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REVIEW ARTICLE

Microplastic pollution interaction with disinfectant resistance genes: research progress, environmental impacts, and potential threats

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Abstract

The consumption of disposable plastic products and disinfectants has surged during the global COVID-19 pandemic, as they play a vital role in effectively preventing and controlling the spread of the virus. However, microplastic pollution and the excessive or improper use of disinfectants contribute to the increased environmental tolerance of microorganisms. Microplastics play a crucial role as vectors for microorganisms and plankton, facilitating energy transfer and horizontal gene exchange. The increase in the use of disinfectants has become a driving force for the growth of disinfectant resistant bacteria (DRB). A large number of microorganisms can have intense gene exchange, such as plasmid loss and capture, phage transduction, and cell fusion. The reproduction and diffusion rate of DRB in the environment is significantly higher than that of ordinary microorganisms, which will greatly increase the environmental tolerance of DRB. Unfortunately, there is still a huge knowledge gap in the interaction between microplastics and disinfectant resistance genes (DRGs). Accordingly, it is critical to comprehensively summarize the formation and transmission routes of DRGs on microplastics to address the problem. This paper systematically analyzed the process and mechanisms of DRGs formed by microbes. The interaction between microplastics and DRGs and the contribution of microplastic on the diffusion and spread of DRGs were expounded. The potential threats to the ecological environment and human health were also discussed. Additionally, some challenges and future priorities were also proposed with a view to providing useful basis for further research.

Keywords Microplastics · DRGs · Formation mechanism · Interaction: Potential threats

Introduction

In recent years, the issue of microplastic pollution has become increasingly serious, and there is growing global concern about its potential risks to the ecological environment and human health. Microplastics are constantly detected in the ocean (Yang et al. 2022), freshwater (Shen et al. 2020), sediments (Yu et al. 2021), soils (Chang et al. 2022), living organisms (Wieczorek et al. 2019), and even human placenta (Ragusa et al. 2021) and blood (Leslie et al. 2022), making them a new global environmental pollution problem. On the premise that plastics are widely used by humans, the abundance of microplastics in the environment is getting higher, resulting in more pollution (Zhang et al. 2022e) and biological damage (Hitchcock 2022; Kakar et al. 2023). Due to their small particle size and large specific surface area, microplastics have a strong adsorption ability for heavy metals, organic pollutants (Shan et al. 2020), pathogenic microorganisms (Shen et al. 2019b), and resistance genes (RGs) (Imran et al. 2019). Microplastics can provide an ideal living environment for microorganisms and enhance their resistance to environmental pressures. Simultaneously, predicting the migration speed and direction of microplastics is impossible due to their small size and light weight. This leads to significant variations in abundance and composition across different regions. In addition, the existence of biofilm makes it easy to be mistaken ingested by predator, thus transferring along the food chain/web even human bodies by the food chain and posing a potential threat to organisms and human health (Shen et al. 2019b).

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The outbreak and spread of COVID-19 have furtherly increased the production and consumption of disposable plastics, as well as disinfectants. Disinfection of homes and public places is a key mean to effectively prevent and control the virus. The use of household disinfectants increased dramatically, from 19.9 to 48.7% during the epidemic (Guo et al. 2021; Yang et al. 2023b). Reasonable and proper use of disinfectants can kill a large number of pathogenic bacteria, and inhibit the spread of viruses (Feng et al. 2023; Macêdo et al. 2019). However, it is problematic that disinfectants were used extensively and in high quantities during the period of epidemic control. Disinfectants containing wastewater may cause water environment pollution and affect the transfer of energy and information along food chain. The residual active chlorine can enter surface water bodies or even groundwater via surface runoff and chlorinated effluent, thereby causing irreversible toxicological effects on aquatic organisms and disturbing microbial community (Dong et al. 2021; Li et al. 2023). The long-term exposure to low dose disinfectants can lead to the gradual development of resistance and increased tolerance in microorganisms (Aase et al. 2000; Lv et al. 2014). The nonstandard use of disinfectants and potential environmental risks have garnered global attention (Davies and Wales 2019; Yang et al. 2023a). Wang et al. (2019) reported that the improvement of hydrophobic membrane protein on the surface of mycobacterium ensured the integrity of cell membrane during chlorine disinfection, which improved the chlorine resistance of microorganisms. Botelho et al. (2019) found that mobile genetic elements were key driving factors for *Pseudomonas aeruginosa* to develop resistance to disinfectants during the disinfection process. Generally, a high dose of disinfectant will achieve a better sterilization effect, while a low dose and long-term fixation, as well as single disinfection, may lead to adverse consequences such as resistance diffusion. A study performed by Guo et al. (2015) has revealed that the low dose of chlorine disinfectant obviously increased the transfer frequency of RGs among the same species by 2–5 times. Another reported carried out by Zhang et al. (2017) also found that the subinhibitory concentrations of disinfectant could increase the frequency of RGs exchange and transfer in intragenera conjugative by 1.5–7.5 times, and 1.4–2.3 times in intergenera conjugative, respectively.

The presence of microplastics in the environment would worsen the potential risks posed by disinfectant-resistant bacteria (DRB) and disinfectant-resistant genes (DRGs) (Shen et al. 2023b). Microplastics are carriers of microorganisms and pollutants, and they also play a crucial role in facilitating microbial gene exchange (Shen et al. 2019b). Microplastics colonized by DRB can promote the diffusion and spread of DRGs through their migration, leading to the accumulation of both DRB and DRGs. Additionally, an excessive amount of residual disinfectant in the influent of the sewage treatment plant can have an impact on the activity of the activated sludge, particularly on the biological treatment system that has a weak resistance to high impact loads. The use of disinfectants may lead to an increase in disinfection by-products in sewage, as well as the formation of dissolved refractory organics, and enhance the environmental tolerance of microbes. On the other hand, microplastics could also significantly reduce the efficiency of water disinfection (Shen et al. 2021b; Xiong et al. 2022). The existence of DRB and DRGs can further decrease the efficiency of disinfection. It is necessary to increase the amount of disinfectant, which leads to additional screening and creates a vicious circle of DRGs. As such, revealing the interaction between microplastics and DRGs is of key significance for studying the potential ecological risks they pose and strengthening environmental governance.

Although studies have shown that low-dose disinfectants in the environment can induce bacteria to develop resistance, the mechanisms of formation and transmission risks of DRGs still need to be explained. The first step to solving the problem is to clarify the selection mechanisms of microplastics and disinfectants for microorganisms. Microplastic pollution is a global issue, as is the widespread use of disinfectants. The potential hazards resulting from the combination of these pollutants are also global. Therefore, it is necessary to explore the joint role and potential risks in the aquatic environment in a timely manner. In this paper, the pollution status of microplastics and disinfectants in the environment is thoroughly discussed, and the ways and mechanisms of microbial resistance to disinfectants are analyzed. The interaction and potential effects of microplastics and DRGs are also clarified. In addition, this study also proposes some challenges and research priorities to establish a scientific foundation for future research.

