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Microplastic-affected pathogens in drinking water supply systems: Survival mechanisms, ecological impacts and control challenges

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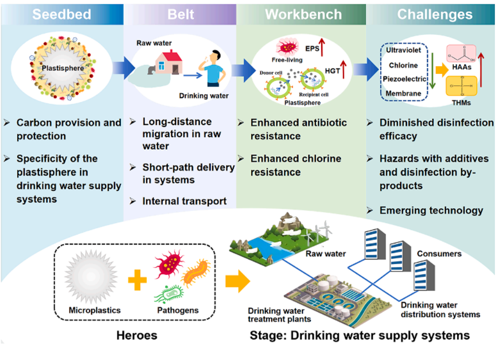
HIGHLIGHTS

- Microplastics promote the growth of pathogens under drinking water supply systems.
- Microplastics act as vectors enabling rapid "source-to-human" pathogen transmission.
- Microplastic exposure enhances pathogen antibiotic and chlorine resistance.
- Microplastics compromise disinfection efficiency and cause secondary risks in drinking water supply systems.
- Integrated pretreatment interception and secondary risk reduction strategies are proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastics (MPs), as emerging pollutants, can affect pathogens, primarily opportunistic pathogens (OPs), and influence their behavior in aquatic environments. However, evidences regarding their impacts in drinking water supply systems (DWSSs) remain scarce. Focusing on the safety of DWSSs, this review synthesizes how MPs affect pathogen proliferation, transport, and resistance development under typical DWSS conditions characterized by low nutrients, high flow rates, oxidative stress, and user demand. MPs can distinctly promote the growth and reproduction of pathogens, act as mobile carriers enabling cross-watershed transport, and facilitate direct migration from source water to humans, thereby increasing health risks. Furthermore, MPs enhance pathogen resistance at both individual and community levels, thereby complicating subsequent control efforts. This study

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further summarizes how MPs compromise existing pathogen control measures in DWSSs and introduce secondary risks, including MP additives and the disinfection by-products from MPs. Finally, a strategy integrating “pre-treatment interception” and “secondary risk reduction” is proposed to control MP-affected pathogens in DWSSs. The review provides valuable insights into mitigating pathogen risks associated with MPs in DWSSs, addressing a significant knowledge gap in safeguarding water security.

1. Introduction

Microplastics (MPs), defined as plastic particles smaller than 5 mm, originate primarily from synthetic resin (Beiras et al., 2021), rubber (Ziajahromi et al., 2023), and fiber particles (Zhang et al., 2022). They have now been detected across diverse environmental compartments, ranging from cellular matrices to entire ecosystems (Danopoulos et al., 2022; Luo et al., 2024; Thompson et al., 2024; Zhao et al., 2025). Previous studies have demonstrated that the primary hazards of MPs stemmed from their direct and indirect toxic effects (Keawchouy et al., 2022). Direct toxicity is attributed to their low-molecular-weight compounds (Zhang et al., 2023b), leaching of additives (Paluselli et al., 2018; Pasanen et al., 2023), and transformation by-products (Peng et al., 2024), which can interfere with endocrine systems (Pasanen et al., 2023), ovarian toxicity (Peng et al., 2024), neurotoxicity (Zhang et al., 2023b), and carcinogenicity (Paluselli et al., 2018). To indirect toxicity, MPs act as vectors for heavy metals (Cao et al., 2021), antibiotics (Stapleton et al., 2023), and pathogens (Bowley et al., 2021) through partitioning and surface sorption (Salawu et al., 2024; Wang et al., 2020). These contaminant-laden MPs persist in aquatic systems for extended periods, migrating with water currents while releasing associated contaminants. During this process, both the released contaminants and leached additives from MPs jointly contribute to composite pollution (Barhoumi et al., 2023; Rai et al., 2022). Such indirect toxicity amplifies environmental and public health risks associated with MPs, warranting focused investigation.

Pathogens, particularly opportunistic pathogens (OPs), represent another key risk factor in aquatic environments. They are widespread in the aquatic environment and cause a wide range of waterborne diseases (Hu et al., 2023; Sheikh et al., 2023; Su et al., 2024b; Wan et al., 2023). More concerning is that certain pathogens are particularly difficult to eradicate (Meade et al., 2021). According to the World Health Organization (WHO), resistance to ciprofloxacin in waterborne *Escherichia coli* (*E. coli*) and *Klebsiella pneumoniae* ranges from 8.4–92.9% and 4.1–79.4%, respectively (World Health, 2023a). Simultaneously, an average of 90% of microorganisms reside in biofilm matrices (Flemming et al., 2019; Oliveira et al., 2024). This protective biofilm architecture confers enhanced resistance, making the eradication of pathogens substantially more challenging (Wan et al., 2024). Current studies have demonstrated that the presence of MPs influences pathogens in aquatic environments, accelerating the emergence of specific species (e.g., antibiotic-resistant) and distinct phenotypic states (e.g., biofilms) of pathogens. Such interactions pose potential risks to environmental and public health security (Li et al., 2024a).

Drinking water supply systems (DWSSs) serve as the critical link between natural water sources to human consumption. They encompass three major components: raw water, drinking water treatment plants (DWTPs), and drinking water distribution systems (DWDSs), which deliver safe drinking water to customers (Chavarria et al., 2023). MPs are inevitably present in DWSSs. They may originate from contamination in raw water (Xu et al., 2024b), detachment from plastic pipelines (Xu et al., 2019), and shedding of membrane materials during filtrations (Ding et al., 2021). Previous reviews have primarily addressed the effects of MPs on the community structure and properties of pathogens in natural environments (Feng et al., 2025; Liu et al., 2025c; Ni et al., 2025). However, insufficient attention has been paid to alterations in the characteristics of MP-affected pathogens and their subsequent control in DWSSs. Although DWSSs generally exhibit low nutrient availability, Chen et al. (2021) demonstrated that under nutrient-limited conditions, OPs, including *Afipia, Curvibacter*, and *Helicobacter*, can utilize nutrients derived from MPs to sustain growth, potentially increasing pathogen dependence on MPs in DWSSs and amplifying MP-mediated pathogen risks. Furthermore, given the direct interface between raw water and end users, even low pathogen loads can translate into threats to public health (Liu et al., 2026). Therefore, there is an urgent need to systematically synthesize existing knowledge and further investigate MP-affected pathogens in DWSSs.

This review is organized into six sections to comprehensively elucidate the multifaceted effects of MPs on pathogens in DWSSs and to suggest future research directions. It summarizes the occurrence of MPs and pathogens in these systems (Section 2), systematically analyzes the impacts of MPs on pathogen colonization (Section 3), transport (Section 4), and resistance (Section 5), and highlights the associated challenges for treatment processes as well as potential control and mitigation strategies (Section 6).

