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Synergistic effects of antibiotics and nanoplastics in wastewater: A growing challenge in aquatic ecosystem, biodiversity and human health protection

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ABSTRACT

The pervasive presence of nanoplastics and antibiotics in wastewater systems presents a dual threat to environmental and public health. Nanoplastics, with particle sizes under 1 µm, have become a major environmental contaminant, primarily due to their durability and potential to absorb harmful chemicals. These particles not only threaten aquatic ecosystems by disrupting microbial communities and harming marine life but also pose risks to human health through bioaccumulation in the food chain. Similarly, antibiotics frequently found in wastewater promote the development of antibiotic-resistant bacteria, further endangering ecological stability and human health. The synergistic effects of nanoplastics and antibiotics exacerbate their impacts, particularly by increasing the bioavailability and toxicity of contaminants in aquatic systems. This paper explores the sources, transport pathways, and combined ecological and health impacts of these pollutants. Additionally, it discusses the limitations of current wastewater treatment technologies in mitigating the effects of nanoplastics and antibiotics and proposes advanced strategies for reducing their environmental footprint. Addressing these contaminants requires a multifaceted approach, integrating technological, regulatory, and community-based solutions to safeguard the ecosystem, biodiversity, and human health.

1. Introduction

Nanoplastics, defined as plastic particles smaller than one µm, are increasingly recognized as ubiquitous environmental pollutants [1]. Rodrigues et al. [2] reported that, nowadays, their size ranges from 1 nm to 1000 nm. They can infiltrate freshwater, marine, and terrestrial ecosystems due to their small size and high mobility. Studies show that micro- and nanoplastics originate from the fragmentation of larger plastics and persist widely across environmental compartments, posing exposure risks via ingestion, inhalation, and trophic transfer to organisms [2]. In contrast, microplastics are generally defined as particles ranging from ~1 µm to 5 mm in size, reflecting a broader, larger size class with different environmental behaviors and transport dynamics [2]. The smaller size of nanoplastics could allow them to cross biological barriers more readily than microplastics, interact at cellular and molecular levels, and be taken up into tissues, increasing their potential for systemic distribution and biological impacts [3]. Both micro- and nanoplastics have been detected in surface waters, sediments, soils, and even the atmosphere, confirming their widespread distribution and persistence in the environment [2].

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Size-dependent effects have been observed in microbial communities; for example, nanoplastics altered soil bacterial composition and significantly increased the abundance of antibiotic resistance genes (ARGs) compared with microplastics, with changes in host bacterial taxa noted [4]. Similarly, nanoplastics can enhance horizontal gene transfer (HGT) of ARGs through oxidative stress, increased conjugation frequency, and upregulation of transfer-related genes [3]. Because nanoplastics exhibit a higher surface-to-volume ratio than larger microplastics [5], they are more reactive, can adsorb other pollutants (such as antibiotics), and create microhabitats (plastisphere) that can facilitate gene transfer events [6]. This elevated interaction potential underscores the heightened ecological and health risks of nanoplastics relative to microplastics, including their role in disseminating antibiotic resistance in microbial communities and their potential impacts on human health. Lehner et al. [8] reviewed the emergence of nanoplastics in the environment and their potential uptake and effects in humans, emphasizing mechanisms such as cellular internalization and particle translocation. They also highlighted the analytical challenges in detecting nanoplastics in complex environmental or biological samples, noting that current methods often rely on model polystyrene nanoparticles that may not fully represent real-world conditions.

Antibiotics, another class of emerging contaminants, are frequently found in wastewater due to their extensive use in medical therapies and agriculture. These compounds can significantly alter microbial communities in aquatic environments, leading to the development of antibiotic-resistant bacteria, which poses a severe threat to public health and ecosystem stability. Keen and Patrick [7] synthesized evidence showing that environmental antibiotic residues disrupt microbial processes, alter ecosystem functions, and contribute to the spread of antimicrobial resistance. They noted, however, that the diversity of study designs, ecosystems, and experimental methods makes it challenging to quantitatively integrate these findings, highlighting the need for standardized approaches to assess environmental antibiotic impacts. The presence of antibiotics in water bodies can disrupt essential ecological processes such as nitrogen transformation and methanogenesis, further complicating the impacts of water pollution.

