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The Impact of Microplastics on Antibiotic Resistance Genes

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Abstract. Antibiotic resistance genes (ARGs) and microplastics represent emerging environmental contaminants with significant implications for ecosystem and human health. While considerable progress has been made in understanding their individual behaviors, their combined effects remain underexplored. This review analyzes current research on the distribution, migration mechanisms, and transfer pathways of ARGs on microplastic surfaces across diverse environmental compartments. The results indicate that microplastics significantly enhance the persistence, mobility, and horizontal transfer of ARGs, acting as hotspots for resistance gene dissemination in wastewater, aquatic, terrestrial, and airborne environments. The study also reveals that microplastic type, morphology, and environmental conditions critically influence ARGs enrichment and spread. This synthesis provides a comprehensive reference for understanding the role of microplastics in ARG transmission and highlights the need for integrated pollution control strategies. Future research should focus on standardized detection methods, field validation, and the development of effective remediation technologies to mitigate the spread of microplastic-associated ARGs.

Keywords: Microplastics, antibiotic resistance genes, transfer

1. Introduction

ARGs and microplastics have drawn considerable public attention due to their potential threats to human health. The widespread presence of ARGs is a significant public health issue on a global scale. Their extensive spread is primarily due to the microbial evolution caused by the overuse of antibiotics. ARGs from farms, urban areas, hospitals, wastewater treatment plants (WWTPs), or as water runoff can be accumulated in water, soil and air, posing multiple threats to the ecosystem [1]. The accumulation and spread of ARGs in bacteria have presented serious challenges to the successful prevention and treatment of chronic diseases. It is estimated that if no effective measures are taken to combat antimicrobial resistance, approximately 10 million people worldwide may die by 2050 [2]. Humans can be exposed to ARGs and their hosts from the environment through multiple pathways. Therefore, only by systematically revealing the migration patterns of ARGs in environmental media can the potential threat to human health be accurately assessed.

Microplastics (particles < 5 mm) are a widespread pollutant in the environment. Initially, due to their inert chemical properties, their potential risks were once overlooked. However, the experience of environmental toxicology of persistent chemicals reminds that chemical inertness does not necessarily stand for environmental safety [3]. Recent studies have indicated that microplastics not

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only create new ecological niches for microorganisms, but also serve as media for the spread of antibiotic resistance genes and harmful substances [4]. Microplastics are extensively distributed in air, soil, water bodies, sediments, and food. This distribution creates multiple exposure pathways for ARGs, pollutants, and pathogenic microorganisms, thereby posing a threat to the health of animals, plants, and humans [5]. Studies indicates that microplastics can serve as highly efficient carriers of ARGs and pollutants, promoting cross-transmission among different environmental media and even leading to long-distance migration [6].

In recent years, remarkable advancements have been achieved in the detection and remediation technologies of ARGs on the surface of microplastics. A diverse range of modern analytical techniques have been extensively employed in the qualitative and quantitative investigations of biofilms and ARGs on microplastic surfaces. These techniques involve scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, fluorescence in situ hybridization (FISH), and high-throughput sequencing technologies [7]. These methods not only enable the identification of the microbial community structure on microplastic surfaces but also allow for the precise detection of the distribution and abundance of ARGs. Regarding management, bioremediation strategies have demonstrated promising potential. For example, specific microorganisms such as Pseudomonas spp. and Bacillus spp. can be utilized to degrade microplastics and their associated surface biofilms [7].

In order to accurately evaluate the health threats of combined pollution and formulate effective intervention strategies, this study systematically summarizes the distribution characteristics, migration rules, and transfer mechanisms of ARGs on the surface of microplastics in different environmental media. The study focuses on (1) clarifying the current pollution status and enrichment characteristics of microplastic-ARGs in typical environments such as wastewater treatment plants; (2) analyzing the migration pathways of ARGs mediated by microplastics through the food web in the environment; (3) revealing the driving mechanism of biofilm formation on the surface of microplastics on the horizontal transfer and genetic evolution of ARGs; (4) proposing future research directions for the prevention and control of microplastic-ARGs combined pollution.

2. Current status of antibiotic resistance genes on the surface of microplastics

2.1. Microplastics-ARGs in WWTPs

WWTPs serve as crucial convergence and emission sources of microplastics and ARGs within the environment. They play a pivotal role in the dissemination of environmental antibiotic resistance [8]. Due to their hydrophobic surfaces, microplastics have a strong tendency to adsorb pollutants such as antibiotics, heavy metals, and persistent organic pollutants in wastewater. This adsorption process forms a "toxic shell," thereby imposing selective pressure on microbial communities and facilitating the enrichment and co-selection of antibiotic-resistant bacteria (ARB) [9].

