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Microplastics as Emerging Vectors of Antimicrobial Resistance in Aquatic Environments: Mechanisms, Evidence, and Research Priorities

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ABSTRACT

Microplastics have emerged as ubiquitous contaminants of aquatic environments, while antimicrobial resistance has become an increasingly important environmental and public-health concern. Although these problems have traditionally been investigated separately, growing evidence indicates that microplastics can provide surfaces on which microorganisms, antibiotic resistance genes (ARGs), mobile genetic elements, and chemical contaminants interact. This review examines the current evidence concerning the role of microplastics in the environmental emergence, persistence, and dissemination of antimicrobial resistance, with particular attention to aquatic ecosystems and wastewater treatment systems. An integrative literature review was conducted using peer-reviewed studies and authoritative scientific and public-health reports addressing microplastics, antibiotic-resistant bacteria, ARGs, mobile genetic elements, wastewater, and aquatic environments. The reviewed evidence indicates that microplastic surfaces can support distinct microbial communities, promote biofilm formation, concentrate chemical contaminants, and create conditions that may favor horizontal gene transfer and the persistence of resistance determinants. Recent metagenomic evidence further suggests that microplastic-associated microbial communities can contain enriched collections of antibiotic, metal, and biocide resistance genes and mobile genetic elements. Wastewater treatment plants represent an important convergence point because they receive microplastics, antibiotics, resistant bacteria, and ARGs while simultaneously generating effluent and sludge capable of transporting these contaminants into receiving environments. However, important uncertainties remain concerning the extent to which microplastic-associated resistance contributes to clinically relevant infections. The review concludes that microplastics should be considered a potentially important component of environmental antimicrobial-resistance pathways rather than an established independent driver of human disease. Standardized monitoring, mechanistic experiments, metagenomic surveillance, and integrated wastewater management are needed to clarify their contribution and reduce environmental risks.

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INTRODUCTION

Antimicrobial resistance (AMR) is one of the most significant challenges confronting modern medicine and environmental health. Resistance occurs when microorganisms develop or acquire mechanisms that reduce or eliminate the effectiveness of antimicrobial agents. Although antimicrobial resistance is often discussed primarily in relation to clinical settings,

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resistance is fundamentally an ecological and evolutionary phenomenon that can develop and circulate across interconnected human, animal, and environmental systems. Environmental microorganisms constitute a large reservoir of resistance genes, and natural and human-impacted environments provide opportunities for resistant organisms and genetic determinants to interact (Larsson & Flach, 2022).

The global scale of antimicrobial resistance illustrates the urgency of the problem. The Global Research on Antimicrobial Resistance study estimated that bacterial AMR was directly responsible for approximately 1.27 million deaths in 2019 and was associated with millions of additional deaths (Antimicrobial Resistance Collaborators, 2022). These estimates primarily concern clinical consequences, but the emergence and dissemination of resistance cannot be understood exclusively within healthcare facilities. Environmental reservoirs can receive antimicrobial compounds, resistant bacteria, resistance genes, metals, disinfectants, and other pollutants, creating conditions under which resistance can persist and potentially spread (Larsson & Flach, 2022; Murray et al., 2024).

The environmental dimension of AMR has received increasing scientific attention. Wastewater treatment plants (WWTPs), hospitals, pharmaceutical manufacturing facilities, and urban drainage systems can act as points at which antibiotics, antibiotic-resistant bacteria (ARB), and antibiotic resistance genes (ARGs) enter aquatic ecosystems. Importantly, conventional wastewater treatment does not necessarily eliminate all resistance determinants. Instead, treatment processes may redistribute resistant microorganisms and genetic material between water, sludge, and receiving environments (Su et al., 2024; Zhao et al., 2024).

At the same time, plastic pollution has become a major environmental problem. Microplastics (MPs), generally referring to plastic particles smaller than 5 mm, originate from the fragmentation of larger plastic materials as well as from direct emissions of small plastic particles such as fibers and industrial or consumer-derived particles. Their small size, persistence, large surface-area-to-volume ratio, and ability to interact with microorganisms and chemical pollutants make them environmentally important contaminants (Thompson et al., 2024).

Microplastics are now recognized as widespread contaminants of aquatic systems. Rivers, lakes, estuaries, coastal waters, sediments, and wastewater systems can all contain microplastic particles. Their environmental significance extends beyond the physical presence of plastic because their surfaces can become colonized by microorganisms. These microbial communities, often described collectively as the plastisphere, may differ from the surrounding free-living microbial community in composition and function.

The formation of microbial biofilms on microplastic surfaces is particularly relevant to antimicrobial resistance. Biofilms create densely populated microbial communities in which organisms are embedded in extracellular polymeric substances. Such environments can increase physical proximity between bacterial cells and potentially facilitate interactions involving genetic material. Consequently, microplastics may function not merely as passive pollutants but as mobile surfaces capable of transporting microorganisms and resistance determinants through aquatic environments.