2. Setting the stage: microplastics and pathogens in drinking water supply systems

2.1. Sources, distribution, and removal limitations of microplastics in drinking water supply systems

According to the projections, plastic waste entering aquatic ecosystems will reach 23–37 million tons by 2040 (Liu et al., 2025c). They are subsequently fragmented into secondary MPs by natural factors and the abundance is more difficult to quantify (Tong et al., 2022). Some of them may enter the raw water. Numerous studies have detected MPs in surface waters and even in groundwater (Table 1). Meanwhile, the increasing utilization of plastic pipes, fittings, and protective coatings (e.g., epoxy resins, and polyurethanes) in DWDSs has introduced MPs into networks (An et al., 2024). Secondary disinfection, end-user hot water demand, and sharp temperature fluctuations associated with external environments in high-latitude and high-altitude regions can promote crack initiation and propagation in plastic pipes, thereby accelerating the release of MPs (Yang et al., 2024). Yang et al. (2023) detected MPs in treated water (1.81×10^3 particles/m^3) and in tap water ($1.74–20.88 \times 10^3$ particles/m^3), indicating that transit through DWDSs may lead to an increase in MP levels. Sheng et al. (2025) demonstrated that polyvinyl chloride (PVC) pipes exposed to a residual chlorine concentration of 1.5 mg/L for 15 days released 1.14×10^8 particles/m^3 MPs. The widespread occurrence of MPs throughout DWSSs, from raw water to tap water, poses an emerging threat to drinking water security.

Unlike studies of vertical distribution in marine environments, analysis of DWSSs focuses on horizontal distribution and variations across treatment stages. The spatial distribution of MPs in raw water exhibits distinct patterns: surface water > groundwater (Shu et al., 2023), coastal areas > open areas (Sun et al., 2021), and urban areas > rural areas (Kunz et al., 2023). In terms of temporal distribution, Huang et al. (2021b) found higher MP abundance in autumn and winter than in spring and summer. Fan et al. (2022) observed more MPs during the rainy season. Jung et al. (2022), however, observed fewer MPs in *Busan* raw water during the rainy months. This opposite phenomenon is mainly due to precipitation and water velocity (Talbot et al., 2022). In DWSSs, larger MPs may deposit in the pipe network, providing substrates for microbial colonization, and smaller MPs persist in a free-floating state, potentially interfering with the overall system and entering the point of

Table 1
Abundance of microplastics in raw water in different areas.

Area	MP abundance (particles/m^3)	Type of raw water	Ref.
Three Gorges, China	1597–12,611	Reservoir	(Di and Wang, 2018)
Danjiangkou, China	530–24,798		(Lin et al., 2021)
Ubolratana Reservoir, Thailand	25–3360		(Kasamesiri et al., 2023)
Jinxing Reservoir, China	9,700		(Zhou et al., 2023)
Southern Brazil	330,200	River water	(Ferraz et al., 2020)
Catalonia, Spain	500–14,200		(Dalmau-Soler et al., 2021)
Bangladesh	4600–35,810		(Islam et al., 2023)
Saudi Arabia	1900–4700		(Almaiman et al., 2021)
North America	20,000	Ground water	(Ferraz et al., 2020)
German	40,000		
Bangkok, Thailand	400–2400		(Ounjai et al., 2022)
Geneva, Switzerland	22.7–53.7	Lake water	(Negrete Velasco et al., 2023)
South Korea	900–3500	River and lake	(Taghipour et al., 2023)
Tibetan Plateau, China	287,370–391,070	Gacial meltwater	(Wang et al., 2023b)
England and Wales	200–113,000	Surface water	(Ferraz et al., 2020)
Hong Kong, China	2015–2346		(Lam et al., 2020)

Table 2
Abundance of microplastics after treatment in drinking water supply systems.

Area	MP type	MP concentration in treated water (particles/m^3)	Size (μm)	Ref.
Czech Republic	PET, PP, and PE	2.43–6.84 × 10^5	1–10	(Pivokonsky et al., 2018)
India	PET and PE	2.75 × 10^3	< 100	(Sarkar et al., 2021)
China	PEST, PS, and nylon	1.323 × 10^4	100–200	(Chu et al., 2022)
Indonesia	PE, PP, and PET	8.5–12.3 × 10^3	351–1000	(Radityaningrum et al., 2021)
Spain	PES and PP	2–10 × 10^3	200–2000	(Dalmau-Soler et al., 2021)
Thailand	PP, PE, and PET	0.24–1.00 × 10^3	< 300	(Chanpiwat et al., 2021)
Sweden	PA, PVC, PS, PE, PU, PP, PLY and PMMA	174	< 150	(Kirstein et al., 2021)
England and Wales (UK)	PS and ABS	0.11	< 25	(Johnson et al., 2020)
China	PET, PP and PE	0.86–1 × 10^3	1	(Wang et al., 2020b)
Bangladesh	PS, PET, PP and PE	50–400	< 300	(Islam et al., 2023)
Eastern China	PA, PVC, PS, PE, PP, and PET	7.3–43 × 10^5	< 2	(Han et al., 2024a)

PE = polyethylene, PP = polypropylene, PET = polyethylene terephthalate, PEST = polyester, PS = polystyrene, PVC = polyvinyl chloride, PU = polyurethane PLY = polyester, PMMA = poly(methylmethacrylate), ABS = acrylonitrile butadiene styrene.

use (Sawma et al., 2024; Yang et al., 2023).

Conventional water treatments (e.g., coagulation, sedimentation, and filtration) commonly remove MPs but have limitations (Table 2). Recent studies demonstrate that while these membranes effectively retain larger MPs, their material composition and operational stress may release submicron plastic fragments into treatment water (Maliwan et al., 2025). Sun et al. (2024b) documented elevated MP abundances in treated water ($12.33 \pm 1.53 \times 10^3$ particles/m^3) compared to raw water sources ($8.00 \pm 2.00 \times 10^3$ particles/m^3). This dual reality of MP treatment implementation and concomitant secondary pollution underscores the persisting technological gaps in DWSSs.

2.2. Occurrence, prevalence and control of pathogens in drinking water supply systems

According to reports, approximately 40 infectious diseases are transmitted through drinking water (Tulchinsky, 2018). These pathogens, predominantly OPs, enter DWSSs via contamination of source waters, biofilm development in pipelines, and water stagnation in storage tanks or at terminal taps (Donohue et al., 2015; Huang et al., 2021a; Lin et al., 2025). Although quantitatively much lower than wastewater, these pathogens can be directly ingested by human beings, posing a more direct ingestion risk. According to the WHO, as of 2022, fecal-contaminated drinking water sources affected approximately 1.7 billion people globally, contributing to an estimated 505,000 annual deaths caused by microbial contamination (World Health, 2023b).

More importantly, certain OPs have antibiotic resistance. *Klebsiella pneumoniae, Enterococci, and Pseudomonas* spp. are widely recognized antibiotic-resistant bacteria (ARB) of public health concern (Li et al., 2023). Antibiotic-resistant pathogens also have been detected in DWSSs. For instance, *E. coli* strains isolated from a drinking water source in Hangzhou exhibited tetracycline resistance (Chen et al., 2017). Meanwhile, evidence suggests that extracellular antibiotic resistance genes (ARGs) can enter pathogens via horizontal gene transfer (HGT) (von Wintersdorff et al., 2016). Research has detected a variety of ARGs in DWSSs, such as *tetA, sul1*, and *ermB*, which may lead to the emergence of more ARB and exacerbate public health risks (Hao et al., 2019).