Current pollution of microplastics and DRGs in the environment

Although plastics are not easily degradable in the environment, they would be gradually decomposed into microplastics under the continuous action of external forces (Auta et al. 2017). Microplastics in water environment mainly come from the aging decomposition of plastic wastes and the discharge of effluent of sewage treatment plants (Pivokonsky et al. 2018). Rivers are the primary transporters of microplastics, while lakes serve as repositories for microplastics. Microplastics in the effluent mainly exist in the form of fiber and debris, and biofilm often exists on the surface. The biofilm makes the environmental behavior of microplastics uncontrollable. Rough surfaces and large surface areas are often important carriers of various pollutants in the environment.

Disinfectants play a vital role in ensuring life safety and ecological health. They are widely used in various aspects of daily life, including medical treatment, agriculture, and water treatment (Tong et al. 2021b). Problematically, unfortunately, the abuse of disinfectants and the lack of scientific management have unfortunately led to the diffusion of DRGs in the environment (Kim et al. 2018). DRGs are functional genes that enable microorganisms to develop resistance to disinfectants. It plays a crucial role in strengthening the stability and integrity of the cell membrane. Additionally, it promotes the efflux of disinfectants, alters the binding sites, and secretes functional enzymes. These mechanisms enhance the resistance of microorganisms to environmental pressure. The emergence of resistance to disinfectants is considered to be the natural evolutionary response of microorganisms to environmental pressure. However, the excessive and unjustified use of disinfectants is the primary cause of the increase in DRB in the environment, particularly since the onset of the global COVID-19 pandemic. The long-term existence of microplastics in the environment and the widespread use of disposable plastic products have led to a significant increase in the number of microplastic particles in the ecosystem, which has now posed potential threats to public health and the ecological environment (Cazares et al. 2020). Zhang et al. (2020) found that the abundance of DRGs in greenhouse soil significantly increased due to long-term substantial application of fungicides. Moreover, chlorine-resistant bacteria pose a huge challenge to the safety of treated water. Wang et al. (2012) demonstrated the presence of chlorine-resistant bacteria in two representative chloramine water treatment disinfection pipelines. Liu et al. (2012) investigated the structure of biofilm in water supply networks in Beijing and Guangzhou, and the findings showed that *M. arupens* and *M. gordonae* were the dominant populations in the biofilm and exhibited greater chlorine resistance. Zhu et al. (2021) indicated that the propagation and diffusion rate of DRB is significantly greater than that of ordinary bacteria.

DRGs can be divided into intracellular DRGs and extracellular DRGs. The various existing forms of DRGs can result in diversity in terms of migration, diffusion, and spread modes. Extracellular DRGs are derived from the loss and transfer of microbial plasmids and the cleavage of dead cells. They can be captured and adsorbed by both the same and different microorganisms in the natural environment, enhancing the cell's resistance to environmental pressure. The removal efficiency of extracellular DRGs in water treatment is very limited, which can have a certain negative impact on the subsequent disinfection process (Guo et al. 2015). Microplastics can further increase the migration and horizontal gene exchange of extracellular DRGs, and they exhibit strong resistance to environmental pressure (Syranidou and Kalogerakis 2022). Intracellular DRGs have strong resistance due to the protection of the cell membrane, but they are more susceptible to removal during water treatment, which reduces their migration ability. Microplastics in the aquatic environment accelerate the diffusion and spread of DRB and DRGs, and can enable microorganisms to develop resistance to disinfectants. Nevertheless, limited information is available on the mechanism of disinfectant resistance, and the interaction with microplastics in the environment is rarely discussed. Therefore, it is crucial to provide a comprehensive summary of the development of DRGs and the role of microplastics in facilitating the transmission of DRGs. This will help address the issues arising from the use of disinfectants.

Formation mechanisms of microbial DRGs

Resistance of microorganisms is a genetic characteristic. Disinfectant resistance refers to the inability of microorganisms to be effectively inhibited by the normal concentration and duration of action. Generally, resistance primarily arises from internal resistance and external input (Zhang et al. 2022a). Internal resistance refers to the inherent genes present in the microbial genome, which confer resistance through transcription and translation or random mutation induced by the environment (Li et al. 2022). The abundance of RGs formed by microbes in the natural ecosystem is relatively low, and the key sources of RGs at present are external inputs. Microorganisms carrying DRGs enter the environment and disperse and diffuse through various environmental media. If the use of disinfectants is not standardized and a disinfectant is used for a long time, it can create favorable conditions for microorganisms to adapt (Zhang et al. 2022a). Additionally, the low concentration of disinfectants entering the environment may have an adverse impact on ecological diversity. Long-term induction can cause mutations in genes related to microbes and enhance environmental tolerance. Microorganisms can enhance their resistance to disinfectants or develop DRGs through phenotypic adaptation, gene mutation, and horizontal gene transfer. Figure 1 illustrates the formation process and mechanisms of microbial DRGs in the environment.

Phenotypic adaption

In general, disinfectants need to bind with membrane proteins on the surface of cell membranes and penetrate the cell membranes, causing the release of small molecular weight substances. The cell membrane is a crucial barrier that prevents disinfectants from entering cells. Microorganisms can reduce or limit the entry of disinfectants into cells, thereby improving their resistance by reducing the permeability of cell membranes. Modifications in the