The dual threat posed by nanoplastics and antibiotics in wastewater underscores the urgent need for comprehensive strategies to mitigate their effects on the environment and human health. The significance of nanoplastics and antibiotics in wastewater cannot be overstated. Nanoplastics can adsorb and carry toxic pollutants, enhancing their bioavailability and potential toxicity to aquatic organisms [7,9]. Their small size allows them to penetrate cell membranes, leading to cellular toxicity and adverse immune responses [10]. Furthermore, the interaction of nanoplastics with dissolved organic matter in the environment can influence their migration and transformation, complicating their assessment and management [11,12]. The presence of antibiotics in wastewater exacerbates these issues, as they can alter the structure and function of microbial communities, facilitating the spread of resistance genes among pathogenic bacteria [8]. This synergistic effect of nanoplastics and antibiotics in wastewater presents a complex challenge for environmental management.

The effects of nanoplastics and antibiotics on aquatic ecosystems are profound and multifaceted. As such, exposure by some aquatic species to nanoplastics can disrupt reproductive processes in marine organisms. Additionally, the presence of antibiotics can lead to shifts in microbial community dynamics, which can further impact nutrient cycling and ecosystem health [8]. The combination of these pollutants can create a toxic environment for aquatic life, leading to reduced biodiversity and altered food webs. The potential for nanoplastics to act as vectors for other pollutants, including heavy metals and persistent organic pollutants, further complicates their ecological impact [7]. In wastewater treatment facilities, the removal of nanoplastics and antibiotics remains a significant challenge. Conventional treatment methods often fail to effectively eliminate these contaminants, allowing them to persist in the effluent that’s discharged into natural water bodies [13]. The poor extraction efficiencies of nanoplastics from biosolids and soils highlight the limitations of current remediation technologies[13,14]. As a result, innovative approaches are needed to enhance the removal of these pollutants from wastewater, including advanced filtration and adsorption techniques [15]. The development of reliable analytical methods for detecting trace levels of nanoplastics in complex environmental samples is also crucial for understanding their distribution and impact [16].

The health risks associated with exposure to nanoplastics and antibiotics are increasingly recognized, albeit very little has been done to regulate their presence in the environment. Nanoplastics have been shown to induce oxidative stress and inflammation in various organisms, raising concerns about their potential effects on human health [17, 18]. The presence of antibiotics in the environment can lead to the emergence of resistant strains of bacteria, which can compromise the effectiveness of medical treatments and pose significant public health risks [8]. The interaction between nanoplastics and antibiotics in the environment can lead to complex ecological consequences. For instance, the adsorption of antibiotics onto nanoplastics can alter their bioavailability and toxicity, potentially enhancing the harmful effects on aquatic organisms [10]. Additionally, the presence of nanoplastics can influence the degradation and transformation of antibiotics in the environment, affecting their persistence and ecological impact [11]. Research on the ecological and health impacts of nanoplastics and antibiotics is still in its infancy, and further studies are needed to elucidate their interactions and long-term effects. The development of standardized methods for assessing the presence and effects of these contaminants in various environmental matrices is crucial for advancing our understanding of their risks [15]. Moreover, interdisciplinary research efforts that integrate environmental science, toxicology, and public health are essential for addressing the challenges posed by emerging contaminants in water systems [7]. The paper focuses on the sources, pathways, and combined effects of nanoplastics and antibiotics in wastewater and aquatic ecosystems. It highlights the persistence, and transport of these pollutants, their potential to contribute to antimicrobial resistance, and their ecological and human health impacts. The paper concludes by proposing advanced strategies for mitigating the environmental risks posed by these emerging contaminants.