Recent research has strengthened this hypothesis. Guruge et al. (2024), for example, identified a microplastic-associated microbial resistome containing antibiotic resistance genes, biocide and metal resistance genes, and mobile genetic elements in aquatic environments. Their work introduced the concept of the "plastiome," referring to a microplastic-associated collection of resistance determinants and mobile genetic elements. The study provides evidence that microplastics can host complex microbial communities with genetic characteristics relevant to antimicrobial resistance.

The relationship is potentially more complicated because microplastics can interact with other environmental contaminants. Antibiotics and other organic compounds can adsorb to plastic surfaces, potentially altering their environmental persistence and spatial distribution. Metals and biocides may also interact with microbial communities associated with microplastics. These interactions are important because exposure to different antimicrobial or chemical stressors may produce co-selection, whereby resistance to one substance is associated with resistance to another (Murray et al., 2024).

Microplastics may therefore participate in several processes relevant to AMR simultaneously. They may provide physical surfaces for microbial attachment, create biofilm habitats, transport resistant microorganisms, concentrate selected contaminants, and bring bacteria carrying resistance genes into close proximity. These processes could potentially increase the opportunity for horizontal gene transfer, particularly through plasmids and other mobile genetic elements.

Wastewater treatment systems are especially important in this context. Wastewater can contain microplastics, antibiotics, resistant bacteria, ARGs, and other pollutants. Thus, WWTPs represent a convergence point between plastic pollution and antimicrobial resistance. Recent research has specifically examined the occurrence, fate, and interactions of MPs and ARGs in WWTPs, highlighting the need to consider these contaminants together rather than independently (Zhao et al., 2024).

However, the existence of ARGs on microplastics does not automatically demonstrate that microplastics cause clinically significant AMR. This distinction is essential. Detection of a resistance gene indicates its presence, whereas demonstration of an environmental pathway leading to infection requires substantially stronger evidence. The transfer of an ARG between microorganisms, successful establishment in a pathogenic organism, subsequent transmission to humans, and clinical expression of resistance represent multiple stages in a complex causal chain (Larsson & Flach, 2022).

Consequently, an important scientific question is not simply whether microplastics carry resistance genes, but under what environmental conditions microplastics increase the probability of resistance development or dissemination and whether this increase is epidemiologically meaningful.

Recent evidence makes this question particularly timely. Studies published in 2024 and 2025 have reported interactions between microplastics and ARGs in aquatic environments and wastewater systems. Experimental work has also suggested that microplastics may influence conjugative transfer during disinfection processes, while field-based metagenomic investigations have identified ARG enrichment associated with specific microplastic types (Zhang et al., 2025; Zhao et al., 2024).

Despite this progress, the literature remains fragmented. Studies differ substantially in microplastic type, particle size, environmental matrix, bacterial species, experimental duration, ARG detection methods, and environmental conditions. Some investigations are laboratory-based, whereas others examine naturally occurring microplastics in rivers or wastewater. Consequently, comparing results across studies remains difficult.

A critical synthesis is therefore needed to determine what is currently established, what remains uncertain, and which mechanisms deserve further investigation. Such a synthesis is also relevant to environmental management because conventional approaches to AMR surveillance and plastic pollution generally treat these problems as separate issues.

Accordingly, this review addresses the following research questions:

1. How do microplastics influence the persistence and distribution of antibiotic-resistant bacteria and antibiotic resistance genes in aquatic environments?
2. What mechanisms may explain interactions between microplastics and antimicrobial resistance?
3. What role do wastewater treatment systems play in the interaction between microplastics and antimicrobial resistance?
4. What are the principal knowledge gaps and research priorities for assessing the environmental and public-health significance of microplastic-associated antimicrobial resistance?

RESEARCH METHODOLOGY

Research Design

This study adopted an evidence-mapping and integrative synthesis approach to examine how microplastics may influence the emergence, persistence, and environmental dissemination of antimicrobial resistance in aquatic systems. Rather than treating microplastics, antimicrobial resistance, and wastewater as separate environmental problems, the review considered them as interconnected components of a common ecological pathway. The methodological focus was therefore placed on identifying evidence that could explain relationships among microplastic surfaces, microbial colonization, antimicrobial resistance genes (ARGs), resistant microorganisms, mobile genetic elements, wastewater processes, and subsequent transport into receiving aquatic environments.

