Impacts of Biofilm Colonization via an In Vitro Protocol. *Environ. Sci. Technol.* **2022**, *56*, 12267–12277.
32. McFall, A.; Coughlin, S.A.; Hardiman, G.; et al. Strategies for biofilm optimization of plastic-degrading microorganisms and isolating biofilm formers from plastic-contaminated environments. *Sustain. Microbiol.* **2024**, *1*, qvae012.
33. Cheng, J.; Jacquin, J.; Conan, P.; et al. Relative Influence of Plastic Debris Size and Shape, Chemical Composition and Phytoplankton-Bacteria Interactions in Driving Seawater Plastisphere Abundance, Diversity and Activity. *Front. Microbiol.* **2021**, *11*, 610231. https://doi.org/10.3389/fmicb.2020.610231.
34. Cloutman-Green, E.; Barbosa, V.L.; Jimenez, D.; et al. Controlling Legionella pneumophila in water systems at reduced hot water temperatures with copper and silver ionization. *Am. J. Infect. Control* **2019**, *47*, 761–766.
35. Parrish, K.; Fahrenfeld, N.L. Microplastic biofilm in fresh- and wastewater as a function of microparticle type and size class. *Environ. Sci. Water Res. Technol.* **2019**, *5*, 495–505. https://doi.org/10.1039/C8EW00712H.
36. Wang, Z.; Gao, J.; Zhao, Y.; et al. Plastisphere enrich antibiotic resistance genes and potential pathogenic bacteria in sewage with pharmaceuticals. *Sci. Total Environ.* **2021**, *768*, 144663. https://doi.org/10.1016/j.scitotenv.2020.144663.
37. Short-Term Plastisphere Colonization Dynamics across Six Plastic Types. Available online: https://enviromicro-journals.onlinelibrary.wiley.com/doi/full/10.1111/1462-2920.16445 (accessed on 19 May 2024).
38. Kye, H.; Kim, J.; Ju, S.; et al. Microplastics in water systems: A review of their impacts on the environment and their potential hazards. *Heliyon* **2023**, *9*, e14359. https://doi.org/10.1016/j.heliyon.2023.e14359.
39. Sun, X.D.; Yuan, X.Z.; Jia, Y.; et al. Differentially charged nanoplastics demonstrate distinct accumulation in Arabidopsis thaliana. *Nat. Nanotechnol.* **2020**, *15*, 755–760. https://doi.org/10.1038/s41565-020-0707-4.
40. Vigeant, M.A.-S.; Ford, R.M.; Wagner, M.; et al. Reversible and Irreversible Adhesion of Motile Escherichia coli Cells Analyzed by Total Internal Reflection Aqueous Fluorescence Microscopy. *Appl. Environ. Microbiol.* **2002**, *68*, 2794–2801. https://doi.org/10.1128/AEM.68.6.2794-2801.2002.
41. Schäfer, A.; Harms, H.; Zehnder, A.J.B. Bacterial Accumulation at the Air—Water Interface. *Environ. Sci. Technol.* **1998**, *32*, 3704–3712. https://doi.org/10.1021/es980191u.
42. He, L.; Rong, H.; Li, M.; et al. Bacteria have different effects on the transport behaviors of positively and negatively charged microplastics in porous media. *J. Hazard. Mater.* **2021**, *415*, 125550. https://doi.org/10.1016/j.jhazmat.2021.125550.
43. Shen, H.; Yang, M.; Yin, K.; et al. Size- and surface charge-dependent hormetic effects of microplastics on bacterial resistance and their interactive effects with quinolone antibiotic. *Sci. Total Environ.* **2023**, *903*, 166580.
44. Ustabasi, G.S.; Baysal, A. Bacterial interactions of microplastics extracted from toothpaste under controlled conditions and the influence of seawater. *Sci. Total Environ.* **2020**, *703*, 135024. https://doi.org/10.1016/j.scitotenv.2019.135024.
45. Xu, J.; Zhou, T.; Tang, C.; et al. Characterization and tolerance of foodborne pathogenic bacteria in microplastic biofilm. *LWT* **2024**, *200*, 116168. https://doi.org/10.1016/j.lwt.2024.116168.
46. Arias-Andres, M.; Klümper, U.; Rojas-Jimenez, K.; et al. Microplastic pollution increases gene exchange in aquatic ecosystems. *Environ. Pollut.* **2018**, *237*, 253–261. https://doi.org/10.1016/j.envpol.2018.02.058.
47. He, S.; Jia, M.; Xiang, Y.; et al. Biofilm on microplastics in aqueous environment: Physicochemical properties and environmental implications. *J. Hazard. Mater.* **2022**, *424*, 127286. https://doi.org/10.1016/j.jhazmat.2021.127286.

48. Bacterial Attachment to Polymeric Materials Correlates with Molecular Flexibility and Hydrophilicity. Available online: https://advanced.onlinelibrary.wiley.com/doi/full/10.1002/adhm.201400648 (accessed on 2 August 2025).