Under the hydraulic conditions prevalent in WWTPs, microplastics offer a stable attachment surface for microorganisms, which is plastisphere. On this surface, biofilms with complex structures and diverse microbial communities can rapidly develop. These biofilms provide an ideal environment for close cell-to-cell interactions and gene exchange processes, such as horizontal gene transfer, thus emerging as "hotspots" for the spread of ARGs [8].

The morphology and polymer type of microplastics significantly influence the enrichment and dissemination of ARGs. Research has shown that fibrous microplastics and fragment-shaped microplastics are the primary carriers for the spread of ARGs and ARB [8]. Among them, fibrous microplastics, owing to their relatively large aspect ratio and unique surface properties, are more

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efficient in adsorbing bacteria and genetic materials compared to fragment-shaped microplastics. In terms of polymer types, polyethylene (PE) microplastics are more likely to accumulate ARGs (such as sul1 and tetC) in leachate and estuarine environments than polypropylene (PP). Conversely, polyvinyl chloride (PVC) exhibits a more prominent role as a carrier of pathogenic bacteria and ARGs in wastewater [10]. Comprehensive risk assessments have indicated that polyamide (PA) microplastics have the highest environmental risk projection value and exhibit a significant positive correlation with ARG abundance. As such, they are regarded as the major high - risk microplastic type in the effluents of wastewater treatment plants [8].

2.2. Microplastics-ARGs in aquatic environments

Aquatic ecosystems represent important sinks and dissemination hubs for the combined pollution of microplastics and ARGs. Similar to the processes occurring in WWTPs, microplastics in the aquatic environment also forms multiple stresses, which drives co-selection mechanisms. For example, microplastics that have adsorbed heavy metals can simultaneously select bacterial strains that are resistant to both heavy metals and antibiotics [10].

These microplastics, laden with pollutants and ARB, act as "marine hitchhikers" and can migrate over long distances in the water column. This results in the cross-ecosystem spread of the microbial communities (including various pathogenic bacteria) attached to their surfaces, thereby posing significant ecological and health risks [11] .For example, numerous studies have detected human and aquatic pathogens such as Vibrio parahaemolyticus and Vibrio splendidus in environmental microplastics [12].

Estuaries and coastal zones, being areas influenced by WWTP discharges and complex hydrodynamic conditions, experience variable environmental factors and are considered hotspots for ARGs exchange and enrichment. Multiple studies have consistently shown that the abundance of ARGs such as sul1, sul2, and tetA in the biofilms on the surfaces of microplastics like PE and PP is significantly higher in these regions [13]. Notably, PE demonstrates a stronger ability to enrich ARGs compared to PP, highlighting the crucial role of microplastics as a medium in the spread of antibiotic resistance in near - shore environments.

2.3. Microplastics-ARGs in terrestrial environments

Terrestrial ecosystems, particularly agricultural soils, have emerged as important sinks and dissemination media for microplastics and ARGs. Different from aquatic environments, microplastics in soil have a longer residence time. They are also influenced by agricultural practices (such as the use of plastic mulch, application of organic fertilizers, and irrigation with reclaimed water) and continuous atmospheric deposition. As a result, their cumulative concentration can reach up to 500,000 particles per kilogram of soil [14]. This high-abundance and diverse microplastic pollution have far-reaching implications for the soil microbiome and its antibiotic resistance gene profiles.

Research has suggested that the diversity of microplastics is a key determinant in driving the enrichment of ARGs in soil [15]. Through microcosm experiments with different levels of microplastic diversity, it has been found that as the diversity of microplastics increases, the total abundance of ARGs, virulence factor genes (VFGs), and mobile genetic elements (MGEs) in the soil also increases significantly [15].

Analogous to the "plasticosphere" in WWTPs and aquatic environments, the diverse array of microplastics in soil provides heterogeneous attachment surfaces for microorganisms. This promotes

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the formation of biofilms and the SOS stress response, both of which are essential mechanisms for the horizontal transfer and enrichment of ARGs. Moreover, the presence of diverse microplastics significantly modifies the physical and chemical properties of the soil, further influencing the structure of microbial communities carrying ARGs and VFGs [15].

2.4. Microplastics-ARGs in air

Although there has been a relatively substantial body of research on microplastics - ARGs in aquatic and terrestrial environments, studies on microplastics in the air as carriers of ARGs remain relatively scarce. Available evidence suggests that microplastics in indoor and outdoor air can potentially act as vectors for the spread of ARGs by adsorbing bacteria and free DNA. This risk may be severely underestimated, especially in urban environments and certain industrial areas.