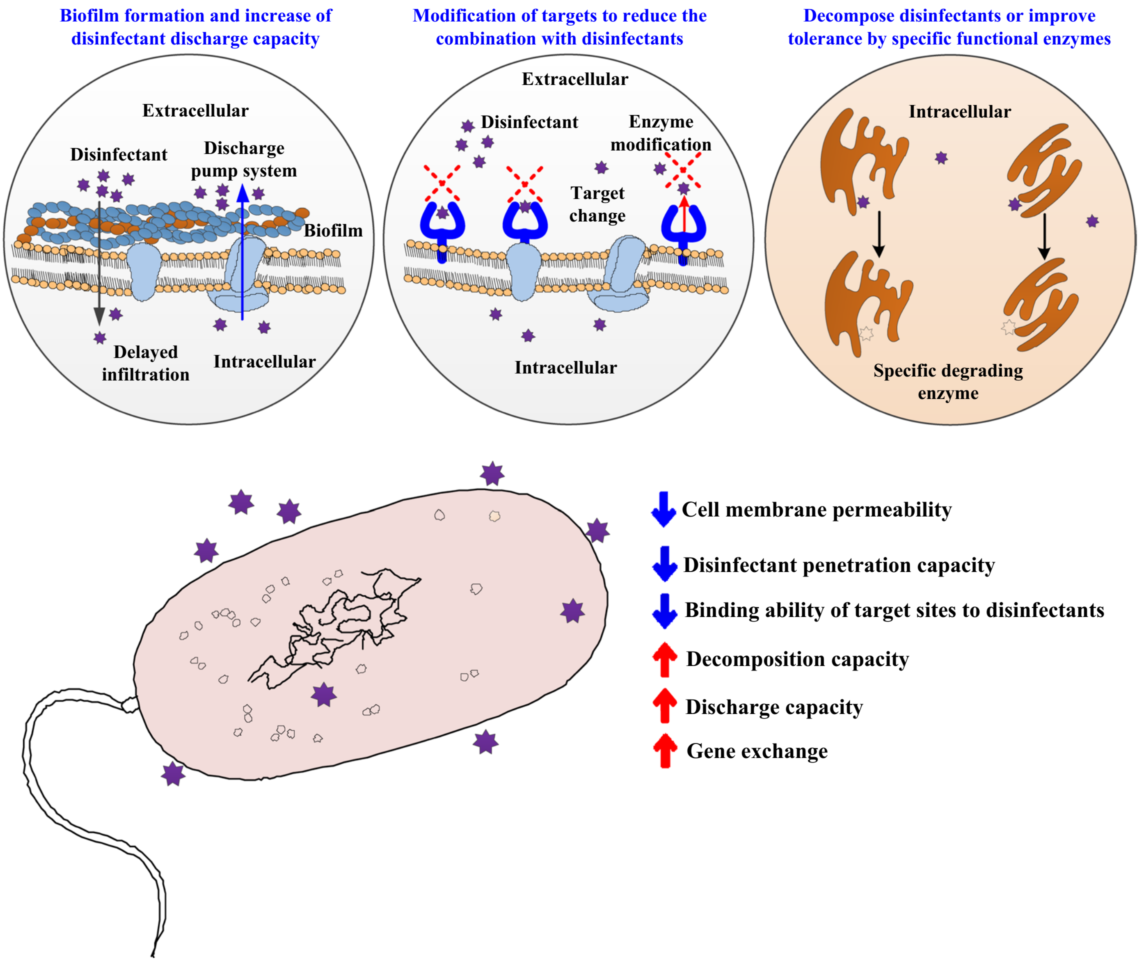


Fig. 1 Response mechanism of microorganism to disinfectant and formation process of disinfectant resistance gene

structure and composition of phospholipids, glycoproteins, and lipopolysaccharides in cell membranes can alter permeability, thereby increasing the tolerance of microorganisms to disinfectants. The phenotypic adaptation of microbes can effectively modify the cell membrane-related proteins to enhance tolerance to disinfectants. Machado et al. (2013) investigated the inactivation effect of benzalkonium chloride on *Pseudomonas aeruginosa*. The findings showed that the cells could reduce membrane fluidity and acquire resistance through the downregulation of lipoprotein and porin expression. This phenotypic adaptation can significantly reduce the exchange ability of cells with external substances (Fig. 1). The functional defect of certain membrane proteins can decrease the sensitivity of cells to disinfectants and can trigger microorganisms to develop corresponding RGs (Futoma-Kołoch et al. 2019). Vikram et al. (2014) revealed that *Pseudomonas fluorescens* can ensure the stable operation of the protein transport system and maintain the stability of the cell membrane by upregulating the transcription and expression levels of related genes. This, in turn, ensures the selective permeability of the cell membrane and prevents the entry of disinfectants.

Additionally, the efflux pump system is considered to be one of the most important resistance mechanisms of bacteria. It is a functional protein that is present in the cell membranes. Microorganisms can effectively and quickly expel the disinfectants that enter the cell through the efflux pump system (Fig. 1). A study done by Møretrø et al. (2017) has revealed that the qacH and bcrABC genes are determinants of mononuclear organisms exhibiting resistance to quaternary ammonium disinfectants. Another report has also demonstrated that the qacH gene was widely detected in mononuclear organisms with resistance to benzalkonium chloride, and some bcrABC genes were also detected (Meier et al. 2017). Hassan et al. (2015) indicated that the AceI encoding gene of the efflux pump system–related protein can induce resistance of Acinetobacter baumannii to chlorhexidine. They further reported that reserpine can effectively inhibit the efficiency of the efflux pump in resistant bacteria and restore the sensitivity of microorganisms to disinfectants.

LaBreck et al. (2020) recently demonstrated that microorganisms with multiple efflux pumps in the disinfection process exhibit greater resistance and increased tolerance to disinfectants.

Environmental induction

Microorganisms can improve their resistance to disinfectants by forming biofilms on surfaces. The combination of extracellular polymers and proteins in the biofilm can form a dense framework, which causes a series of transportation restrictions and affects the disinfection efficiency (Fig. 1). The biofilm can also react aggressively with the disinfectant molecules, reducing the effective dose in the local environment and thereby enhancing the tolerance of microorganisms. Luther et al. (2015) showed that during ethanol and isopropanol disinfection, the transcription levels of the genes icaA and icaD, which are associated with biofilm formation in Staphylococcus aureus, were significantly increased. The upregulation of these expression levels contributed to the production and secretion of cell polysaccharide adhesins. van der Veen and Abee (2010) also demonstrated that the expression of the response transcription factor hrcA and the molecular chaperone dnaK, which are related to biofilm formation and resistance during disinfection. Legner et al. (2019) found that the strength of biofilm was positively correlated with the level of microbial resistance. Additionally, microorganisms were found to be able to resist the effects of disinfectants by slowing down the rate of cell production. Vikram et al. (2015) investigated the disinfection performance of glutaraldehyde against *Pseudomonas aeruginosa* and *Pseudomonas fluorescens*; the results showed that the presence of disinfectants could induce the synthesis of polyamine and lipid biological regulators. Microplastic surfaces in the environment are often covered in biofilm, and these compounds can significantly reduce sterilization effectiveness. In addition, disinfectants containing chlorine can exacerbate the biofouling of reverse osmosis membranes during the disinfection process. Furthermore, microorganisms in biofilms that are resistant to chlorine can resist the effectiveness by intensifying membrane biofouling (Ribič et al. 2017). The presence of microplastics can greatly contribute to membrane biofouling during filtration, thus compromising disinfection effectiveness (Enfrin et al. 2021).