2. Methodology

A thorough literature search was conducted to ensure comprehensive coverage of studies addressing the interactions between nanoplastics and antibiotics in wastewater and aquatic environments. The search was performed in Scopus, Web of Science, and Google Scholar databases, covering peer-reviewed articles published between January 2010 and June 2025. The following keywords were used: *"nanoplastics"*, *"microplastics"*, *"antibiotics"*, *"wastewater"*, *"synergistic effects"*, *"antibiotic resistance genes"*, *"antimicrobial resistance"*, and *"One Health"*. The initial search yielded 195 records, which were screened by titles and abstracts to remove duplicates, non-English publications, conference abstracts, and studies not relevant to environmental or wastewater contexts. Full-text assessment was subsequently conducted based on predefined inclusion criteria focusing on (i) occurrence, fate, or transport of nanoplastics and/or antibiotics in wastewater or aquatic systems, (ii) evidence of combined or synergistic effects, and/or (iii) implications for antimicrobial resistance or One Health. Reviews lacking environmental relevance and studies focused solely on engineered nanoparticles or clinical settings were excluded. Ultimately, 148 articles met the inclusion criteria and were included in the qualitative synthesis and critical analysis presented in this review. Given the conceptual breadth and interdisciplinary nature of nanoplastics–antibiotic interactions, this study adopted a narrative review design to integrate mechanistic, ecological, and health-related evidence. As such, the methodological rigor required for a full systematic review was intentionally not applied, although a structured and transparent literature search strategy was applied.

3. Wastewater and One Health: Focus on Nanoplastics and Antibiotics

The presence of these pollutants in wastewater poses significant challenges to both environmental health and public safety. This is concerning as treated wastewater has been identified as a significant source of pollutants, including microplastics and nanoplastics in different environmental matrices and food systems with One Health implications [19,20]. Figure 1 illustrates the pathways that pollutants like antibiotics and nanoplastics follow after entering wastewater systems [21,22].

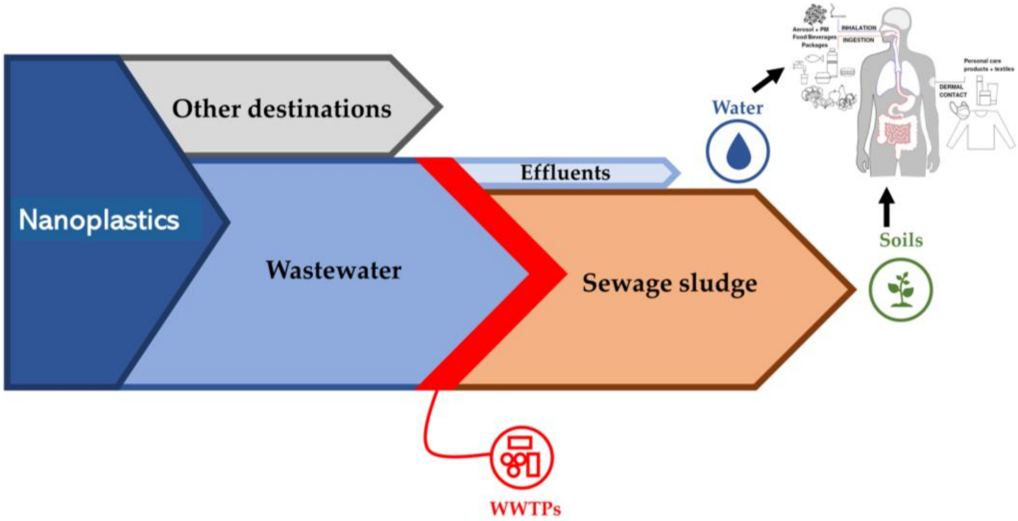

Fig. 1. Destination of nanoplastics from aquatic ecosystems. (Source: Adapted from: Collivignarelli et al. [21] and Urani et al. [22].)

Originating from diverse sources such as pharmaceuticals, personal care products, packaging, and textiles, they are either captured in sewage sludge during wastewater treatment or discharged into water bodies via effluents.

Human, environmental, and biodiversity exposure occurs through (bio)accumulation, biomagnification, ingestion, inhalation, and dermal contact, with potential impacts on both environmental and human health [23-27].

The aggregation behavior of nanoplastics in wastewater is influenced by various factors, including ionic strength and the presence of organic matter, which can complicate their removal. Recent advancements in treatment technologies, such as the use of alternative coagulants, have shown promise in enhancing the removal efficiency of these contaminants [28,29]. The ecological implications of nanoplastics in wastewater are profound. They can adsorb harmful chemicals and pathogens, potentially leading to bioaccumulation in aquatic organisms and subsequent entry into the food chain[7]. Furthermore, nanoplastics can disrupt microbial communities within wastewater treatment systems, affecting processes such as nitrogen removal, which is crucial for maintaining water quality[30]. The interaction between nanoplastics and microbial communities can lead to altered ecosystem dynamics, potentially impacting biodiversity and ecosystem services [30].