Microplastic aerosols carrying ARGs and ARB can undergo long-distance migration along with air currents. This phenomenon results in the cross - regional dissemination of antibiotic resistance, thereby presenting a "borderless" potential health risk. Comprehensive risk assessments have revealed that atmospheric deposition serves as a crucial input pathway for microplastics and ARGs in the environments of urban areas and remote regions, such as mountainous areas and polar regions. This highlights the pivotal role of atmospheric deposition as a medium in the global cycle of antibiotic resistance dissemination [16].

3. The migration mechanism of ARGs mediated by microplastics

3.1. Migration in aquatic environments

Microplastics, serving as crucial vectors for gene transfer in aquatic environments, have demonstrated a notable impact on promoting the dissemination of ARGs. This phenomenon is particularly pronounced within WWTPs. The surface of microplastics readily fosters the formation of biofilms, which significantly enhances HGT. Specifically, microplastics provide a platform for bacteria to adhere densely, thereby increasing the opportunities for conjugative transfer. Moreover, the additives released from microplastics can induce oxidative stress in bacteria and enhance membrane permeability, further promoting plasmid transfer. Metagenomic analyses have revealed that the effluent of sewage treatment plants contains a diverse array of novel MGEs. These MGEs are closely associated with the spread of intracellular ARGs (iARGs) and facilitate the interconversion between extracellular ARGs (eARGS) and iARGs [8].

Microplastics originating from sewage sources contribute more than 50% of the iARGs in receiving water bodies such as estuaries and tend to accumulate a greater number of clinically relevant ARGs. Microplastics possess a strong adsorption affinity for eARGs, effectively safeguarding ARGs from environmental degradation. As a result, the concentration and persistence of ARGs within the plastisphere are significantly higher than those in the surrounding water, and the natural transformation efficiency is also greater than that of natural minerals [8].

In aquatic ecosystems, microplastics function as "floating gene shuttles", enabling the long-distance transport of ARGs. Their low density allows them to carry attached microorganisms and ARGs from pollution sources to the open ocean and even polar regions, thus breaching geographical isolation barriers [17]. Additionally, microplastics often accumulate in regions such as estuaries and oceanic gyres, forming local ARG "hotspots" and further elevating the frequency of HGT.

Furthermore, microplastics can facilitate the cross-media transfer of ARGs through water flow, biological uptake, and pollutant adsorption. Their large specific surface area and hydrophobic nature

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enable them to accumulate pollutants such as heavy metals and antibiotics, creating selective pressures that promote the colonization of host bacteria. Research has indicated that the abundance of antibiotic-resistant bacteria associated with microplastics in aquaculture systems can be 100 - 5000 times higher than that in the surrounding water, and PE is more prone to accumulating ARGs compared to PP [18]. Microplastics can also enter the food web via biological ingestion or aggregation and sedimentation processes, thereby altering the ecological transmission routes of ARGs.

3.2. Migration in terrestrial environments

In terrestrial environments, microplastics serve as crucial vectors for the migration and dissemination of ARGs. Their behavior is shaped by agricultural activities and soil ecological processes. Microplastics in agricultural soils primarily originate from residues of agricultural mulch films, sludge-based fertilization, and irrigation water. These pathways directly introduce microplastics, along with the ARGs adhered to them, into the soil environment [15]. Microplastics have the ability to adsorb pollutants such as pesticides or heavy metals. Once ingested by soil fauna, they can disrupt the intestinal microbiota, thereby facilitating the transfer of ARGs. For instance, the co - exposure of tetracycline and microplastics can significantly elevate the level of resistance [18].

Microplastics interact with soil minerals to form aggregates of varying particle sizes, thereby exerting a profound influence on the distribution and migration of ARGs. Fibrous microplastics often play a dominant role in micro-aggregate formation, markedly inhibiting the vertical migration of nanoparticles. This results in the enrichment of ARGs in the surface soil layers. In greenhouse vegetable fields, long - term exposure to large-sized and highly weathered microplastics can substantially increase the abundance of ARGs. Moreover, the types of resistance are correlated with the degree of weathering. Agricultural practices, such as the application of fungicides and monoculture, can also lead to the enrichment of specific ARGs subtypes and virulence factors. These practices can alter the microbial community structure, reduce nucleotide diversity, and potentially enhance horizontal gene transfer [15].

In the vertical dimension, microplastics can migrate downward with infiltrating water, transporting ARGs to deeper soil strata and even groundwater. Horizontally, they can disperse across different regions via runoff, animal foraging activities, and wind action [15]. Of particular concern is the fact that the microplastic-ARG complexes can be taken up by crops and subsequently transferred through the food chain, thus posing a potential threat to food safety. Microplastics not only modify the rhizosphere microbial community, thereby facilitating the uptake of ARGs by plants, but also protect ARGs from degradation, thereby prolonging their persistence in the environment [15].