The literature search was conducted across major multidisciplinary and biomedical scientific databases, with the search strategy developed around four interconnected concepts: microplastic contamination, antimicrobial resistance, microbial genetic exchange, and aquatic or wastewater environments. Combinations of terms such as *microplastics*, *antimicrobial resistance*, *antibiotic resistance genes*, *resistant bacteria*, *plastisphere*, *biofilm*, *horizontal gene transfer*, *mobile genetic elements*, *wastewater treatment*, and *aquatic ecosystems* were used to identify relevant publications. Search terms were combined using Boolean operators and modified where necessary to accommodate differences in database indexing and terminology. The reference lists of particularly relevant studies were subsequently examined to identify earlier investigations that were not retrieved through the primary database searches, while citation tracking was used to locate more recent studies building on influential findings.

The evidence was assessed according to its contribution to understanding the microplastic–resistance relationship rather than solely according to publication type. Primary experimental studies were prioritized where they provided direct evidence of microbial colonization, ARG enrichment, resistant bacteria, biofilm development, or genetic transfer associated with microplastics. Field-based investigations were considered particularly important for evaluating whether patterns observed under controlled laboratory conditions were also detectable in natural or wastewater-impacted environments. Metagenomic and molecular studies were incorporated to provide evidence concerning changes in microbial community composition, resistance determinants, and mobile genetic elements. Review articles were used primarily to establish conceptual frameworks and identify important primary studies rather than as substitutes for original evidence.

Studies were retained when they provided evidence relevant to at least one component of the proposed environmental pathway, including microbial colonization of microplastic surfaces, enrichment or detection of ARGs, association of resistant microorganisms with microplastic biofilms, interactions involving mobile genetic elements, horizontal gene transfer, co-selection involving antibiotics or antimicrobial contaminants, or the behavior of microplastics and associated resistance determinants within wastewater treatment systems and receiving waters. Research focused exclusively on agricultural plastic applications was excluded because it did not correspond to the environmental focus of the review. Publications that discussed microplastics without addressing microbial, genetic, or antimicrobial-resistance dimensions were likewise excluded, as were studies in which antimicrobial resistance was unrelated to microplastic-associated processes.

Data Analysis

The selected evidence was synthesized through comparative and mechanistic analysis rather than quantitative pooling. Each study was examined in terms of the environmental setting investigated, type and characteristics of microplastics considered, microbial or genetic indicators measured, principal findings, and the mechanism proposed to explain the observed association. Particular attention was given to whether reported resistance patterns represented simple surface colonization, enrichment of resistance determinants, altered microbial community structure, increased opportunities for horizontal gene transfer, or co-selection resulting from the simultaneous presence of antibiotics, heavy metals, biocides, and other contaminants.

The evidence was subsequently organized along an environmental continuum extending from microplastic colonization and biofilm formation to resistance enrichment, genetic exchange, wastewater-mediated transport, and potential ecological exposure. This approach allowed findings from laboratory experiments, wastewater studies, environmental surveys, and molecular investigations to be compared within a common conceptual framework while preserving differences in their evidentiary strength. Where findings were inconsistent, the analysis considered differences in polymer type, particle characteristics, environmental conditions, microbial communities, experimental duration, and analytical methods as possible explanations rather than treating contradictory results as equivalent evidence.

Because the reviewed studies differed substantially in research design, environmental matrices, microplastic characteristics, molecular targets, and outcome measures, statistical meta-analysis was not undertaken. The principal analytical objective was instead to determine whether convergent evidence supports a mechanistic relationship between microplastics and antimicrobial resistance and to identify the environmental conditions under which that relationship appears most pronounced. This synthesis also provided the basis for distinguishing relatively well-established observations from emerging hypotheses and unresolved questions requiring targeted experimental and field investigation.

RESULTS

Microplastics Create Distinct Microbial Habitats

The literature consistently indicates that microplastic surfaces can support microbial colonization and biofilm formation. Once introduced into water, plastic particles undergo physical and chemical changes that influence microbial attachment. Surface roughness, polymer composition, weathering, hydrophobicity, and the formation of an environmental coating can all influence microbial colonization. Microplastic-associated communities are not necessarily identical to microbial communities in the surrounding water. This distinction is important because microplastics can provide relatively stable surfaces in otherwise dynamic aquatic environments. Microorganisms attached to these surfaces can therefore experience different ecological conditions from free-living cells.

Thompson et al. (2024) emphasized that microplastics are environmentally ubiquitous and can interact with biological systems across multiple levels of organization. The formation of microbial communities on plastic surfaces represents one important dimension of this interaction.

The presence of a biofilm also changes the physical environment immediately surrounding bacterial cells. Extracellular polymeric substances can trap nutrients and pollutants and may create localized gradients in oxygen, pH, and chemical concentrations. Consequently, the microplastic surface can become a biologically active microhabitat rather than simply a piece of inert material. This characteristic provides a plausible ecological basis for the association between microplastics and AMR.