2.3. Research status, hotspots, and evolution of microplastic-affected pathogens: A bibliometric perspective

As can be seen from Fig. 1, the source and distribution of MPs and pathogens in DWSSs are widespread. These pollutants potentially induce combined contamination that poses a synergistic threat to drinking water security, characterized by a “more-than-additive” risk.

To analyze the current research trends on MP-affected pathogens, a systematic search was conducted in the Web of Science (WOS) database using the query: TS = (“microplastic*”) AND (“pathogen* OR pathogenic* OR virus* OR fungi* OR protozoan* OR bacteria*”) AND (“water* OR aquatic*”). A total of 1776 publications were identified as of October 2025, and after excluding duplicates and low-relevance studies, 333 articles remained for analysis. The annual publication count has surged exponentially since the first study emerged in 2013, reaching a 66% growth rate by 2024, which reflects heightened scientific interest in this field (Fig. 2a). Keyword clustering analysis via *Vos viewer* revealed that current research predominantly focuses on “plastisphere”, “diversity”, “degradation”, “transport” and “antibiotic-resistance” (Fig. 2b). Overlay visualization (Fig. S1) reveals a shift in research focus from the diversity of pathogens on MPs to their antibiotic resistance over the past decade. However, when narrowing the scope to DWSSs using the refined query: TS = (“microplastic*”) AND (“pathogen* OR pathogenic* OR virus* OR fungi* OR protozoan* OR bacteria*”) AND (“water supply” OR “domestic water” OR “drinking water” OR “raw water”), only 37 studies met the require. This limitation underscores that research in DWSSs remains at an early stage, warranting further analysis and dedicated investigation.

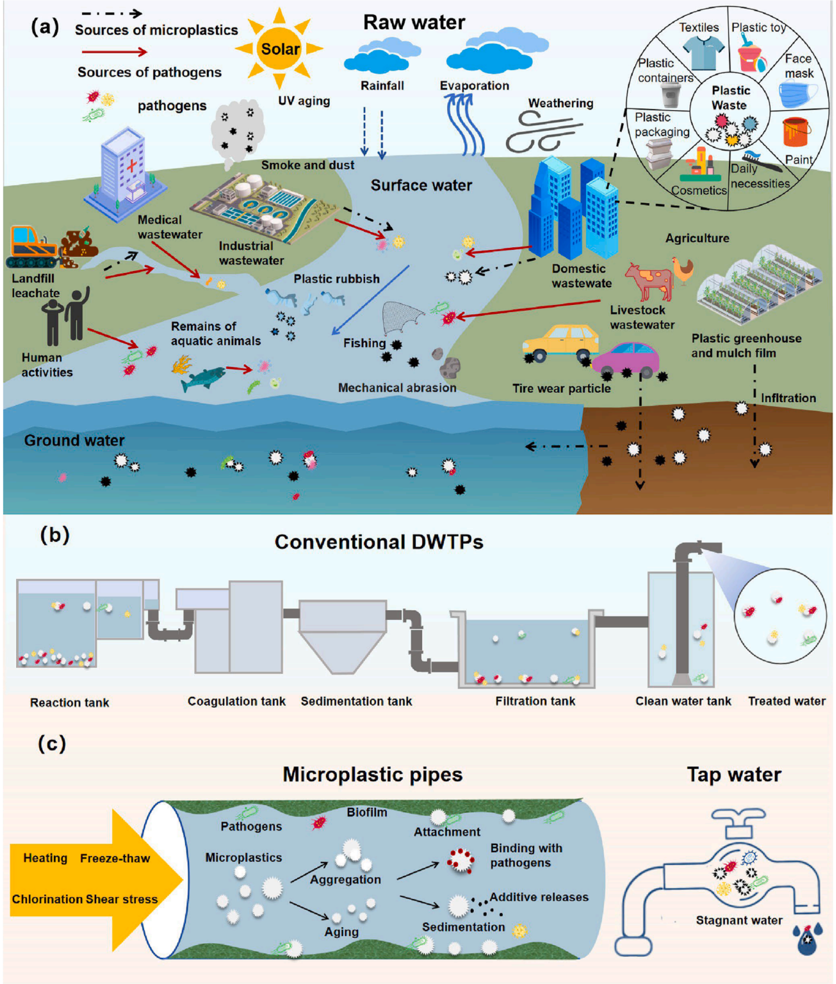

Fig. 1. Main sources and pathways of microplastics and pathogens in (a) raw water, (b) drinking water treatment plants and (c) drinking water distribution systems.

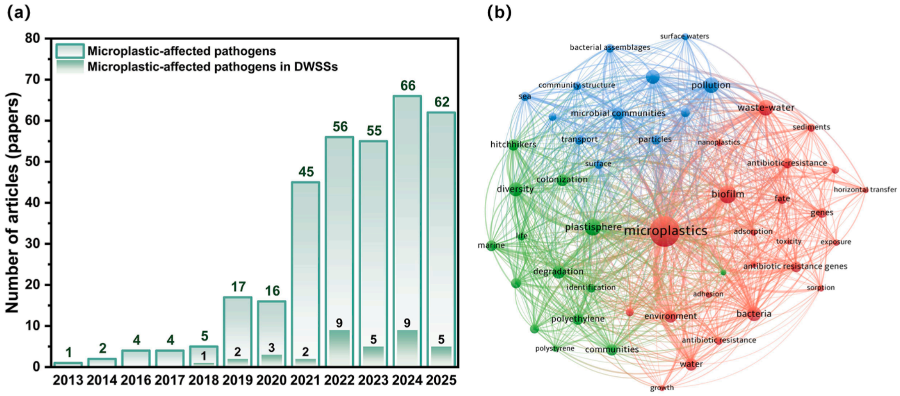

Fig. 2. (a) Graph representing the number of publications on "microplastic-affected pathogens" and "microplastic-affected pathogens in drinking water supply systems" in the WOS database from 2013 to 2025; (b) The network visualization map of co-occurrence keywords for the publications on "microplastic-affected pathogens".

3. Microplastics as a "seedbed" for pathogens

By providing colonizable surfaces and nutrients, MPs facilitate the formation of plastispheres that can enhance pathogen survival and persistence. Emerging evidence has further revealed the presence of pathogens on the plastisphere (Dudek et al., 2020; Zhong et al., 2023b). Although MPs and pathogens occur at lower concentrations in DWSSs, their unique hydraulic and chemical conditions may impose distinct selective pressures on plastisphere dynamics.

3.1. Plastisphere formations in drinking water supply systems

Recent studies have reported the presence of plastisphere communities in DWSSs. For instance, Hu et al. (2021) identified 58 human pathogenic species on PE and polypropylene (PP) surfaces in the *Ganjiang River*, Jiangxi's primary drinking water source. In Italian source waters, *Salmonella* spp., *Legionella* spp., and *Pseudomonas aeruginosa* have been identified on the plastisphere (Di Pippo et al., 2022). Meanwhile, certain parts in DWSSs are conducive to the plastisphere. For example, long-distance raw water pipelines accumulate sediment at their base, promoting the plastisphere development with *Acinetobacter, Pseudomonas* and *Proteus* (Tao et al., 2023). In DWDSs, water stagnation accumulates MPs, which can favor the plastisphere development and increase microbial risks (Chen et al., 2022; Ye et al., 2022b).