Moreover, microorganisms can change the target sites on the cell membrane surface or modify enzymes to decrease their interaction with disinfectants. The alterations in target sites can effectively reduce the affinity of biofilms to disinfectants and change the sensitivity of microorganisms through the expression of related enzymes (Fig. 1). Skovgaard et al. (2013) indicated that the mutation of genes related to triclosan increased the expression of the target site fabI, thereby enhancing the resistance of Staphylococcus epidermidis to disinfectants. Because there are multiple disinfectant target sites on the surface of microorganisms, there are relatively few changes or mutations induced by the environment on the surface of biofilm. In addition, the increase in the secretion of specific enzymes can effectively eliminate disinfectants in cells, reducing damage or improving tolerance (Fig. 1). Nontaleerak et al. (2020) found that *Pseudomonas* sp. can produce specific enzymes by upregulation the expression level of the gene rcsA encoding the intracellular alkyl hydroperoxidase AhpD during chlorine disinfection. Tong et al. (2021a) also found that upregulating the expression of antioxidant enzyme-related genes can change the fundamental metabolism of *Pseudomonas* sp. cells to effectively remove intracellular disinfectants containing chlorine. Furthermore, the existence of certain enzymes can confer microorganisms with resistance to various disinfectants. Liffourrena and Lucchesi (2014) suggested that *Pseudomonas putida* A could accelerate the decomposition of disinfectants and enhance resistance to quaternary ammonium disinfectants by upregulating the expression of the fad coding gene. Vikram et al. (2015) showed that the application of glutaraldehyde stimulated Pseudomonas fluorescens enhanced the synthesis of related proteases, including ClpB1 and HslU. This stimulation also resulted in increased ATP production, thereby enhancing tolerance. Gabale et al. (2020) also reported that certain gram-negative bacilli have the ability to produce specific enzymes that alter their own characteristics. These bacteria can develop resistance by modifying active sites and regulating the structure and composition of the cell membrane surface.

Horizontal gene exchange

Microbes can develop resistance to disinfectants by acquiring DRGs carried on plasmids, chromosomes, and transposons. Jin et al. (2020) have shown that the gene responsible for microbial efflux pumps primarily exists in mobile genetic elements such as plasmids, transposons, and integrons within cells. This discovery suggests that there is a potential for horizontal transfer of RGs between both the same species and different species. Mobile genetic elements are crucial carriers for microorganisms to acquire and disseminate drug resistance genes (DRGs). The transfer of these elements among microorganisms can cause the emergence of novel plasmids and genes, resulting in a range of genetic effects. Botelho et al. (2019) indicated that mobile genetic elements were a key driving factor for Pseudomonas aeruginosa to develop resistance to disinfectants during disinfection. Horizontal exchange of DRGs can also lead to the co-evolution of microorganisms, improving their adaptability and resistance to environmental pressures.

Moreover, the changes of disinfectant concentration during disinfection can also affect the exchange and transfer of DRGs among microorganisms. Lu et al. (2020) reported that exposure to triclosan at environmental concentrations increased reactive oxygen species production in microbial cells by 1.3–1.5 times. By damaging the cell membrane and upregulating the expression of genes that code for membrane proteins, the likelihood of microorganisms acquiring exogenous RGs was significantly increased. Khan et al. (2021) showed that disinfectants can facilitate the loss and transfer of plasmids carrying DRGs, thereby exacerbating the potential hazards associated with widespread disinfectant use. These DRGs can be exchanged through the loss and transfer of bacterial plasmids and are not easily eliminated from the environment. Luprano et al. (2016) demonstrated that peracetic acid disinfectant could not completely eliminate RGs in the environment. Extracellular DRGs exhibit stronger migration and diffusion abilities, making them more readily able to couple with microbial cell membranes. Additionally, microplastics are significant reservoirs of microorganisms and RGs in the aquatic environment. The biofilm on the surface of microplastics can weaken the effectiveness of disinfectants and significantly enhance the transfer and exchange of RGs among different microorganisms. There is a wide genetic diversity and multiple resistance of microbial communities in the biofilm. Abundant nutrient conditions, high-density microorganisms, and a large number of mobile genetic elements can promote the horizontal transfer of RGs.

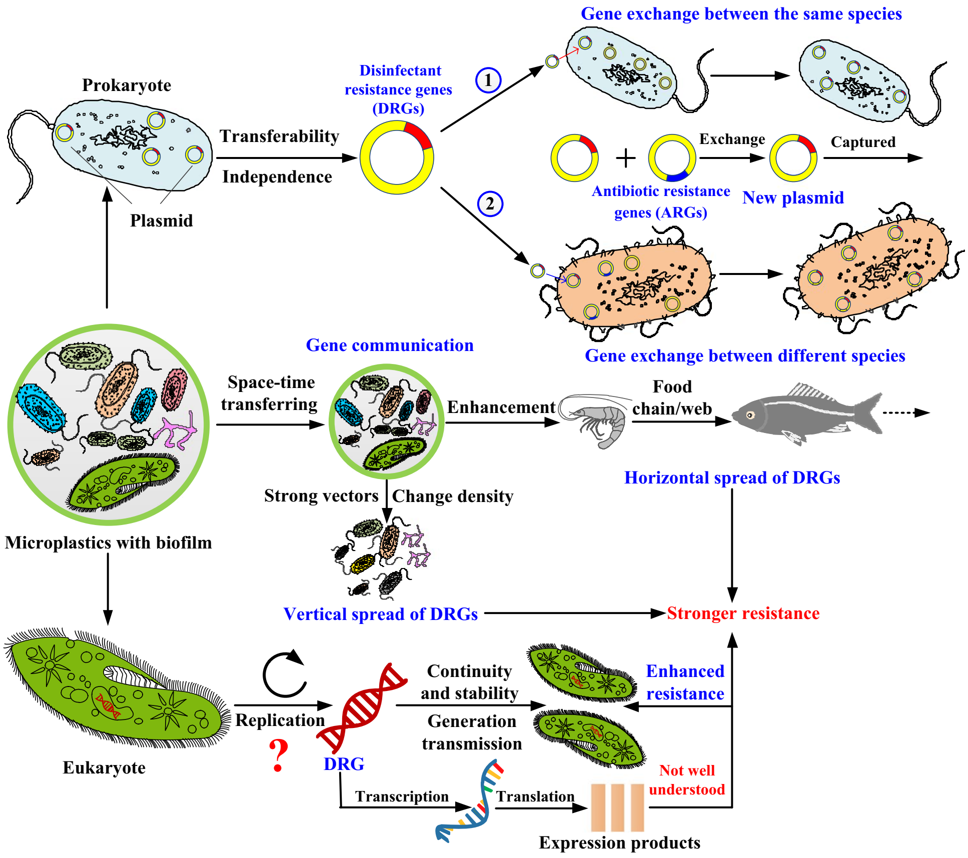
Interaction between microplastics and DRGs

Reservoirs of DRB

Microplastics can not only help microorganisms to resist environmental pressure, thus providing a relatively stable habitat (Shen et al. 2021a; Zhang et al. 2019). Microbial communities within the biofilm on microplastic surfaces include heterotrophs, autotrophs, and predators, significantly enhancing energy and information transmission within the ecosystem (Fig. 2). The formation of biofilm varies with the surrounding environment, temporal and spatial changes, and microplastic characteristics (Oberbeckmann et al. 2014). The biofilm can not only affect the environmental behavior of microplastics, but also interference with the diffusion ability of microorganisms. The migration of microplastics can cause the spread and transmission of pathogens, RB and RGs, because microplastics can carry RB in aquatic environment (Jiang et al. 2018; Liu et al. 2022; Yu et al. 2022). Some bacterial hosts of RGs are found only on microplastics, but on in the surrounding environment (Loiseau and Sorci 2022).