Microplastics can Concentrate Antibiotic Resistance Determinants

Multiple studies have reported ARGs in microbial communities associated with microplastics. Importantly, the presence of ARGs has been reported in environmental settings where antibiotics, resistant bacteria, and other pollutants coexist. Zhao et al. (2024) reviewed evidence concerning the origin, fate, and environmental effects of microplastics and ARGs in wastewater treatment plants. Their synthesis indicates that WWTPs can simultaneously receive and redistribute these contaminants.

More direct evidence comes from Guruge et al. (2024), who characterized microplastic-associated microbial communities in aquatic environments and identified associations among ARGs, metal and biocide resistance genes, and mobile genetic elements. Their findings suggest that microplastics may function as reservoirs of a broader resistance system rather than carrying isolated ARGs.

This is scientifically significant because resistance genes rarely exist in complete isolation from other genetic and environmental factors. A microplastic surface supporting bacteria carrying several resistance determinants may provide opportunities for co-selection and genetic exchange.

Mobile Genetic Elements are Particularly Important

The potential importance of microplastics to AMR depends not only on the abundance of ARGs but also on their mobility. ARGs can be located on chromosomes or mobile genetic elements such as plasmids, integrons, and transposons. Mobile genetic elements can facilitate movement of resistance determinants among bacteria, including bacteria that are ecologically or taxonomically distinct. Guruge et al. (2024) reported substantial associations between microplastic-associated microbial communities and mobile genetic elements. Their findings support the idea that the microplastic-associated resistome may have greater significance when ARGs are genetically mobile.

This distinction is critical when evaluating environmental risk. A resistance gene that is present but genetically isolated does not necessarily have the same dissemination potential as a resistance gene located on a transferable plasmid. Consequently, future assessments should move beyond simply measuring total ARG abundance and should investigate genetic context and mobility.

Biofilms may Increase Opportunities for Horizontal Gene Transfer

Horizontal gene transfer is one of the central mechanisms by which resistance genes can spread among bacteria. Three major mechanisms are generally recognized: conjugation, transformation, and transduction. Conjugation is particularly relevant to environmental AMR because plasmids can transfer genetic material directly between bacterial cells. Microplastics can potentially facilitate horizontal gene transfer by increasing bacterial density and physical contact within biofilms. A floating or suspended microplastic particle may transport bacteria through water while maintaining a concentrated microbial community on its surface.

Laboratory evidence has provided support for this mechanism. Zhang et al. (2025) reported that microplastics increased conjugative transfer of ARGs during ultraviolet disinfection experiments. Their findings indicated that conventional and biodegradable microplastics could influence ARG transfer under disinfection conditions, with mechanisms involving light shielding, reactive oxygen species, and particle-associated effects.

These findings are important because disinfection is generally intended to reduce microbial risks. If specific environmental conditions allow microplastics to protect bacteria or alter genetic-transfer processes during treatment, the interaction deserves greater consideration in wastewater management. Nevertheless, laboratory evidence should not automatically be interpreted as proof that the same magnitude of effect occurs in natural environments.

Environmental systems are considerably more complex, and factors such as particle concentration, natural organic matter, temperature, microbial diversity, sunlight, hydrodynamics, and pollutant mixtures can alter outcomes.

Antibiotics are Only One Part of the Selection Environment

The relationship between microplastics and AMR should not be reduced to antibiotics alone. Environmental microbial communities are exposed simultaneously to numerous chemical stressors. Metals, disinfectants, biocides, pharmaceuticals, and other contaminants can contribute to selection for resistance. Some resistance determinants may also be genetically linked, meaning that selection for resistance to one contaminant can indirectly increase the persistence of another resistance trait.

Murray et al. (2024) emphasized the importance of environmental contaminants in the co-selection of antibiotic resistance. Their review demonstrates that environmental resistance cannot be understood solely through antibiotic concentrations. Microplastics may intensify this problem because their surfaces can interact with chemical contaminants and microbial communities simultaneously. The result is potentially a localized environment where chemical selection and microbial gene exchange occur together. This mechanism is especially important in polluted waterways and wastewater systems where multiple contaminants are present simultaneously.

Wastewater Treatment Plants are Major Convergence Points

The literature indicates that wastewater treatment plants are particularly important environments for studying microplastic-associated AMR. Municipal wastewater can contain microplastics originating from domestic activities, textiles, personal-care products, urban runoff, and fragmentation of larger plastic materials. At the same time, wastewater contains human-associated bacteria, antibiotics and pharmaceutical residues, ARGs, and mobile genetic elements.

Consequently, WWTPs bring together nearly all components necessary for the proposed microplastic–AMR interaction. Su et al. (2024) described WWTPs as important interfaces between human activities and aquatic environments because they receive large quantities of microorganisms and resistance determinants and discharge treated effluent into receiving waters.