The formation of plastisphere occurs in three stages (Fig. 3): (i) pathogens adsorb onto MP surfaces while organic pollutants accumulate on MPs via molecular interactions (Kutralam-Muniasamy et al., 2024; Qin et al., 2024). (ii) Adsorbed organic matter and biomolecules form an eco-corona, providing carbon sources and nutrients that accelerate colonization (Jia et al., 2024; Yang et al., 2025b). (iii) The biofilm environment facilitates the accumulation and exchange of quorum-sensing (QS) signal molecules, thereby regulating functional genes to affect extracellular polymeric substances (EPS) secretion and accelerate gene transfer (Feng et al., 2025; Israel et al., 2023; Liu et al., 2024). Specially, for fungi, hyphae have been observed forming large clusters and mats on MPs (Ormsby et al., 2024).

This formation of plastispheres may create favorable conditions for pathogen proliferation. Studies have shown that under high mixed MP (PVC, PP, PE, and polyethylene terephthalate (PET)) exposure (2,000 mg/L), bacterial abundance on plastisphere can be up to 10 times higher than that of free-living microbes (Chen et al., 2022). They not only form a protective physical barrier around the pathogens but also stimulate increased EPS secretion, thereby significantly enhancing the overall bio-barrier effect (Deng et al., 2021; He et al., 2022). Meanwhile, pathogens in plastispheres demonstrate more potent metabolic synergy than their free-living counterparts, facilitating the establishment of stable micro-niches (Hall-Stoodley et al., 2004; Stewart et al., 2001; Zhong et al., 2023a). Beyond enhancing resistance, MPs can serve as a bioavailable carbon source. Chen et al. (2022) reported that PVC in tap water can release approximately 0.4 μg/mg of assimilable organic carbon (AOC). Fan et al. (2025) found that organic compounds leached from polypropylene random (PPR) pipes increased the relative abundance of pathogens by several hundred- to thousand-fold. *Acinetobacter calcoaceticus* and *Stenotrophomonas maltophilia* can even metabolize MP additives as carbon sources (Pereira et al., 2024). Collectively, these MP-derived nutrient inputs may increase pathogen dependence on MPs in the oligotrophic conditions of DWSSs, potentially leading to elevated and system-specific microbial risks.

3.2. *Specificity of plastispheres in drinking water supply systems*

The biofilm that forms on different types of MP varies. Low-density polyethylene (LDPE) tends to enrich *Alcanivorax* species (Zhang et al., 2024b). *Rhodobacteraceae* aggregates preferentially on polyamide 6 (PA6) surfaces (Liu et al., 2025b). Aged PP exhibits a higher relative abundance of cyanobacteria (Li et al., 2025a). Compared with conventional plastics, biodegradable MPs (polyhydroxyalkanoates (PHA) and polylactic acid (PLA)) exhibit a greater propensity to enrich pathogens than non-biodegradable MPs (Wang et al., 2024). Specificity also exists between plastics in different water bodies. Freshwater plastispheres display less complexity, more modules, higher modularity, and more competitive links, whereas in the marine pattern is reversed (Li et al., 2021).

Building on the above findings, plastispheres in DWSSs may exhibit system-specific characteristics. In DWSSs, the dominance of PP, PE, and PVC (Sun et al., 2024a), together with the low concentrations of nitrogen and phosphorus (Lehtola et al., 2002), may jointly influence plastisphere formation, which warrants further investigation. Moreover, the unique environmental conditions of DWSSs also affect plastisphere formation. For example, plastispheres in DWSSs are thinner and smaller than other biofilms, yet they contain a higher proportion of ARB (Tsvetanova et al., 2022).

3.3. *Factors affecting plastisphere development in drinking water supply systems*

In raw water, variations in temperature, seasonal precipitation, and anthropogenic inputs drive substantial fluctuations in nutrient availability, which directly shape microbial growth and reproduction dynamics (Costa et al., 2022; Glibert et al., 2017). AOC can provide a sustained carbon source for pathogens. In DWTPs, the presence of MPs can further elevate AOC concentrations following pre-oxidation. Park

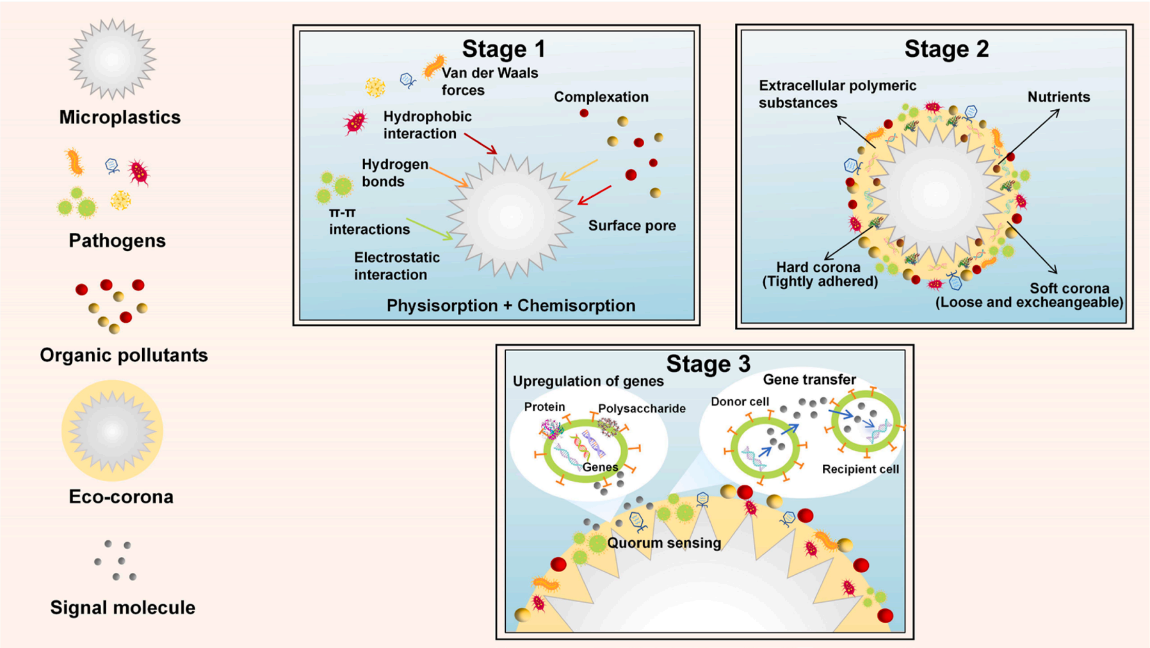

Fig. 3. Three stages of colonization of microplastics by pathogens: (i) Primary adsorption stage, (ii) nutrient enrichment stage, and (iii) plastisphere maturation stage.

et al. (2021) reported that pre-chlorination leads to a substantial rise in AOC levels. They potentially provide additional nutrients that support pathogen growth (Chen et al., 2021). In DWSSs, the higher flow velocities (0.8–2.0 m/s), generally hinder biofilm development. However, specific pathogens, including *Burkholderia, Chryseobacterium, and Microbacterium*, increase in abundance with rising flow velocity, elevating the proportion of pathogens (Chen et al., 2023). Under high flow conditions ($\geq$1.14 m/s), plastispheres developed into thin and coalescent patches that extensively colonized the flume bottom, which facilitates constant cell renewal at their surface (Chen et al., 2023). Consumer demands also shape colonization processes. The usage of warm water accelerates the release of MPs from plastic pipes and promotes the growth and proliferation of pathogens (Yang et al., 2024). Moreover, intermittent water usage by consumers leads to the formation of stagnant zones, providing more favorable conditions for the resuscitation of VBNC (Nisar et al., 2020; Ren et al., 2025).