In the same way, antibiotics in wastewater represent another significant ecological concern. Wastewater treatment plants (WWTPs) serve as hotspots for antibiotic-resistant bacteria (ARB) and antibiotic-resistance genes (ARGs) due to the high concentrations of residual antibiotics present [31,32]. The presence of antibiotics in wastewater can select for resistant strains of bacteria, which may then spread into the environment, posing risks to human and animal health[31]. The treatment of antibiotic-production wastewater is particularly challenging, as these effluents contain high concentrations of residual antibiotics that can persist even after treatment [33,34]. To mitigate the risks associated with antibiotics and nanoplastics in wastewater, it is essential to improve treatment infrastructure and adopt advanced removal technologies. For instance, the integration of adsorption methods with existing wastewater treatment processes has been suggested as a viable strategy to enhance the removal of pharmaceuticals and microplastics [35]. Although the author's report is for microplastics, it could be relevant to nanoplastics removal as well. Additionally, the development of biosolids-derived materials, such as biochar, has shown potential for removing contaminants like triclosan from wastewater[36]. Moreover, regulatory frameworks need to evolve to address the emerging challenges posed by these pollutants. The European Union has begun to implement stricter regulations on the release of hazardous substances in wastewater, emphasizing the need for industries to innovate and reduce the discharge of harmful contaminants [37].

The intersection of wastewater management and the One Health framework will continue to garner increasing attention due to the emerging threats posed by nanoplastics and antibiotics. The presence of these particles in wastewater treatment systems poses significant risks, as they can adsorb harmful chemicals and pathogens, potentially leading to their release into the environment post-treatment[20]. Furthermore, traditional wastewater treatment methods, such as coagulation, have shown limited effectiveness in removing nanoplastics, often resulting in residual metal contaminants that could pose additional health risks [38]. The interaction between nanoplastics and antibiotics in wastewater is particularly concerning. Nanoplastics can facilitate the transport of antibiotics, thus enhancing their bioavailability and potentially leading to increased resistance in microbial populations [39]. This interaction highlights the need for integrated approaches that consider both pollutants in the context of One Health. The presence of antibiotics in wastewater can select resistant bacteria, which may then be transferred through the food chain, impacting both livestock and human health [39,40]. Additionally, the accumulation of nanoplastics in agricultural soils, particularly those treated with sewage sludge, raises questions about their long-term effects on soil health and crop safety [41].

The health implications of nanoplastics are still being elucidated, but emerging evidence suggests potential adverse effects on gut microbiota and overall health because of the obstructive potential of these pollutants and their biomaterials, like ARGs. The process through which antibiotic-containing effluents from municipal and hospital wastewater systems contribute to the development of antibiotic resistance is multifaceted [42]. As antibiotic-rich wastewater enters natural water bodies, it exerts selective pressure on microorganisms, enabling the survival and proliferation of drug-resistant organisms while eliminating sensitive ones. These resistant organisms, once introduced into the environment, pose a significant public health risk as they can enter the human population, reducing the efficacy of existing antibiotics.

Studies indicate that nanoplastics can disrupt gut microbiota composition, which is crucial for digestion, immune response, and overall health [43]. Furthermore, the inhalation and ingestion of nanoplastics can lead to systemic exposure, raising concerns about their role in various health issues, including reproductive health and chronic diseases [44]. The potential for nanoplastics to act as vectors for other contaminants, including heavy metals and pathogens, further complicates the risk assessment[8,39]. At this time, it is imperative to develop effective wastewater treatment technologies that can efficiently remove both nanoplastics and antibiotics. Current methods, such as ionic liquid-assisted extraction and advanced filtration techniques, show promise but require further optimization for practical application [45]. Moreover, regulatory frameworks must evolve to incorporate the risks associated with nanoplastics and antibiotics, ensuring that both environmental and public health are safeguarded [46,47].