Actually, microplastic pollution promotes the enrichment of RB and RGs on microplastic surface. Galafassi et al. (2021) found that microplastics affect the distribution

Fig. 2 Transmission and diffusion of disinfectant resistance genes on microplastics and their interactions



and diffusion of RGs. Additionally, microorganisms living on the surface of microplastics exhibit greater resistance to environmental pressure. Yang et al. (2019) reported that the abundance of ARGs in the microplastics was 5.69 times higher than that in surrounding seawater, and the biodiversity is also higher than that in surrounding seawater. Wu et al. (2019) indicated that microplastics could act as a vector for ARGs and pathogens to enter the new environment in river water, thereby resulting in adverse impacts. Li et al. (2021) demonstrated that the abundance and diversity of ARGs on microplastics exhibit a clear spatial pattern, with higher levels observed in urban rivers, rivers around cities, and rural areas. The authors further pointed out that urbanization was also one of the potential reasons for the widespread of ARGs on microplastics.

The enrichment of microplastics in DRGs is influenced by various factors, including local disinfectant pollution, hydrological conditions, and the type of microplastics. Wu et al. (2022) found that there was a significant different in the enrichment capacity of RGs between PVC and PLA microplastics. The environmental behavior of different microplastics should be considered, even under the same conditions. Zhang et al. (2022c) also showed that the relative abundance of RGs on PET and PVC was higher compared to that on PE microplastics. Dai et al. (2020) reported that the selective capacity of RGs on microplastics in freshwater was far greater than in seawater, especially for pathogens and various RB, which may increase the risks to ecosystems and human health.

Key place for DRG exchange

The composition of microbial communities in biofilm on microplastics is complex. A large number of microorganisms can have intense gene exchange, such as plasmid loss and capture, phage transduction, and cell fusion. Microplastics can facilitate gene exchange among microorganisms. According to the location of DRGs, they can be divided into two categories: plasmid mediated and chromosome mediated (Fig. 2). Plasmid-mediated DRGs can increase the number of RB through horizontal gene transfer, and can also facilitate the diffusion of DRGs through vertical transmission. Li et al. (2017) found that qacF resistance gene and blaCTX-M-15 gene could be to transferred in *Escherichia coli* cells. Partridge et al. (2018) proposed that horizontal exchange of resistance genes (RG) among species contributes to rapid spread, and horizontal exchange of RG mediated by plasmids was an important driving force for the emergence and diffusion of new RB and RG. DRGs can be transferred to another plasmid and cell through plasmid loss and capture (Fig. 2). Carlie et al. (2020) have revealed that DRGs can move between different integrons and maintain long-term effectiveness. The integrons can be captured by microorganisms again, and the DRGs can be transferred to the receptor. Moreover, mutations, insertions, and deletions of chromosome genes may cause corresponding resistance in microorganisms. The chromosome mediated DRGs can be inherited to the next generation through microbial reproduction, and can also produce resistance to disinfectants by the upregulation of related gene expression (Fig. 2). YdgE and ydgF coding genes are common DRGs mediated by chromosomes, which are located on a pair of homologous chromosomes (Tong et al. 2021b). Jiang et al. (2016) found that monocytosis bacteria can enhance their tolerance to benzalkonium chloride via the upregulation of chromosome mediated efflux pump DRG expression, and obtain related resistance.

Wang et al. (2020) found that RGs can enhance the susceptibility to bacterial colonization during direct contact with microplastics. Qian et al. (2021) indicated that microplastics produce free radicals during weathering, which negatively impact the production of microorganisms. These free radicals also accelerate the destruction of bacterial cell membranes and the release of DNA, and promote the diffusion of DRGs. Arias-Andres et al. (2018) reported that the rate of DNA transfer in biofilm on microplastics was much higher than that of free microorganisms. Eckert et al. (2018) showed that the levels of functional enzymes associated with microplastics increased as the concentration of microplastics increased. However, there was no significant increase observed in the surrounding waters. The exchange and transfer of DRGs on microplastic surface is an interactive and complex process, and its mechanism and influencing factors still need to be further studied. As microplastics are organic particles discharged from areas of human activity, they can carry pathogenic bacteria that contain a variety of pathogenic genes. These genes have the potential to spread through water flow via gene transformation, transduction, and other mechanisms, leading to the emergence of pathogenic outbreaks.

Vector to accelerate transmission and spread of DRGs

Microplastics can provide a stable living space and nutrients for microorganisms (Shen et al. 2019b). Due to the strong migration ability of microplastics, biofilm can move horizontally and vertically over long distances in the aquatic environment, along with the microplastics (Fig. 2). This migration can accelerate the spread and diffusion of microplastic surface RGs and RB. Evidence showed that microplastics could be transported to remote regions or even polar areas through the action of ocean currents or precipitation (Bergmann et al. 2019; Mishra et al. 2021; Rota et al. 2022; Zhang et al. 2022d). The aggregation of microplastics may induce gene exchange among microorganisms, resulting in the uncontrollable transmission of different RGs and the large-scale outbreak of multidrug-resistant bacteria. Particularly, with the migration of microplastics, there may be an ecological risk that a large number of invasive species may invade new habitats and alter the local biodiversity.

In addition, the vertical movement of microplastics can have an adverse impact on the structure and composition of microbial communities in deep water and sediments. It can also promote the transfer of DRGs (Galgani et al. 2022; Laju et al. 2022; Niu et al. 2021). As the density of seawater increases with depth, sunken microplastics may remain suspended at different depths. Most microplastics would slowly sink and eventually reach the sediment. The sedimentation process of microplastics alters the composition and structure of microorganisms in the biofilm. The enrichment of microorganisms on the surface of microplastics promotes the formation of biofilms, which also changes the density and hydrophobicity of microplastics during this process (Shen et al. 2023a; Shen et al. 2019b). The microbial community and structure indicated by microplastics will undergo changes. Surface microorganisms on the water body will gradually enter the deep-water zone. As microplastics settle, microorganisms in the deep-water zone gradually replace them to alter the composition and structure of microorganisms in the biofilm. Current movement or erosion may cause microplastics to resurface in the water. Such redistribution has a significant impact on microbes at different depths of the water column. Sediment plays a vital role in regulating aquatic habitats. Therefore, it is crucial to understand the ecological role of microplastics in order to investigate the impact of vertical migration of microplastics on microbial communities in sediment, as well as the diffusion and transmission of DRGs.