49. Hossain, M.R.; Jiang, M.; Wei, Q.; et al. Microplastic surface properties affect bacterial colonization in freshwater. *J. Basic Microbiol.* **2019**, *59*, 54–61. https://doi.org/10.1002/jobm.201800174.
50. Mathew, J.; Warraich, H.; Das, R.K.; et al. Curcumin-based-fluorescent staining and microfluidic detection of microplastics in wastewater effluent. *Chem. Commun.* **2025**, *61*, 16242–16245. https://doi.org/10.1039/D5CC02304A.
51. Wang, J.; Liu, X.; Li, Y.; et al. Microplastics as contaminants in the soil environment: A mini-review. *Sci. Total Environ.* **2019**, *691*, 848–857. https://doi.org/10.1016/j.scitotenv.2019.07.209.
52. Particle Deposition and Aggregation. Available online: https://shop.elsevier.com/books/particle-deposition-and-aggregation/elimelech/978-0-7506-0743-8 (accessed on 18 September 2025).
53. Surface properties of Beached Plastics. Available online: https://link.springer.com/article/10.1007/s11356-015-4332-y (accessed on 18 September 2025).
54. Ferris, F.G.; Fyfe, W.S.; Witten, T.; et al. Effect of mineral substrate hardness on the population density of epilithic microorganisms in two Ontario rivers. *Can. J. Microbiol.* **1989**, *35*, 744–747.
55. Tuson, H.H.; Weibel, D.B. Bacteria–surface interactions. *Soft Matter* **2013**, *9*, 4368–4380.
56. Crawford, C.B.; Quinn, B. Physiochemical Properties and Degradation. In *Microplastic Pollutants*; Crawford, C.B., Quinn, B., Eds.; Elsevier: Amsterdam, The Netherlands, 2017; pp. 57–100. https://doi.org/10.1016/B978-0-12-809406-8.00004-9.
57. Mammo, F.K.; Amoah, I.D.; Gani, K.M.; et al. Microplastics in the environment: Interactions with microbes and chemical contaminants. *Sci. Total Environ.* **2020**, *743*, 140518. https://doi.org/10.1016/j.scitotenv.2020.140518.
58. Ermis, H.; Collins, C.; Saha, S.K.; et al. Beyond Visibility: Microorganisms for tackling plastic and microplastic problems for cleaner future. *Chem. Eng. J.* **2024**, *497*, 154585. https://doi.org/10.1016/j.cej.2024.154585.
59. Sorption of Four Hydrophobic Organic Compounds by Three Chemically Distinct Polymers: Role of Chemical and Physical Composition. Available online: https://pubs.acs.org/doi/10.1021/es301386z (accessed 2 August 2025).
60. Liu, G.; Zhu, Z.; Yang, Y.; et al. Sorption behavior and mechanism of hydrophilic organic chemicals to virgin and aged microplastics in freshwater and seawater. *Environ. Pollut.* **2019**, *246*, 26–33. https://doi.org/10.1016/j.envpol.2018.11.100.
61. Forero-López, A.D.; Brugnoni, L.I.; Abasto, B.; et al. Plastisphere on microplastics: *In situ* assays in an estuarine environment. *J. Hazard. Mater.* **2022**, *440*, 129737. https://doi.org/10.1016/j.jhazmat.2022.129737.
62. Van Oss, C.J.; Good, R.J.; Chaudhury, M.K. The role of van der Waals forces and hydrogen bonds in 'hydrophobic interactions' between biopolymers and low energy surfaces. *J. Colloid Interface Sci.* **1986**, *111*, 378–390.
63. Monika, M.; Sharma, K. Challenges Associated with Preventive Measures and Environmentally Acceptable Techniques to Control Microplastics. In *Microplastics*; Singh, B., Upadhyay, S.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2025; pp. 317–339. https://doi.org/10.1016/B978-0-443-29804-2.00013-5.
64. Kirstein, I.V.; Kirmizi, S.; Wichels, A.; et al. Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. *Mar. Environ. Res.* **2016**, *120*, 1–8. https://doi.org/10.1016/j.marenvres.2016.07.004.
65. Bowley, J.; Baker-Austin, C.; Porter, A.; et al. Oceanic Hitchhikers—Assessing Pathogen Risks from Marine Microplastic. *Trends Microbiol.* **2021**, *29*, 107–116. https://doi.org/10.1016/j.tim.2020.06.011.
66. Are Microplastics Spreading Infectious Disease? Available online: https://www.pnas.org/doi/10.1073/pnas.2311253120 (accessed on 2 August 2025).
67. Ortiz, D.; Munoz, M.; Nieto-Sandoval, J.; et al. Insights into the degradation of microplastics by Fenton oxidation: From surface modification to mineralization. *Chemosphere* **2022**, *309*, 136809.
68. Dey, S.; Rout, A.K.; Behera, B.K.; et al. Plastisphere community assemblage of aquatic environment: Plastic-microbe interaction, role in degradation and characterization technologies. *Environ. Microbiome* **2022**, *17*, 32.
69. Koelmans, A.A.; Nor, N.H.M.; Hermsen, E.; et al. Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. *Water Res.* **2019**, *155*, 410–422. https://doi.org/10.1016/j.watres.2019.02.054.