4. The transfer and evolution of ARGs on microplastic surfaces

The surface of microplastics serves as an efficient "reactor" for the transfer and evolution of ARGs. The dense biofilm that forms on its surface significantly facilitates HGT. As a result, the efficiencies of conjugation, transformation, and transduction are far higher than those in aquatic or sedimentary environments. Specifically, the conjugation transfer efficiency can even be enhanced by two orders of magnitude [7].

Microplastics not only adsorb extracellular DNA in the environment, thereby increasing the likelihood of transformation, but also release additives and adsorb pollutants such as antibiotics and heavy metals. This creates a synergistic selective pressure that enriches multi-drug-resistant bacteria and accelerates the emergence of novel ARGs [7]. Additionally, the abundance and diversity of

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mobile genetic elements on the surface of microplastics are markedly elevated, which accelerates the recombination and dissemination of ARGs.

The unique "plastisphere" microbial niche enriches potential pathogens. A positive correlation exists between the increase in its functional diversity and the abundance of ARGs. Moreover, an increase in microplastic diversity may also indirectly drive the evolution and spread of ARGs by altering the structure of the microbial community [15].

5. Research challenges and future directions

Although remarkable progress has been achieved in research on the dissemination of ARGs mediated by microplastics, this field still confronts numerous challenges. The current research methodologies lack standardization. Present quantitative studies on ARGs on the surface of microplastics exhibit inconsistencies in aspects such as detection methods, microplastic characterization, and environmental parameters. This lack of uniformity renders it arduous to compare results from different studies and accurately evaluate the true contribution of microplastics to the environmental dissemination of ARGs. In the future, it is imperative to establish standardized methods for the isolation, identification, and quantification of biofilms and ARGs on the surface of microplastics.

Meanwhile, the majority of existing studies are conducted under laboratory-controlled conditions. As a result, they struggle to faithfully reflect the intricate interactions between microplastics and various pollutants in real-world scenarios, including wastewater treatment plants and eutrophic lakes, and the impact of these interactions on the enrichment kinetics of ARGs. There is a pressing need to conduct more field monitoring and experiments to uncover the synergistic effects under combined pollution conditions.

Furthermore, only a limited number of studies have directly investigated the migration mechanisms of microplastic-ARGs complexes in soil, and the process of ARGs dissemination by airborne microplastics remains largely uncharted. Additionally, the patterns of ARGs transfer in the food chain mediated by microplastics and the associated human health risks remain ambiguous. Thus, interdisciplinary exploration integrating microbiology, epidemiology, and toxicology is essential.

There are also inadequacies in targeted remediation and control technologies. Currently, there is a dearth of mature techniques for efficiently removing environmental microplastics and interrupting the ARG dissemination mediated by them. In the future, efforts should be directed towards developing efficient wastewater treatment processes, exploring environmentally friendly alternative materials, and formulating more targeted policies and regulations. Simultaneously, it is urgent to investigate the potential influence of microplastics derived from biodegradable plastics on ARG dissemination [15].

6. Conclusion

In conclusion, this review systematically synthesizes current knowledge on the distribution, migration mechanisms, and transfer pathways of ARGs on microplastic surfaces across diverse environmental media, including wastewater treatment plants, aquatic systems, terrestrial soils, and the atmosphere. Microplastics serve as persistent vectors and hotspots for ARG enrichment and dissemination, significantly enhancing horizontal gene transfer and long-distance spread of antimicrobial resistance, thereby amplifying ecological and health risks. Microplastic type, polymer composition, surface properties, and environmental conditions critically influence ARG

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accumulation and transfer dynamics. These findings provide important insights into the role of microplastics in the environmental spread of ARGs and reinforce the need for integrated strategies to mitigate combined pollution. This work offers a foundational reference for future risk assessment and source control, particularly in highlighting the understudied pathways such as atmospheric transport and food web transmission.

However, limitations remain in the current body of research, including a lack of standardized methods for microplastic and ARG detection, and heavy reliance on laboratory-based studies which may not fully represent real-world scenarios. Furthermore, comparative analyses of ARG abundance and diversity between microplastics and surrounding environments are still inconclusive, and the behavior of biodegradable microplastics in ARG transport is poorly understood. Future studies should prioritize field-based experiments to validate mechanistic understandings under realistic conditions. There is also an urgent need to explore the vertical and horizontal transport of ARG-carrying microplastics in different environmental matrices, investigate the role of plastisphere biofilms in ARG maintenance and transfer, and assess the human exposure risks via food chains.

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