Overall, the excessive use of disinfectants greatly increases the formation of DRGs in the environment, and the presence of microplastics once again increases the risk of transfer and spread of DRGs and DRB. However, there is currently a lack of research on the potential ecological effects of microplastics and DRGs. How to effectively remove microplastics and DRGs and evaluate the ecological risks of their complexes to the environment is a key issue that urgently needs to be addressed. Studying the mechanism and contribution of microplastics in the transfer and diffusion of d DRGs is a prerequisite for solving the problem. In addition, in the future, efforts should be made to strengthen the research on the transfer of resistance levels of plasmid, which is an important carrier for the transmission of disinfectant resistance through microplastics.

The relationship between DRGs and other RGs

Antibiotic resistance of microorganisms has attracted worldwide attention. ARB and ARGs have been identified in water (Jiang et al. 2022), sewage treatment plants (Wang and Chen 2022), and other sources (Zhang et al. 2022b). Disinfectants and antibiotics both belong to chemical substances with special bacteriostatic effects, and there is a certain correlation between DRGs and ARGs. Figure 3 illustrates the correlation between DRGs and disinfectants, microorganisms, environmental factors, and other RGs. Amsalu et al. (2020) conducted a study on the resistance of *Pseudomonas aeruginosa* to disinfectants and antibiotics in various environments. The findings revealed that the bacterium exhibited a certain level of resistance to both disinfectants and antibiotics. The authors further suggested that the upregulation of MexAB OprM efflux pump encoding gene and regulating gene mexR, nalC or nalD expression caused by corresponding amino acid mutation was the main reason for *Pseudomonas aeruginosa* to have two kinds of resistance at the same time.

Besides, RB induced by exposure to disinfectants can also enable bacteria to withstand certain concentrations of antibiotics and even facilitate the emergence and dissemination of ARGs. Thorrold et al. (2007) reported that treatment with chlorine containing disinfectants made *Salmonella* and *Escherichia coli* obtain resistance to tetracyclines and fluoroquinolones. Disinfection by-products can also induce microorganisms to form antibiotic resistance, causing the spread of ARGs in the microbial community. Jin et al. (2020) found that by-products can promote the horizontal transfer of bacterial plasmids, leading to the diffusion of RGs and the formation of new RGs during water disinfection. The authors further pointed out that some non-resistance bacteria could be induced into RB, and the RGs were hardly to be removed. Lv et al. (2014) demonstrated that four typical disinfection by-products could induce Pseudomonas aeruginosa to develop resistance to a variety of antibiotics, and the multi resistance has also been improved.

In addition, pollutants can promote the formation of multiple resistance genes through co-selection mechanism in the environment. The coexistence of metals, disinfectants, and antibiotics on microplastics has brought server environmental pressure to microbes, resulting in the generation and spread of multi resistance bacteria through co-selection (Imran et al. 2019; Ye et al. 2017). Romero et al. (2017) have confirmed that bacteria isolated from seafood produce multiple resistance to metals, antibiotics, and pesticides through co-selection mechanism. Mixed pollutants adsorbed onto microplastics create favorable conditions for co-selection, particularly in landfill leachate. Su et al. (2021) showed that free DNA in leachate is a significant source of RGs on microplastics. Problematically, there are still knowledge gaps in the study of co-selection effects, and related mechanisms are still being explored. Therefore, it is required to further discuss the correlation between DRGs and other RGs in detail. It is important to clarify the co-selection mechanism and transmission route in the context of mixed pollution environments.

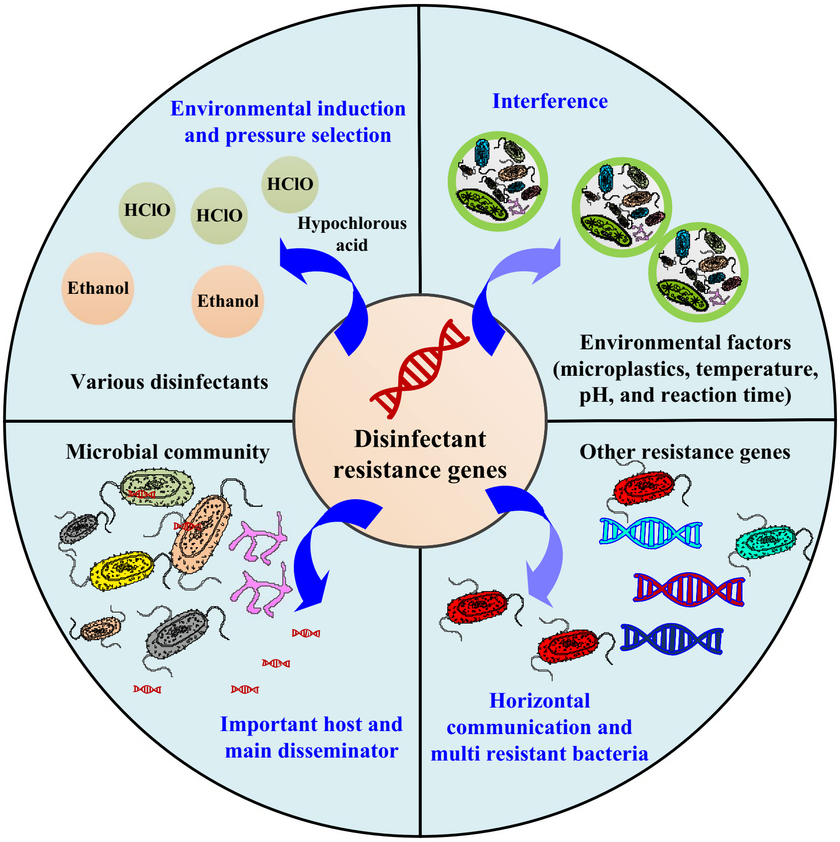


Fig. 3 Correlation characteristics between disinfectant resistance genes and disinfectants, microorganisms, environmental factors, and other resistance genes

Potential threats of microplastics, disinfectants, and DRGs

Potential threats to the ecological environment

Microplastics are important carriers of microorganisms and plankton in the environment. They play a vital role in energy and information transmission, as well as material circulation in the ecosystem (Fig. 4). Research indicated that microplastics could accelerate the transfer of RGs and affect the evolution of microbial communities (Lu et al. 2019; Yu et al. 2023). With the increasing prevalence of microplastics and the pollution of resistance genes, their interactions will become more complex. Dong et al. (2021) showed that the increase in microplastic concentration promoted the exchange frequency between RGs and RB. The existence of multidrug-resistant bacteria will lead to the use of stronger disinfectants and antibiotics, thus creating a vicious cycle (Zhang et al. 2020). These changes, in turn, have a negative impact on all levels of the ecosystem, causing changes in the food chain and potentially leading to ecological imbalance.