Zhao et al. (2024) similarly highlighted the simultaneous occurrence of MPs and ARGs in wastewater treatment systems. Their review indicates that treatment can reduce some contaminants while concentrating or redistributing others in sludge and effluent.

The problem is therefore not simply whether treatment "removes" microplastics or ARGs. A more useful question is where the contaminants end up after treatment**.**

Microplastics may Transport Resistance Beyond Wastewater Treatment Plants

Microplastics are environmentally mobile. Their buoyancy, density, particle size, and aggregation behavior determine whether they remain suspended, settle into sediments, or move downstream. A microplastic particle carrying a biofilm can therefore potentially transport microorganisms and genetic material between different environmental compartments. This creates an important distinction between conventional dissolved pollution and particle-associated pollution. Dissolved contaminants may disperse relatively rapidly, whereas a particle can provide a persistent physical substrate.

Recent field evidence reinforces this concern. Guruge et al. (2024) investigated microplastics in rivers and found that plastic-associated microbial communities displayed stronger associations among resistance genes, metal/biocide resistance genes, and mobile genetic elements than surrounding river water. These observations suggest that the environmental behavior of microplastics may influence the spatial organization of resistance determinants.

Polymer Type and Particle Characteristics Matter

Not all microplastics behave identically. Polyethylene, polypropylene, polystyrene, polyethylene terephthalate, polyvinyl chloride, and biodegradable polymers differ in surface chemistry, density, degradation behavior, and environmental persistence. Particle size also matters. Smaller particles have relatively larger surface areas per unit mass and may therefore provide greater surface area for microbial attachment and chemical interactions.

Fibers and fragments may also behave differently from spherical laboratory particles. Natural environmental microplastics are often irregular, weathered, and chemically aged, whereas experimental studies frequently use standardized particles. This difference represents a major methodological challenge. Findings obtained with commercially manufactured spherical polystyrene particles cannot necessarily be generalized to weathered fibers released from textiles or fragmented polyethylene particles found in rivers. The 2025 study by Zhang et al. illustrates this complexity by demonstrating different effects between conventional and biodegradable microplastics during ultraviolet disinfection.

Recent Field Evidence Strengthens the Environmental Significance

A particularly important development in the literature is the increasing use of metagenomics and high-throughput molecular approaches. Traditional culture-based methods detect only organisms that can grow under selected laboratory conditions. In contrast, metagenomic approaches can characterize a much broader range of genetic material, including resistance genes from uncultured microorganisms.

Recent field research has reported ARG–microplastic associations in waters receiving wastewater. Zhang et al. (2025) reported that sewage discharge increased ARG–MP complexes in receiving waters and that fibrous and fragmented microplastics displayed enhanced ARG enrichment. Such evidence moves the field beyond laboratory speculation and demonstrates that microplastic-associated resistance determinants can occur under real environmental conditions. However, field detection still does not establish a direct pathway to human infection. The epidemiological significance of these environmental reservoirs remains one of the most important unresolved questions.

DISCUSSION

The findings of this review support a conceptual shift in the way microplastics are understood in relation to antimicrobial resistance (AMR). Microplastics should not be regarded solely as persistent physical pollutants because their surfaces can become biologically active habitats that support microbial attachment, biofilm development, and the accumulation of antibiotic resistance genes (ARGs) and mobile genetic elements (MGEs). This ecological habitat, commonly referred to as the plastisphere, can develop microbial communities that differ from those present in the surrounding environmental matrix. Evidence from riverine, wastewater, and soil systems indicates that microplastics can selectively shape microbial communities and resistance profiles rather than simply passively carrying microorganisms through the environment (Xu et al., 2022; Wang et al., 2024; Guruge et al., 2024). Xu et al. (2022), for example, found clear differences between the ARG profiles associated with microplastics and those present in surrounding river water, with microplastics selectively enriching particular resistance determinants and showing associations between ARGs and MGEs. Similarly, Guruge et al. (2024) identified a mobile resistome on aquatic microplastics that included antibiotic, metal, and biocide resistance genes together with MGEs. These findings suggest that the ecological importance of microplastics lies not simply in their physical persistence but in their ability to create localized microbial niches in which resistance determinants and their potential hosts occur in close proximity.