The information above indicates that MPs, influenced by low nutrient conditions, high flow rates, oxidative stress and consumer demands in the DWSS, may accelerate the growth and proliferation of pathogens. However, empirical investigation remains limited. Future research on MPs and pathogens in DWSSs necessitates long-term and large-scale field studies.

4. Microplastics as a “conveyor belt” for pathogens

MPs act as Trojan horse vectors, introducing pathogens into diverse aquatic systems. Compared to other aquatic environments, the transport of MPs in DWSSs directly leads to human exposure through a short “source-to-human” pathway (Fig. 4), posing a significantly higher risk than cumulative exposure in natural environments.

4.1. *Microplastics as an pathogen vector in the system: entry routes and food chain implications*

The unique physicochemical properties of MPs render them efficient vectors for long-distance transport of pathogens. Simultaneously, leachates released from MPs enhance biofilm stress resistance by promoting densification, thereby prolonging pathogen viability during transport and collectively maintaining the overall stability of pathogens (Wang et al., 2022). Bowley et al. (2021) revealed that *Vibrio alginolyticus* readily adheres to PS and PVC, enabling effective dispersion through river ecosystems. Liu et al. (2025d) identified invasive pathogens on MPs in raw water that were previously absent from surrounding waters. In addition to long-distance transmission, pathogens migrating from highly contaminated areas will interact with local pathogens. Zhang et al. (2023a) demonstrated that pathogens carried by MPs interact with native bacterial communities to form stabilized assemblages.

Beyond cross-regional transport in the raw water, MPs continue to act as vectors during treatment processes in DWTPs, aiding pathogens in evading removal. Nguyen et al. (2023) have summarized that nine species of ARB can survive on MPs during treatment processes and enter DWDSs. In DWDSs, MPs generated from the detachment of pipe coatings during distribution can carry biofilm fragments into the tap water delivered to consumers (Świetlik et al., 2025). Previous studies in natural aquatic systems have shown that MPs, together with their associated pathogens, can be transferred and accumulated along the food chain, but biomagnification does not occur (Li et al., 2024b; Ortega-Sanz et al., 2025). Therefore, compared with food-chain accumulation, this short-range pathway directly introduces MPs and their associated pathogens into drinking water, posing more immediate and substantial risks to both ecosystems and human health.

4.2. *Microplastics as a pathogen vector in human exposure: ingestion routes and health risks*

Drinking water, particularly tap water, is an essential pathway for human exposure to MPs. Cox et al. (2019) estimated that individuals in the United States ingest approximately 39,000–5200,000 MP particles annually, of which about 4000–90,000 particles originate from drinking water. Consistently, MP abundances averaged 62.38 particles/L in tap water and 38.45 particles/L in bottled water (Zhu et al., 2024). Previous studies have demonstrated that mice ingested PS carrying *chikungunya* virus through drinking water, leading to *transient viremia* (Rawle et al., 2022). Similarly, the plastisphere harbors human-specific pathogens that may be ingested through drinking water, potentially triggering various diseases (Laverty et al., 2020).

Following internalization, MPs persist in transporting OP cargo

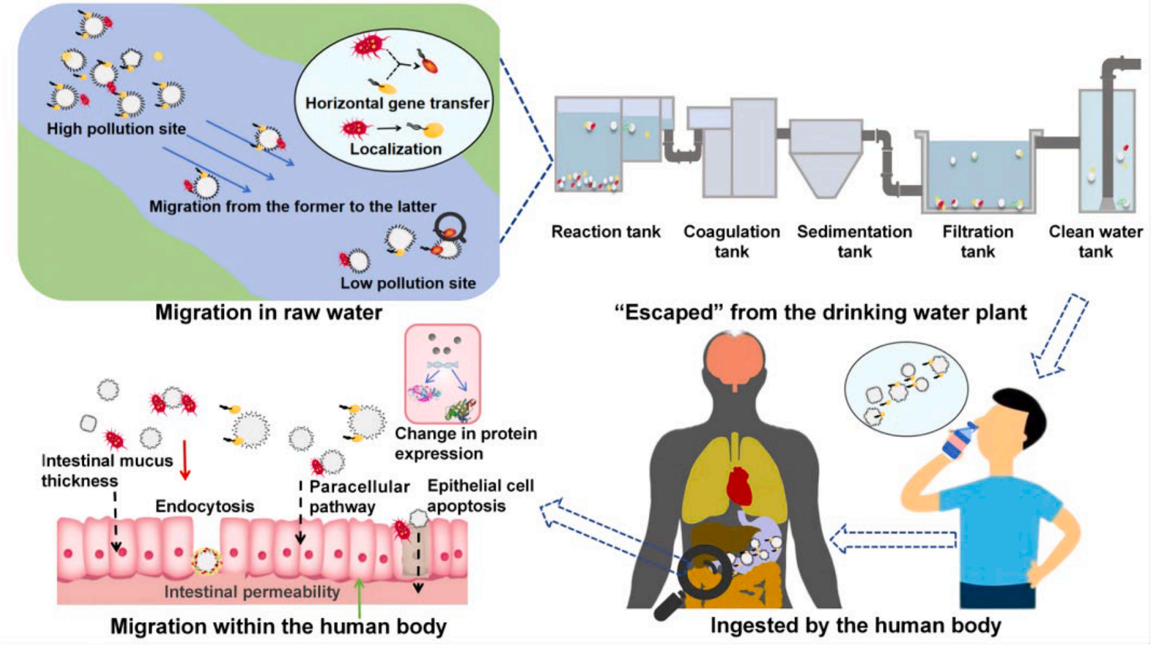

Fig. 4. Transmission of microplastics as carriers of pathogens from raw water to the human body.

through host systems. Synergistic interactions with associated microbes expand dissemination pathways. MP translocation primarily occurs via the paracellular pathway, which relies on tight junction modulation (Kim et al., 2024). This route is reinforced by OPs, which secrete proteases and alter junctional protein expression, ultimately enhancing the translocation of MPs (Su et al., 2024a). Concurrently, biofilm-coated MPs undergo endocytosis in specialized cells (Tavelli et al., 2022). Certain bacteria further compromise tissue integrity, enabling MP penetration into subepithelial layers and intestinal dissemination (Zhi et al., 2024). Simultaneously, MP ingestion reduces intestinal mucosal mucus thickness and downregulates the expression of mucin-producing genes, which may facilitate greater pathogen penetration (Jia et al., 2023).