In addition, microplastics can migrate downward to deep water bodies or sediment environments (Fig. 4). Continuous movement of sinking and floating microplastics may continuously release resistance genes (RGs) into diverse water bodies. Microplastics can impact the composition, structure, and diversity of microbial communities in the sediment environment, especially in the case of biodegradable plastics. The contact and communication between microorganisms are stronger than those in the suspended state in the environment. The migration of microplastics in various environmental media promotes gene exchange between RGs and RB and environmental microorganisms. The transmission effect can occur on a wide range of space-time scales.

Moreover, the active chlorine in the water environment can destroy the enzyme activity of phytoplankton cells, which hinders their ability to absorb nitrogen. This, in turn, affects the reproductive capacity of phytoplankton (Saetae et al. 2014). Although phytoplankton has a strong potential for recovery and can quickly respond to residual chlorine stress damage, its recovery leads to significant changes in the community structure (Fig. 4). The disruption of phytoplankton productivity may cause a scarcity of food for organisms that depend on photosynthesis, either directly or indirectly, for energy. In severe cases, it can impact the growth, reproductive capacity, or overall survival of different organisms in regions with limited productivity. Therefore, the extensive use of disinfectants not only has an adverse impact on individual aquatic species but also has the potential to significantly affect the community structure and ecological succession. This, in turn, can disrupt the material cycle and ultimately damage the balance of the aquatic ecosystem.

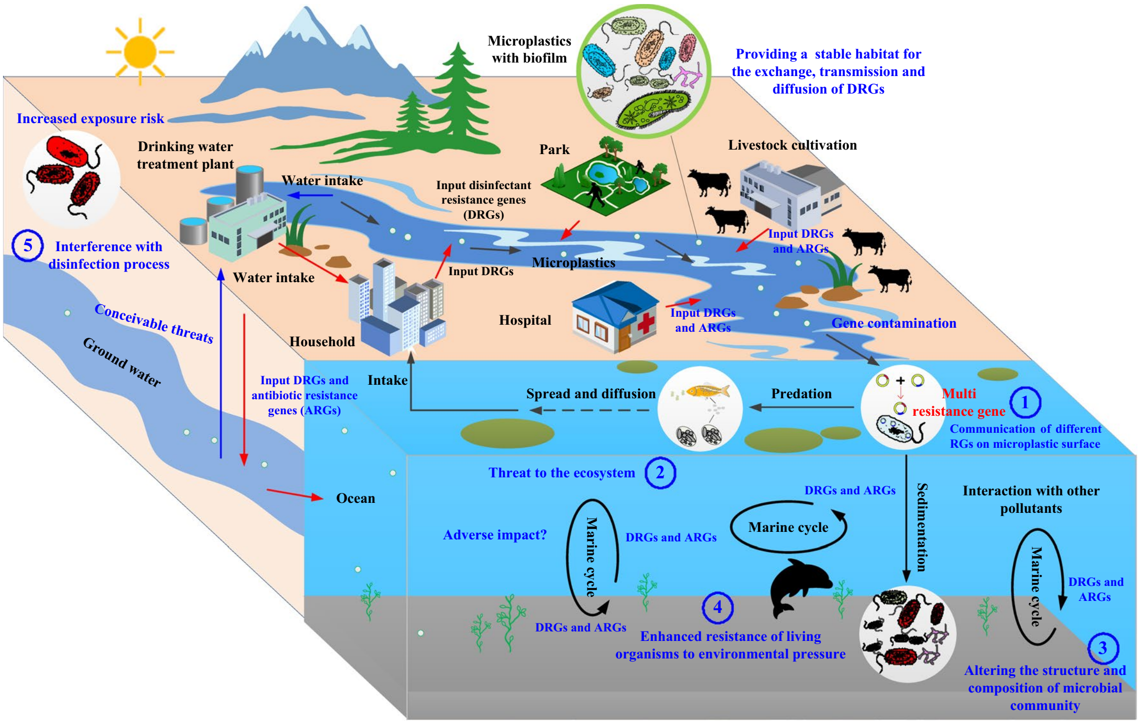


Fig. 4 Interaction between disinfectant resistance gene and microplastics and its potential impact and threats on ecosystem

Interference with water disinfection process

Chlorination and UV disinfection are the most widely used methods of disinfection, commonly employed in the treatment of drinking water and sewage. Unfortunately, however, microplastics and DRGs pose serious challenges to the disinfection process. Shen et al. (2021b) showed that microplastics can have a significant impact on the disinfection process and serve as a secure and stable attachment matrix for bacteria. Shi et al. (2013) found that chlorine disinfection can not only change the microbial community but also concentrate RGs and the mobile genetic elements involved in RG transfer. Munir et al. (2011) indicated that chlorine disinfection had a very limited effect on RB and RGs in water, and the abundance of RGs in water did not significantly decrease. Xu et al. (2016) showed that there were still residual amounts of RGs in the effluent treated by the water supply plant. Furthermore, RGs were also detected even after the implementation of activated carbon filtration. In addition, low doses of chlorine are generally maintained in the tap water supply to inhibit the growth of microorganisms. However, the presence of chlorine can facilitate the detachment of RB from the biofilm in the supply pipe, leading to the release of RGs into the effluent.

Unlike chlorine disinfection, UV disinfection has the potential to effectively inactivate RGs. Ultraviolet radiation can destroy the transformation ability of RGs in DNA, thus reducing the risk of horizontal transfer. McKinney and Pruden (2012) demonstrated that UV radiation can indeed reduce the abundance of RGs in drinking water, but the UV dose required for this reduction is much higher than that used for water disinfection. Microorganism death, as reported by Tan et al. (2019), leads to simultaneous re-release of RGs. The free RGs are actively absorbed by other bacteria, thus creating new risks.

In addition, the complex water supply pipeline network allows for the formation of biofilm by microorganisms on the pipe wall. The presence of RB in the biofilm facilitates the transmission of RGs. RGs can spread among different bacteria, leading to an increase in RGs in the effluent and posing a significant threat to human health. However, research on the horizontal communication of RGs and the transmission of RB in water supply systems is still in its infancy. How to effectively remove RGs in a water treatment system is a key problem that needs to be urgently addressed. It is necessary to clarify the process and mechanism of how DRGs influence the disinfection process to effectively address any potential impact.