The concept of the plastisphere is particularly useful for interpreting these observations because it provides an ecological explanation for why microplastic-associated microbial communities may behave differently from free-living communities. Once colonized, a plastic particle provides a surface on which microorganisms can attach and develop biofilms, potentially increasing cell density and cell-to-cell contact. Such conditions are relevant to horizontal gene transfer (HGT), particularly conjugation, because successful transfer requires physical interaction between donor and recipient cells. Experimental evidence supports this mechanism. Feng et al. (2023) demonstrated biofilm formation on several types of microplastics incubated in wastewater-treatment tanks and found that ARGs associated with microplastic biofilms were transferred horizontally at higher frequencies than those observed in the corresponding water samples. This finding is important because it moves the discussion beyond simple correlation between microplastics and ARG abundance and provides experimental evidence that microplastic-associated communities can participate in resistance-gene transfer. However, the results of Feng et al. (2023) should not be interpreted as evidence that all microplastics promote HGT equally. The same study found differences among microplastic types in their capacity to enrich bacteria and ARGs, indicating that the properties of the polymer and the surrounding environment influence the process.

Evidence from natural aquatic environments further supports this context-dependent interpretation. Xu et al. (2022) found that microplastics collected from the Huangpu River had ARG profiles that differed from those of surrounding water and selectively enriched resistance genes associated with rifamycin and vancomycin resistance. Their network analysis also indicated associations between ARGs and MGEs on microplastics, suggesting that plasmid-associated resistance determinants may be particularly relevant to the plastisphere. Importantly, however, the overall abundance of ARGs was not necessarily higher on microplastics than in water. This finding is significant because it demonstrates why the role of microplastics cannot be evaluated simply by comparing total ARG abundance. A particle may contain a lower overall abundance of ARGs while still selectively enriching particular resistance determinants or bacterial hosts that are important for resistance dissemination. Thus, the ecological effect of microplastics may be better understood in terms of community composition, selective enrichment, gene mobility, and host–gene associations rather than total ARG abundance alone (Xu et al., 2022). This interpretation is consistent with Guruge et al. (2024), who reported that aquatic microplastics contained a distinct assemblage of resistance genes and MGEs and showed stronger associations among microbial hosts, resistance genes, and mobile elements than those observed in surrounding river water.

The evidence from wastewater systems is particularly important because wastewater can provide conditions in which microplastics, resistant bacteria, ARGs, MGEs, antibiotics, and other contaminants occur simultaneously. Wang et al. (2021) demonstrated that microplastic-associated biofilms in sewage were enriched in ARGs and MGEs and that the presence of pharmaceuticals influenced these resistance-associated communities. Their findings also showed that polyethylene and polyvinyl chloride differed in their capacity to support microbial attachment and that the coexistence of microplastics and tetracycline increased the potential for ARG and MGE dissemination. These observations suggest that microplastics should not be considered independently of the chemical environment in which they occur. Instead, their role may depend on interactions between the physical properties of the particle, microbial colonization, and selective pressures generated by antimicrobial compounds. The results of Feng et al. (2023) strengthen this interpretation by demonstrating that wastewater-associated microplastic biofilms can provide conditions conducive to horizontal ARG transfer. Together, these studies suggest that wastewater-treatment systems may represent important environmental interfaces at which the physical, biological, and chemical components of AMR converge (Wang et al., 2021; Feng et al., 2023).

Recent field evidence provides further support for the importance of wastewater discharge. Silva et al. (2025) investigated riverine plastispheres upstream and downstream of wastewater-treatment-plant discharge and found that wastewater effluent substantially altered microplastic-associated microbial communities. Their quantitative analysis indicated a 2.3-fold increase in ARG abundance on microplastics downstream of the wastewater discharge, while clinically relevant resistance genes, including *bla*CTX-M, *bla*VIM, and *bla*IMP, were enriched on plastisphere communities relative to water. The study also demonstrated that polymer type influenced the composition of microbial communities, resistomes, and mobilomes (Silva et al., 2025). These results are important because they provide evidence under relatively realistic environmental conditions that wastewater discharge can modify the resistance characteristics of microplastic-associated microbial communities. They also reinforce the argument that polymer type cannot be ignored in assessments of microplastic-associated AMR. Different polymers provide different physicochemical surfaces and may therefore select different microbial assemblages and resistance profiles.

The presence of clinically important resistance determinants on microplastics provides an additional reason for concern, although it should be interpreted cautiously. Silva et al. (2024) recovered carbapenem-resistant Enterobacterales from microplastics collected from river water and detected clinically important carbapenemase genes, including *bla*KPC-3 and *bla*GES-5. Notably, higher carbapenem resistance was observed on microplastics after wastewater-treatment-plant discharge. These findings demonstrate that microplastics can become colonized by bacteria carrying resistance determinants that are directly relevant to clinical medicine. Similarly, beach-sand plastispheres have been reported to contain ARGs that were more prevalent or abundant on microplastics than in surrounding beach sand, including genes associated with multidrug resistance and *bla*KPC (Environmental Pollution, 2024). Such findings extend the concern beyond wastewater facilities and demonstrate that resistance-associated plastispheres can occur in receiving environments. Nevertheless, the presence of clinically relevant resistant bacteria on microplastics does not establish that microplastics are responsible for clinical infections. Environmental colonization is an important component of a potential transmission pathway, but it does not by itself demonstrate successful transmission from environmental microplastics to humans or animals (Silva et al., 2024).