5. Microplastics as a “workbench” for pathogens

Studies have demonstrated that MPs enhance bioluminescence in *Luminescent bacteria* (Yu et al., 2025), increase photosynthesis in benthic *Cyanobacteria* (Yang et al., 2025a), and elevate microcystin release in *Microcystis aeruginosa* (Liu et al., 2025a). For pathogens in DWSSs, MP-induced alterations in their resistance to antibiotics and chlorine pose a significant threat to drinking water safety, warranting particular attention.

5.1. Impacts of microplastics on pathogen antibiotic resistance

Recent evidence highlights the ability of MPs to promote antibiotic resistance in pathogens. Gross et al. (2025) reported that *E. coli* exposed to 500-μm PS (40 MP/mL^{-1}) for 10 days exhibited markedly increased resistance to *ampicillin, ciprofloxacin, doxycycline*, and *streptomycin*. Likewise, nanoplastics (NPs) (200 and 600 nm) can enhance the antibiotic resistance of *Serratia marcescens* (Xu et al., 2024a).

Summarizing the current research, MPs influence antimicrobial resistance in pathogens via two primary pathways (Fig. 5). For free-living pathogens, exposure to MPs stimulates oxidative stress responses, inducing elevated reactive oxygen species (ROS) production, which further promotes bacterial uptake of extracellular DNA and leads to genetic mutations. Zhang et al. (2024a) demonstrated that localized collisions of PE or PP in aqueous systems significantly increased intracellular ROS levels in *Sphingobium yanoikuyae*. Additionally, MPs stimulate EPS secretion, thereby strengthening microbial protective barriers and enhancing antibiotic resistance (Feng et al., 2025). These changes in resistance caused by the stimulation of MPs are more likely to be a short-term response. With long-term DWSS operation, plastispheres on plastic pipe walls and deposits accumulate diverse pathogens and ARGs, serving as a platform for ARG exchange (Jiang et al., 2022). Pathogens without intrinsic resistance acquire these genes via HGT mechanisms (Jiang et al., 2022). Moreover, the abundant mobile genetic elements (MGEs) on MP surfaces further facilitate gene exchange (Guruge et al., 2024). Gene transfer has allowed pathogens to acquire stable drug resistance.

In DWSSs, the disinfection process further exacerbates the evolution of antibiotic resistance. Chlorine disinfection contributes to an increase in the total abundance of ARGs and induces the conjugation of ARGs by enhancing efflux and oxidative stress (Ye et al., 2022a). UV-aged MPs exhibit increased adsorption capacity for ARGs carried by *bacteriophage λ*, leading to a higher frequency of ARG transfer (Yuan et al., 2022). Additionally, the release of organic compounds during aging induces the production of intracellular ROS and upregulates genes associated with HGT (Yuan et al., 2022). These unique factors further increase the biological risks in DWSSs.

5.2. Impacts of microplastics on pathogen chlorine resistance

Compared to antibiotic resistance, changes in chlorine resistance of pathogens are of greater concern in DWSSs. Wang et al. (2022) reported that MPs promote biofilm formation in DWDSs and enhance resistance to free chlorine. Zhang et al. (2024a) have demonstrated that under the influence of MPs, the chlorine resistance of free-living pathogens was increased. However, the underlying mechanisms remain poorly understood. Based on the limited available studies, this review draws parallels with antibiotic resistance mechanisms to propose analogous adaptive pathways.

According to previous studies, the mechanisms of MPs on disinfectant resistance pathogens are analogous to those of antibiotic resistance, mainly by (i) stimulating the activity of pathogens and enhancing the secretion of EPS and antioxidant enzymes, and (ii) increasing the transmission and exchange of resistance genes (Shen et al., 2023). Consistent with the mechanisms described for antibiotic resistance, MPs stimulate EPS secretion, thereby strengthening pathogen surface

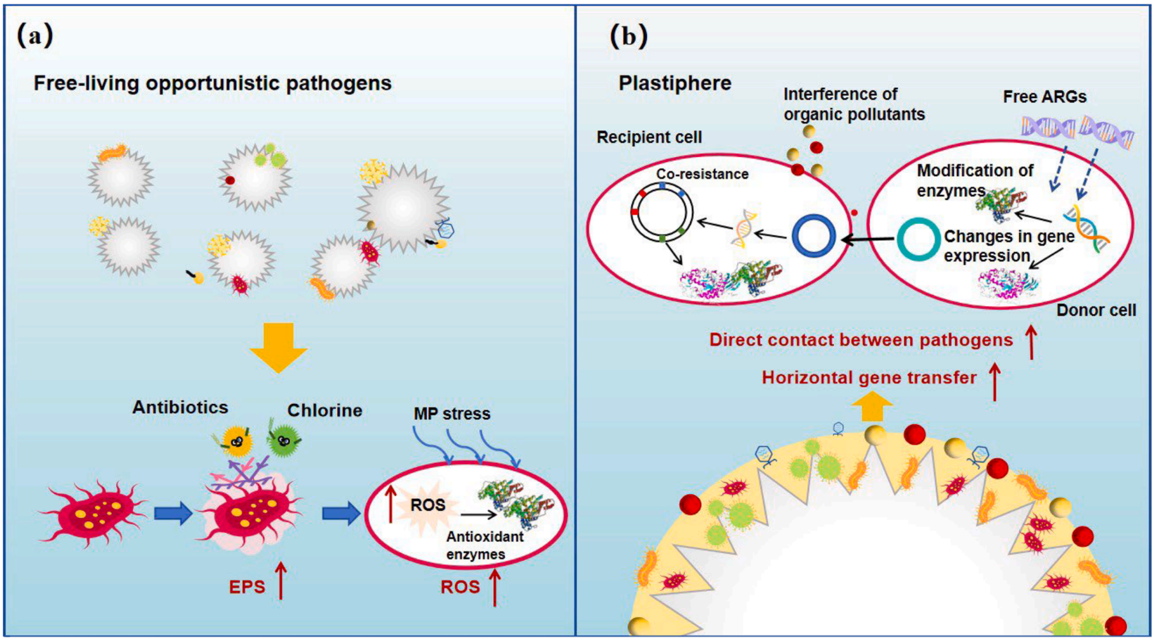

Fig. 5. Mechanism of the effect of microplastics on antibiotic and chlorine resistance of pathogens to (a) free-living pathogens and (b) the plastisphere.

protection. Wang et al. (2022) found that phthalate esters released by MPs can stimulate the densification of biofilms and improve the elasticity of biofilms, thereby enhancing their antioxidant capacity. However, the difference is that MP exposure upregulates *superoxide dismutase, catalase* and *glutathione*, which mitigate oxidative damage and enhance disinfectant resistance, as substantiated across multiple microbial studies (Table 3). Chlorine resistance genes (CRGs), analogous to ARGs, exhibit the capacity for horizontal transfer across pathogens. Free CRGs exhibit robust migratory and diffusional potential, enabling their capture and uptake by conspecific and heterospecific pathogens, and facilitating their coupling with microbial cell membranes (Weisberg et al., 2023). CRGs can translocate between distinct integrons while retaining long-term functionality. These combined integrons may be re-acquired by microorganisms, thereby contributing to the intracellular dissemination of CRGs within microbial populations (Souque et al., 2021). Such changes in characteristics impede the critical disinfection processes within DWSSs. Consequently, further mechanistic investigations into disinfectant resistance are imperative to establish a foundational framework for the development of control technologies.