Ionic liquid-assisted extraction and advanced filtration techniques present significant promise for removing nanoplastics and antibiotics from wastewater; however, they are not without limitations. One of the primary challenges associated with ionic liquid-assisted extraction is the variability in extraction efficiency, which is heavily influenced by the physicochemical properties of the ionic liquids used, including their structure and the nature of the target analytes [7,48]. The extraction yields can vary significantly depending on the ionic liquid's anion and cation composition, which complicates the optimization of extraction processes for diverse contaminants [48]. Furthermore, while ionic liquids are touted for their environmentally friendly characteristics, their disposal and potential toxicity remain controversial, mainly when used in large quantities or concentrated forms [48]. In terms of advanced filtration techniques, such as membrane filtration, the removal efficiency of nanoplastics and antibiotics is often hindered by the size and nature of the contaminants. For instance, smaller nanoplastics can evade conventional filtration systems, leading to significant quantities escaping treatment and entering the effluent [20]. Additionally, the presence of fouling agents in wastewater can severely impact the performance of membrane filtration systems, leading to reduced flow rates and increased operational costs due to the need for frequent cleaning and maintenance[49].

Moreover, while granular activated carbon (GAC) and other filtration materials have shown effectiveness in removing a range of micropollutants, including pharmaceuticals, their efficiency can be inconsistent and is often dependent on the specific characteristics of the contaminants and the operational conditions of the treatment system [50]. Integrating these techniques into existing wastewater treatment frameworks also poses logistical challenges. For instance, the need for specialized equipment and the potential for increased energy consumption can limit these methods' scalability and economic feasibility for widespread application[51]. Furthermore, the potential formation of toxic by-products during treatment, mainly when using advanced oxidation techniques in conjunction with filtration, raises additional environmental and health concerns [52]. Overall, while ionic liquid-assisted extraction and advanced filtration techniques offer innovative approaches to addressing the pressing issues of nanoplastic and antibiotic contamination in wastewater, their limitations necessitate further research and development to enhance their efficacy and sustainability in practical applications.

4. Sources and Pathways of Nanoplastics and Antibiotics in Wastewater

The primary sources of nanoplastics include the degradation of larger plastic materials, which can occur through mechanical weathering, photodegradation, and chemical processes, leading to the fragmentation of plastics into smaller particles [53,54].

Cunningham et al. [53] identified critical gaps in nanoplastics research that limit robust ecological and human health risk assessments, including the scarcity of environmentally relevant test materials and limited exposure data. They further emphasized that most toxicity studies use simplified laboratory models and commercial nanoplastics, which may not accurately capture the complexity of environmental nanoplastics, highlighting the need for more realistic experimental designs. Typically, wastewater often contains a diverse range of contaminants, including antibiotics and nanoplastics, which pose significant environmental and public health risks. Antibiotics found in wastewater can include classes such as beta-lactams, tetracyclines, fluoroquinolones, and sulfonamides, which are commonly used in human and veterinary medicine. Their presence in wastewater can promote the development of antibiotic-resistant bacteria, complicating efforts to treat infectious diseases.

Both antibiotics and nanoplastics in wastewater can disrupt aquatic ecosystems, bioaccumulate in organisms, and potentially enter the human food chain, underscoring the need for effective wastewater treatment and pollution prevention strategies. Additionally, nanoplastics are found in various consumer products, particularly in cosmetics and personal care items, where they are intentionally added for aesthetic purposes [55,56]. Industrial runoff also contributes to the presence of nanoplastics in aquatic environments, as manufacturing processes often release plastic particles into water systems [7]. Table 1 shows the pathways of nanoplastics and antibiotics in wastewater systems. The pathways through which nanoplastics enter wastewater systems are multifaceted. Domestic waste, including household products containing secondary nanoplastics, could be a significant contributor to the influx of these particles into WWTPs.

González-Pleiter et al. [66] investigated the ecotoxicological effects of secondary nanoplastics formed from the abiotic degradation of polyhydroxybutyrate microplastics under environmentally representative conditions. The study produced nanoplastics in the ~75–200 nm range and confirmed their presence through comprehensive physicochemical characterization. When exposed to three freshwater organisms, these secondary nanoplastics significantly impaired cellular growth and altered physiological parameters [66]. Importantly, control experiments using ultrafiltration demonstrated that the observed toxicity was attributable to the nanoplastic particles themselves rather than dissolved degraded byproducts, strengthening the conclusion that secondary nanoplastics can be hazardous even when derived from biodegradable plastics [66]. Furthermore, industrial effluents, particularly from sectors that utilize plastics extensively, can introduce nanoplastics directly into aquatic systems [67].