This distinction between environmental potential and demonstrated clinical causation is essential. The current evidence supports several components of a plausible pathway linking microplastics with environmental AMR: microplastics can support biofilms; ARGs can occur in microplastic-associated communities; MGEs can be present; resistant bacteria can colonize microplastic surfaces; and experimental studies have demonstrated enhanced HGT under specific conditions (Wang et al., 2021; Feng et al., 2023; Guruge et al., 2024). However, these findings do not establish the complete causal sequence from microplastic contamination to human infection. The detection of an ARG demonstrates the presence of resistance-associated genetic material but does not demonstrate that the gene is expressed, transferred, or acquired by a clinically relevant pathogen. Likewise, demonstrating enhanced HGT in a controlled experiment does not establish that the same transfer occurs at comparable rates in natural rivers, sediments, wastewater effluent, or marine environments. This distinction is particularly important because the effects of microplastics on HGT are not uniformly positive. Wang et al. (2024), in their review of micro- and nanoplastics and ARG transfer, concluded that plastic effects can vary according to particle type, size, concentration, and environmental conditions and emphasized the need for standardized assays and environmentally realistic experiments. Thus, the most scientifically defensible interpretation is that microplastics are potential ecological facilitators of AMR dissemination, rather than an established direct cause of clinically significant antimicrobial resistance.

The possibility that microplastics facilitate resistance transfer is nevertheless strengthened by experimental evidence concerning conjugative gene transfer. Zhang et al. (2025) investigated the effects of conventional polystyrene and biodegradable polylactic acid microplastics during ultraviolet disinfection and found that both types of microplastics enhanced conjugative transfer of ARGs relative to ultraviolet treatment alone, although polystyrene microplastics produced a stronger effect. The authors attributed this effect to several mechanisms, including light shielding, oxidative stress, increased membrane permeability, and the formation of nanoplastics during ultraviolet irradiation. These results are particularly relevant because they demonstrate that the influence of microplastics may persist even within a treatment process designed to reduce microbial hazards. Rather than being uniformly removed from the resistance-transfer process during disinfection, microplastics may modify the conditions under which surviving bacteria interact. However, this study was performed under controlled experimental conditions, and its findings should therefore be regarded as mechanistic evidence rather than direct evidence of equivalent effects in full-scale treatment systems (Zhang et al., 2025).

The results concerning biodegradable plastics are especially important because they challenge the assumption that biodegradability automatically eliminates the environmental risks associated with conventional plastics. Zhang et al. (2025) found that biodegradable polylactic acid microplastics also enhanced conjugative ARG transfer during ultraviolet disinfection, although their effect was lower than that of polystyrene. This indicates that the environmental evaluation of alternative plastics should not be based solely on their persistence or degradation rate. A material can degrade more readily while still influencing microbial colonization, chemical interactions, or resistance dynamics during the period in which it remains environmentally active. Therefore, the environmental assessment of biodegradable plastics should include their effects on microbial communities, ARG abundance, MGEs, and HGT in addition to conventional indicators such as degradation and ecotoxicity. The finding that polymer type can influence resistance-related processes is also consistent with field studies showing that different polymers support distinct microbial, resistome, and mobilome profiles (Xu et al., 2022; Silva et al., 2025).

Another important finding emerging from the literature is that microplastic diversity itself may influence resistance dynamics. Wang et al. (2024) experimentally examined the effects of increasing microplastic diversity in soil and found that greater diversity of microplastic types was associated with increased abundances of ARGs, virulence-factor genes, and MGEs. The study also identified changes in microbial communities and metabolic functions that were associated with increased ARG abundance. This result is important because environmental exposure rarely consists of a single polymer type. Natural and urban environments contain mixtures of particles differing in polymer chemistry, size, shape, color, and degree of weathering. Consequently, experiments involving a single pristine polymer may underestimate the complexity of actual microplastic-associated microbial communities. At the same time, the soil findings should not automatically be extrapolated to aquatic systems because the ecological processes governing plastisphere formation differ among soil, freshwater, wastewater, and marine environments. Instead, the study demonstrates the importance of considering microplastic diversity as an environmental variable in its own right (Wang et al., 2024).