6. Challenges posed by microplastic-affected pathogens in DWSSs

The aforementioned impacts of MPs on pathogens ultimately undermine pathogen control in DWSSs, posing risks to drinking water security (Fig. 6) and introducing additional secondary hazards. To address these challenges, it is essential to develop composite pollution control strategies from source to tap to safeguard drinking water safety.

6.1. *Adverse effect of microplastics on pathogen control efficiency*

Disinfection, the final treatment barrier in DWTPs, is key to safeguarding water safety. MPs significantly undermine disinfection efficacy through several mechanisms. Hu et al. (2024) demonstrated that higher concentrations of MPs reduce UV transmittance, leading to a 1.5-log reduction in MS2 virus inactivation. Tang et al. (2022) reported, in controlled laboratory experiments designed for mechanistic analysis, that increasing turbidity in MP suspensions from 5 NTU to 20 NTU led to a 1.6-log decrease in *E. coli* inactivation efficiency during chlorination. Shen et al. (2021) showed that PE (10 mg/L) significantly inhibited chlorine disinfection, leaving approximately 4.0×10^2 CFU/mL of *E. coli* after 30 min at an effective chlorine concentration of 0.9 mmol/L. Novel disinfection technologies are also vulnerable to MP interference. The presence of MPs can not only bind to piezoelectric materials, reducing their direct contact with pathogens, but may also affect energy conversion in them by altering water flow dynamics (Lan et al., 2022).

Beyond disinfection processes, membrane filtration is increasingly critical in drinking water treatment. Recent analyses confirm that ultrafiltration (UF) and nanofiltration (NF) effectively control pathogens (Burke et al., 2025; Michael et al., 2022). However, in NF, MPs accelerate membrane clogging, elevating short-term and long-term fouling resistance by 46% and 27%, which promotes the accumulation of proteins, polysaccharides, and humic-like substances on membrane surfaces and potentially worsens drinking water contamination (Lin et al., 2024). Similarly, in UF, MPs stimulate microbial activity and increase the production of EPS, leading to membrane fouling (Xiong et al., 2021).

6.2. *Secondary risks from microplastic-affected pathogen control processes*

Over 4200 additives in plastics with persistence, bioaccumulation, mobility or toxicity have been identified in recent studies, including trace metals, antioxidants, and plasticizers (Monclús et al., 2025). Most additives that are not covalently bound to polymer chains are released more rapidly, posing toxicity risks to drinking water environments (Yang et al., 2024). Fan et al. (2025) reported that during a 30-day operation period, 13 organic additives, including bisphenols and organophosphate esters, were released from plastic pipes. These compounds exhibit endocrine-disrupting, neurotoxic, and reproductive toxic effects. Moreover, such additives can enrich pathogens and promote biofilm densification, thereby further increasing risks to drinking water safety (Fan et al., 2025; Wang et al., 2022).

MP-derived dissolved organic matter, such as additives, oligomers, and monomers, also contributes to disinfection by-product formation through reactions with disinfectants (Table 4). Beyond the commonly cited trihalomethanes (THMs) and haloacetic acids (HAAs), studies have revealed that certain nitrogen-containing MPs generate nitrogenous disinfection by-products such as N-nitrosamines upon photoaging, which are recognized as one of the most carcinogenic among disinfection by-products (Guo et al., 2025; Zhou et al., 2025). Besides disinfection processes, membrane cleaning often employs sodium hypochlorite and sodium citrate, which promote the release of dissolved organic matter from plastics (Maliwan et al., 2025; Xiong et al., 2022). Studies also have found that leachates from chlorine-aged MPs double the relative abundance of pathogens and exacerbate the risks of virulence and antibiotic resistance transmission (Yang et al., 2024).

6.3. *How to control microplastic-affected pathogens*

Based on a comprehensive analysis, this review proposes that future

Table 3

Effects of microplastic exposure on antioxidant enzyme secretion in microorganisms.

Microorganism	MP types	Exposure concentration	Exposure duration	Antioxidant enzyme response	Ref.
Brachionus calyciflorus	PS	1×10^4 -10^7 particles/mL	24 hours	SOD: Activity increased (+4 % to +13 %) at low concentrations (≤1 × 10^6 particles/mL); declined (>3%) at high concentrations; CAT: Trend similar to SOD;PHEDEx: Activity decreased (−3% to −18%) down-regulation of gene expression (−11% to −44%).	(Liang et al., 2021)
Pseudomonas aeruginosa	Surgical masks, Water bottles, Paper cups, Milk bottles	N/A	7 days	CAT: Significant increase in activity (up to +169 per cent) at high temperatures (35 °C);GR: significant increase in activity (+137% to +144%);SOD: less change in activity (+1% to +21%).	(Saygin et al., 2024)
Staphylococcus aureus				SOD and GR: Activities were significantly increased; CAT: No significant change in activity.	
E.scherichia coli O157:H7	PS	10, 25, 50, 75, 100, 125, and 150 mg/L	7–15 days	MDA levels were increased.	(Nath et al., 2025)
Trichoderma harzianum	LDPE	2 g/L	72 hours	SOD: Increased activity, peaked at 24 hours; CAT: Increased activity, peaked at 72 hours.	(Jasińska et al., 2022)
E.scherichia coli Bacillus cereus	PS (0.1–5 μm)	160–320 mg/L	24 hours	LDH and MDA: Significant increase in activity.	(Yi et al., 2021)

SOD = Superoxide Dismutase, CAT = Catalase, PHEDEx = Phospholipid hydroperoxide glutathione peroxidase gene, GR = Glutathione Reductase, LDH = Lactate Dehydrogenase, and MDA = Malondialdehyde.

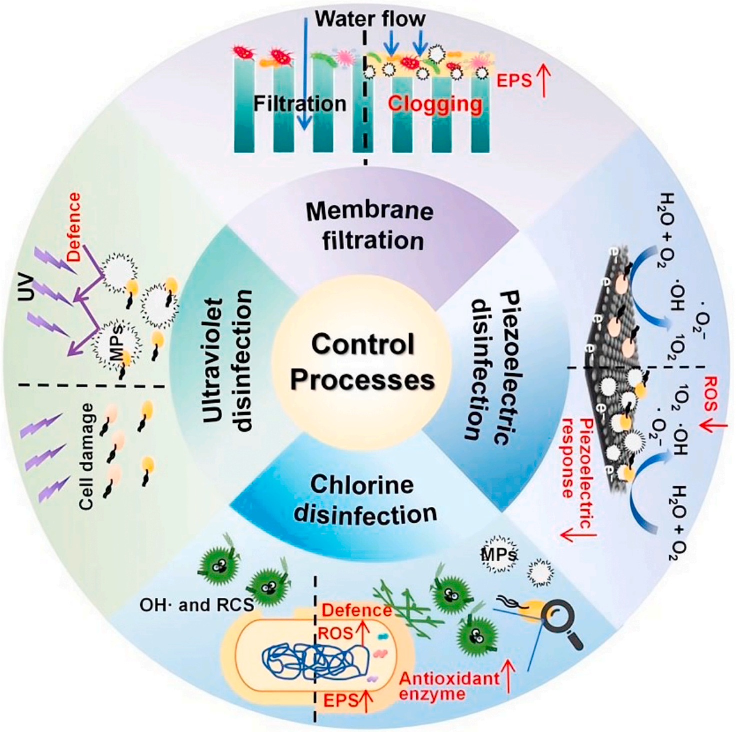

Fig. 6. Adverse effect of microplastics in drinking water supply systems on the control of pathogens (Red text denotes adverse effects of microplastics on pathogen control.).