Once in the wastewater systems, nanoplastics can evade filtration processes in WWTPs, leading to their eventual release into natural water bodies[66]. This escape is exacerbated by the small size of nanoplastics, which makes it difficult to detect and remove during wastewater treatment [53]. The presence of antibiotics in wastewater systems is another pressing issue, with sources primarily stemming from pharmaceutical use, agricultural runoff, and improper disposal of medications.

Table 1. Sources and pathways of nanoplastics and antibiotics in wastewater systems.

Wastewater Type	Sources and Pathways	Implications	References
Domestic Wastewater	Nanoplastics, antibiotics from personal care, pharmaceuticals, laundry.	Released into water bodies due to incomplete wastewater treatment.	[57]
Agricultural Runoff	Pesticides, fertilizers, antibiotics from farm practices via runoff.	Spreads contaminants, causing antibiotic resistance and ecosystem harm.	[58]
Industrial Discharge	Pharmaceuticals, nanoplastics from manufacturing and textile industries.	Overwhelms treatment, risks aquatic life, affects water supplies.	[59]
Hospital Wastewater	Antibiotics and related compounds from medical facilities.	Promotes bacterial resistance in treatment plants and nature.	[60]
Wastewater Treatment Plants	Residual antibiotics, nanoplastics in effluent or sludge fertilizers.	Spreads contaminants to water bodies and agricultural lands.	[61]
Landfill Leachate	Plastics, pharmaceuticals from poorly managed landfills seep into systems.	Leaches persistent contaminants, polluting groundwater and surface water.	[62]
Aquaculture and Animal Farms	Antibiotics, nanoplastics from feed, packaging, and farming runoff.	Drives resistance, impacting ecosystems and human health.	[63]
Surface Runoff to Rivers/Lakes	Nanoplastics, antibiotics entering aquatic environments via runoff.	Harms biodiversity, food chains, and water quality.	[64]
Atmospheric Deposition	Airborne nanoplastics from tires, combustion, industry in rain.	Introduces pollutants to remote and untouched ecosystems.	[65]

Antibiotics are frequently discharged into wastewater from hospitals, households, and farms, where they can accumulate and exert selective pressure on microbial communities.

Maghsodian et al. [68] reviewed the presence of antibiotics in aquatic environments (seas, rivers, lakes, and organisms) in different parts of the world, with most studies conducted in 2018 (15%) and 2014 (11%). Antibiotics were found in water at concentrations of <1 ng/L–100 µg/L, with fluoroquinolones showing the highest concentrations in water (460 ng/L), sediments (406 ng/g), and organisms (68,000 ng/g). The results highlighted Asia as the most studied region and identified sulfonamides and fluoroquinolones as significant ecological threats due to their high abundance and persistence [68]

Oharisi et al.[69] monitored 16 antibiotics (amoxicillin, ampicillin, azithromycin, ciprofloxacin, doxycycline, erythromycin, gentamicin, metronidazole, norfloxacin, ofloxacin, penicillin, sulfamethoxazole, sulfapyridine, sulfamethizole, tetracycline, and trimethoprim) in two wastewater treatment plants and two effluent-receiving rivers in Northern Pretoria, South Africa, using ultra-high-performance liquid chromatography with mass spectrometry. Antibiotics in influent samples ranged from 0.78 to 96.8 ng/mL, while effluent concentrations were lower (0.12–9.89 ng/mL), with doxycycline (30.9–120 ng/mL) and sulfamethoxazole (2.52–96.8 ng/mL) being most abundant. Hazard quotients ranged from 0.24 to 889, indicating significant ecological risks, and findings suggested that wastewater treatment plants contributed to antibiotic pollution, necessitating improved treatment technologies [69].

The pathways for antibiotic entry into wastewater are complex; for instance, agricultural practices often lead to runoff that carries antibiotic residues into nearby water bodies, while hospitals may discharge wastewater containing high concentrations of antibiotics [70, 71]. This accumulation poses significant risks for the development of antibiotic-resistant bacteria, as the presence of these compounds can facilitate horizontal gene transfer among microbial populations [70].