These methodological concerns also have implications for environmental monitoring. Conventional AMR surveillance often focuses on resistant bacterial isolates, phenotypic antimicrobial susceptibility, or selected ARGs. Such approaches remain necessary, but they may not adequately capture the ecological processes occurring within microplastic-associated communities. The evidence from metagenomic studies indicates that microplastics can harbor complex resistomes and mobilomes that differ from those of surrounding environmental matrices (Xu et al., 2022; Guruge et al., 2024). Metagenomics is therefore valuable for identifying the diversity of ARGs, MGEs, microbial hosts, and associated functional traits. However, molecular detection alone is insufficient to demonstrate functional resistance or active gene transfer. A stronger surveillance framework would combine metagenomic analysis with quantitative PCR, culture-based isolation, antimicrobial susceptibility testing, plasmid characterization, MGE analysis, and experimental HGT assays. Such an integrated approach would make it possible to distinguish between the presence of resistance determinants and their ecological mobility and functional significance.

The evidence collectively suggests that wastewater should be treated as a particularly important research and monitoring environment. Microplastics entering wastewater systems encounter high microbial densities and may simultaneously interact with antimicrobial compounds, ARGs, MGEs, and resistant bacteria. Experimental studies have already demonstrated ARG accumulation and horizontal transfer on microplastic-associated biofilms in wastewater-treatment systems (Wang et al., 2021; Feng et al., 2023), while more recent field research has demonstrated changes in plastisphere resistance profiles following wastewater discharge (Silva et al., 2025). The recovery of carbapenem-resistant Enterobacterales from riverine microplastics downstream of wastewater discharge further suggests that these processes can involve organisms and resistance mechanisms of direct clinical importance (Silva et al., 2024). These observations provide a strong rationale for incorporating microplastic characterization into environmental AMR monitoring around wastewater-treatment plants. Nevertheless, monitoring should not focus exclusively on microplastic abundance. Polymer type, particle size, biofilm characteristics, ARG composition, MGEs, antimicrobial concentrations, and environmental conditions should be evaluated simultaneously because their interactions are likely to determine the actual resistance potential of the plastisphere.

The policy implications of these findings should consequently focus on integrated pollution management rather than treating plastic pollution and AMR as entirely separate environmental problems. The evidence does not yet justify the development of policies based on the assumption that microplastics are a major direct cause of human AMR. It does, however, justify greater attention to environments where microplastics and resistance determinants occur together. Wastewater-treatment plants are especially relevant because they represent points at which resistant microorganisms, antimicrobial residues, ARGs, MGEs, and microplastics may converge before being released into receiving environments. Reducing the release of untreated wastewater and improving the removal of both microplastics and resistance-associated contaminants could therefore address several potential pathways simultaneously. The experimental evidence that microplastics can influence ARG transfer during ultraviolet disinfection also suggests that treatment processes should be evaluated not only in terms of contaminant removal but also in terms of whether treatment conditions inadvertently alter microbial gene-transfer processes (Zhang et al., 2025).

CONCLUSION

The evidence reviewed in this study demonstrates that microplastics represent more than persistent physical pollutants in aquatic environments. Their surfaces can support microbial biofilms and provide ecological interfaces where antibiotic resistance genes, resistant bacteria, mobile genetic elements, antibiotics, metals, and other contaminants interact.

The available evidence indicates that microplastics can contribute to the persistence, concentration, transport, and potential transfer of antimicrobial resistance determinants. Recent field and molecular studies strengthen this conclusion by demonstrating associations among microplastics, resistance genes, mobile genetic elements, and microbial communities in aquatic environments. Wastewater treatment plants are particularly important because they represent convergence points where microplastics and multiple components of the environmental resistome occur simultaneously.

Nevertheless, the current evidence should be interpreted carefully. The presence of ARGs on microplastics and increased gene-transfer rates under experimental conditions do not, by themselves, establish that microplastics are a major cause of clinically relevant antimicrobial resistance in humans. The quantitative contribution of the microplastic pathway to human disease remains uncertain.

The most defensible conclusion is therefore that microplastics should be regarded as potential vectors and facilitators of environmental antimicrobial resistance. Their importance is likely to depend on polymer type, particle characteristics, microbial community composition, contaminant exposure, environmental conditions, and the presence of mobile genetic elements.

Future research should prioritize environmentally realistic experiments, standardized sampling and analytical methods, field-based metagenomic surveillance, characterization of mobile resistance determinants, and direct investigation of gene transfer to clinically relevant bacteria. Wastewater management should also be considered a priority because it represents a major intersection between plastic pollution and antimicrobial resistance.

Ultimately, addressing microplastic-associated AMR will require an integrated environmental-health approach. Reducing plastic pollution, improving wastewater treatment, controlling pharmaceutical contamination, and strengthening environmental AMR surveillance can collectively reduce the conditions that allow resistance determinants to persist and circulate. Such an approach is consistent with the broader understanding of AMR as a problem extending beyond clinical settings into interconnected environmental systems.

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