control technologies should advance in two directions:

Conventional water treatment processes can achieve up to 90 % removal efficiency for MPs larger than 20 μm (Chen et al., 2025). For larger MPs (≥10 μm) present in the early stages of treatment, optimizing pretreatment processes is critical to intercept MPs and minimize their subsequent contact with pathogens. For example, Li et al. (2025b) demonstrated that ferrous iron/peracetic acid pretreatment promoted the aggregation of MPs, thereby improving membrane filtration performance. Future studies should explore the safer application of coagulation-based pretreatment in DWSSs. Meanwhile, the development of novel adsorbents, including modified activated carbon (Xing et al., 2023), magnetic particles (Shi et al., 2024), and hydrogels (Han et al., 2025), shows promise in adsorbing both M- and NPs, and could be applied as pretreatment options for the early-stage removal of MPs.

For small-sized MPs (< 10 μm), NPs and those released in distribution networks, the focus should shift toward enhancing disinfection and mitigating the secondary risks posed by MPs. Combined disinfection strategies can strengthen pathogen removal while controlling MPs. For example, UV-mediated grafting of biocidal Ag-MOFs onto polymeric membranes enables simultaneous MP retention and pathogen control (Pejman et al., 2021). UV irradiation and chlorination enhance MP settling and diminish their adsorption capacity, thereby lowering their potential as vectors for organic contaminants and associated risks to drinking water consumers (Liu et al., 2022). Furthermore, emerging materials such as magnetic graphitized biochar can remove most tetrabromobisphenol A, an additive from MPs, via electron transfer mechanisms, thereby reducing subsequent secondary contamination (Ye et al., 2022c).

Although current strategies may indirectly mitigate the co-pollution of MPs and pathogens, there is a pressing need to develop more direct, economical, and environmentally friendly approaches to control MP-pathogen complexes in DWSSs environments.

7. Conclusion and future perspectives

This review systematically discussed the MP-affected pathogens in DWSSs and analyzed the challenges of control treatments:

(i) MPs are prevalent in DWSSs, difficult to remove and can form complex co-contaminants with pathogens.
(ii) MPs act as a seedbed for pathogens, providing both nutrients and physical protection under oligotrophic, high-flow, and oxidative stress conditions typical of DWSSs.
(iii) MPs serve as a conveyor belt, enabling long-distance cross-waterbody transport as well as short-range transmission from “source to human”, thereby facilitating the entry of pathogens into the human body and posing health risks.
(iv) MPs function as a workbench that enhances pathogen resistance by inducing oxidative stress and promoting EPS thickening. Moreover, the plastisphere enriches ARGs and CRGs. These genes accelerate HGT, thereby enhancing pathogen resistance to both antibiotics and chloramine through this mechanism.
(v) These synergistic effects weaken the control efficiency of pathogens and promote the release of harmful additives and disinfection by-products. Control needs to focus on MP control at the pretreatment and the reduction of secondary hazards.

Based on existing research, the following research efforts are recommended to fill knowledge gaps:

(i) Future studies should prioritize integrated, long-term monitoring of MPs and associated pathogens across the entire DWSSs, from raw water through treatment processes to DWDSs. In parallel, machine learning could be applied to predict long-term system behavior and support quantitative risk assessment under prolonged operational conditions.
(ii) Future research should investigate the interaction mechanisms between MPs and pathogens under DWSS conditions, including

Table 4
Secondary hazards in pathogen control processes under microplastic coexistence conditions.

Control processes	MPs types	Control conditions	Secondary hazards	Ref.
Chlorine disinfection	PE	The free chlorine (2.0 mg/L); 96 hours	80.48 ± 4.53 μg/L THMs and 4.33 ± 0.18 μg/L HANs	(Yan et al., 2024b)
	PS		125.48 ± 8.90 μg/L THMs and 6.92 ± 0.21 μg/L HANs	
	PE	The free chlorine (100 mg/L); 72 hours	20 μg/L chloroform	(Liu et al., 2023a)
	PP, PE and PVC	3 times than DOC concentration	61.85–240.97 μg/L THMs and 420.67–1234.71 μg/L HAAs	(Zhou et al., 2022)
Chlorine dioxide disinfection	PVC	Chlorine dioxide (0.5 mg/L); 168 hours	Dimethyl phthalate, Diethyl phthalate, Diisobutyl phthalate, Di-n-octyl phthalate	(Wang et al., 2022b)
Ozone disinfection	PS	Ozone (4.1 mg/L)	Formic acid, phenol, acetophenone and hydroquinone	(Dogruel et al., 2025)
UV disinfection	PP, PE, PS, PVC and PET	UV365 (12.3 W); 2000 hours	Generation of aliphatic ketones, esters, aldehydes and aromatic ketones	(Liu et al., 2023b)
	PU	UV365 (100 W); 336 hours	35.143 ± 0.3 mg/ L DOM	(Yao et al., 2024)
	PE	UVA (8 W); 14 hours	40.3–439.8 μg/L THMs	(Yang et al., 2023a)
	PS		29.2–453.3 μg/L THMs	
Ultrafiltration	PE	Continuous-flow UF system; 1 mg/L NaOCl	515 μg/L THMs and 12.1μg/L TCNM	(Xiong et al., 2022)
		Chemically enhanced backwashing; 10 mM NaOCl	>100 μg/L THMs and HAAs	(Guo et al., 2025)
	PVDF	1500 mM NaOCl	14.14 mg/L TOC	(Wang et al., 2025)

PVDF = Polyvinylidene fluoride, THMs = Trihalomethanes, HANs = Haloacetonitriles, HAAs = Haloacetic Acids, and TCNM = Trichloronitromethane.

low nutrient availability, flow dynamics, and the presence of disinfectants.

(iii) Investigations are needed to reveal the interactions between MPs and fungi under DWSS-relevant conditions, including their survival, transport, and potential health implications.

(iv) Future studies should explore treatment processes capable of simultaneously and efficiently removing MPs, pathogens or their complexes during drinking water treatment or secondary control in distribution networks.

CRediT authorship contribution statement

Ruidi Xu: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Qiqi Wan:** Writing – review & editing, Validation, Supervision, Conceptualization. **Ruihua Cao:** Writing – review & editing, Validation, Supervision, Methodology. **Yanghui Xu:** Writing – review & editing, Validation, Conceptualization. **Huan Tang:** Writing – review & editing, Validation, Supervision. **Gang Liu:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Gang Wen:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2025.125294.

Data availability

Data will be made available on request.

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