Potential threats to human health

Microplastics, DRGs and pathogenic bacteria have been detected in various aquatic products. Continuous pollution and contamination result in significant food and health safety issues, ultimately impacting human health (Imran et al. 2019). Long-term contact of gastrointestinal flora with RB can lead to the transfer of RGs to human pathogens through binding. The zoonotic pathogens carrying RGs can be indirectly transmitted to human and animal hosts through direct contact or foodborne infection. Pollutants and RB released from the microplastic surface may contribute to intestinal oxidative stress, particularly in patients with digestive tract diseases (Shen et al. 2019a).

In addition, drinking water is also an important source of human RGs and RB. The concentration of microorganisms and RGs in tap water at the end of the household is higher than that in highly treated drinking water. However, at this stage, the assessment of the ecological impact of microplastics and DRGs and the potential risks to human health are very limited, and the basis for DRGs and dose response curve and the exposure assessment method has not yet been formed. Without timely intervention, medical treatment may face significant challenges. In addition, if the pathogen becomes resistant to disinfectants, foodborne diseases can continue to spread, posing a serious threat to life and health. It has become a global strategic issue to prevent the emergence of highly resistant strains and disinfectant resistance. Although research on the horizontal transfer of DRGs is very limited, it may be an important factor contributing to the growth of DRB.

Challenges and perspectives

With the increasing pollution of microplastics and disinfectants, the global concern has shifted towards the co-transmission and diffusion of microplastics and DRB. Microplastics can accelerate the acquisition of drug resistance genes (DRGs) by microorganisms and enhance their tolerance to environmental pressures. However, due to limited research and reports on the formation process, transmission path, and interaction between microplastics and DRGs, the relevant mechanisms are still unclear. It is crucial to summarize the formation and transmission of DRGs. It has become a global consensus to guard against the emergence of multiresistant bacteria. In addition, it is urgent to study reduction and control strategies in order to effectively eliminate the ecological threats caused by the co-diffusion and migration of microplastics and DRGs. Targeted selection of treatment processes and technologies that can effectively reduce resistance genes, along with comprehensive source control and efficient end treatment, are crucial measures to address environmental pollution caused by DRGs. Therefore, in order to obtain more information about the interaction between microplastics and disinfectants, the research should focus on the following four aspects:

Interaction of microplastics and disinfectants in the environment

The key to solving the problem is to understand the interaction between microplastics and DRGs. Disinfectant resistance depends on various environmental factors, exposure time, the bacterial attachment environment, and the cultural state. The existing research mainly focuses on the interaction between microplastics and ARGs in the environment, while the research on DRGs is still very limited. With the intensification of global microplastic pollution and the increasing use of disinfectants, especially since the outbreak of the global epidemic, the potential risks have become more apparent. Therefore, it is necessary to investigate the mechanism behind the coexistence of microplastics and disinfectants in the formation of DRGs, as well as the impact of microplastic migration on diffusion and transmission. The study on the interaction between microplastics and ARGs can provide a solid foundation. In addition, current research on resistance primarily relies on short-term theoretical experiments. However, studying the effects of long-term exposure to low concentrations of disinfectants and microplastics on the formation and horizontal transfer of DRGs is more beneficial in understanding their potential impact.

Effects of microplastic and DRGs on the sewage treatment process

Strong oxidizing disinfectants can react with reducing organic and inorganic substances in sewage, resulting in a decrease in the chemical oxygen demand of influent water. The high content of disinfectant in the influent has an impact on the activity of the wastewater biological treatment system, especially the biological treatment system with weak impact load resistance. In addition, DRGs diffuse in the treatment process with the migration of microplastics. The diffusion of disinfectant resistance genes may lead to changes in the microbial community and abundance in activated sludge, thereby affecting the effectiveness of sewage treatment. Disinfectants can lead to an increase in disinfection by-products in sewage, the formation of dissolved, and hard-to-biodegrade organics, and can affect the quality of effluent and the ecological security of receiving water. Disinfection by-products can also induce microorganisms to produce corresponding RGs, but research in this area is limited. Sewage treatment plants are also key sites for removing DRGs. Upgrading the existing treatment process to effectively remove DRGs is needed.

Effects of microplastics and DRGs on water disinfection

Microplastics and DRGs pose serious challenges to the water treatment and disinfection process. Unfortunately, limited information is available in this area. Therefore, it is necessary to study the interference process and mechanism of DRGs and microplastics on the disinfection process. The key to solving the problem of DRGs in tap water is to understand the diffusion and horizontal transfer mechanisms of DRGs in the water supply network. In addition, it is worth exploring to effectively remove RB and RGs in water before disinfection and develop new disinfectants or substitutes. The existence of microplastics in the water has raised concerns about the removal of DRGs. The removal of DRGs, especially free DRGs, and DRB while removing microplastics is a key link to solve the problem of interference in the disinfection process.

Control and reduction measures of DRGs

The most direct method is to control or inhibit the production of DRB and DRGs at the source. The resistance of microorganisms to disinfectants is usually related to increased environmental pressure on their living conditions. Controlling or regulating the use of disinfectants is helpful to reduce DRB with weak adaptability. Strictly regulating the use of disinfectants is key to blocking the spread of DRGs. Formulating monitoring standards for DRGs is an effective measure to address the threats. The traditional activated sludge process can largely remove microplastics, but it is difficult to reduce the RGs, especially the free RGs. The reduction of free RGs is the most important step in water treatment. Advanced oxidation process has great advantages in removing organic pollutants and RGs, such as environmentally friendly and efficient removal. Therefore, it is an urgent problem to explore a coupling process to remove microplastics and DRGs at the same time, which is an important link to reduce RB and RGs trying to enter the environment through microplastics.

Conclusions

Microplastic pollution and excessive use of disinfectants increase the environmental resilience of microorganisms. Biofilm promotes the horizontal exchange and transfer of DRGs, leading to the diffusion of DRGs and the formation of multi resistant bacteria. However, the research on the interaction between microplastics and DRGs is still very limited. The proliferation of microplastic pollution and the rise in disinfectant consumption are expected to be significant factors driving the growth of resistant bacteria. The existence of DRGs also seriously interfere with the water disinfection process, which eventually threaten human health. The global COVID-19 pandemic continues, and the use of disposable plastics and disinfectants also continues to increase. Significantly, while controlling the spread of the epidemic, the basic goal is to minimize the microplastic pollution and the transmission of DRGs. There is still a huge knowledge gap in this regard. Microplastics and DRG pollution bring us more questions than answers, and these issues require our attention and solutions. The scale and scope of the potential risks are uncertain. It is necessary to reveal the formation of DRGs, clarify the relationship between microplastics and DRGs, and develop an integrated process for the efficient removal of microplastics and RGs.

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