The co-occurrence of nanoplastics and antibiotics in wastewater systems raises concerns about their synergistic effects on aquatic ecosystems and human health. In this context, “synergistic effects” refer to both chemical interactions and biological impacts. Chemically, nanoplastics can adsorb antibiotics, altering their environmental fate, bioavailability, and degradation rates. Biologically, these combined exposures can affect aquatic organisms by increasing toxicity, modifying microbial community composition, and promoting the horizontal transfer of antibiotic resistance genes.

Research has indicated that the presence of nanoplastics can enhance the bioavailability and toxicity of antibiotics, potentially leading to increased resistance among microbial communities [7]. The interaction between nanoplastics and antibiotics may alter the ecological dynamics within wastewater systems, as microbes adapt to the combined stressors of plastic pollution and antibiotic exposure[72]. This phenomenon underscores the need for a comprehensive understanding of how these contaminants interact and their implications for environmental health. Nanoplastics can also impact the fate and transport of antibiotics in aquatic environments. The adsorption of antibiotics onto nanoplastic surfaces may influence their bioavailability and degradation rates, potentially leading to prolonged exposure of aquatic organisms to these harmful substances [7,53].

Moreover, the presence of nanoplastics can affect the microbial community structure in wastewater systems, potentially favoring the proliferation of antibiotic-resistant strains. This relationship between nanoplastics and antibiotics highlights the complexity of managing emerging contaminants in wastewater treatment and the need for innovative solutions to mitigate their impacts.

The environmental implications of nanoplastics and antibiotics extend beyond wastewater systems, as these contaminants can enter the food chain through trophic transfer. Aquatic organisms, including fish and shellfish, can ingest nanoplastics and antibiotics, leading to bioaccumulation and potential health risks for humans who consume contaminated seafood [73,74]. The long-term effects of such exposure are still not fully understood, but preliminary studies suggest that both nanoplastics and antibiotics may disrupt metabolic pathways and contribute to adverse health outcomes [75]. This risk underscores the urgency of addressing the sources and pathways of these contaminants to protect both environmental and human health. In addition to their ecological impacts, the presence of nanoplastics and antibiotics in the environment poses significant challenges for regulatory frameworks and risk assessment. Current methodologies for detecting and quantifying nanoplastics in environmental samples are still in development, complicating efforts to monitor their prevalence and impacts [53]. Furthermore, the regulatory landscape surrounding antibiotic use and disposal is often fragmented, leading to inconsistent practices that exacerbate the problem of antibiotic resistance[69]. A coordinated approach that integrates research, policy, and public awareness is essential to effectively address the dual threats posed by nanoplastics and antibiotics in wastewater systems.

The synergistic interactions and combined effects of nanoplastics and antibiotics in wastewater systems also highlight the need for interdisciplinary research to develop effective mitigation strategies. Collaborative efforts among environmental scientists, microbiologists, and public health experts are crucial to understanding the complex interactions between these contaminants and their effects on ecosystems[72]. Innovative technologies for wastewater treatment, such as advanced filtration systems and bioremediation techniques, may offer solutions to reduce the release of nanoplastics and antibiotics into the environment [67]. Additionally, public education campaigns aimed at reducing plastic use and promoting responsible antibiotic disposal can play a vital role in mitigating these issues.

5. Accumulation and Transport Mechanisms for Nanoplastics and Antibiotics in Water

The small size of nanoplastics allows them to evade traditional wastewater treatment processes, leading to their accumulation in water bodies and sediments. Studies indicate that nanoplastics can originate from the degradation of larger plastic debris, which undergoes fragmentation through physical, chemical, and biological processes in the environment [55,76]. This fragmentation results in a continuous influx of nanoplastics into aquatic systems, where they can remain for extended periods due to their resistance to degradation [7,77]. The persistence of nanoplastics in these environments raises concerns about their potential ecological impacts, particularly in terms of bioaccumulation and trophic transfer within aquatic food webs.

The transport of nanoplastics through rivers, lakes, and oceans is facilitated by various physical and chemical processes. Their small size and high surface area-to-volume ratio enable them to be easily transported by water currents and to adsorb a variety of pollutants, including heavy metals and organic contaminants [78]. This transport mechanism not only increases their distribution across vast aquatic environments but also enhances their potential to interact with aquatic organisms. For instance, studies have shown that nanoplastics can be ingested by zooplankton, which mistake them for food, leading to their entry into the food web [79]. The transport dynamics of nanoplastics are influenced by environmental factors such as water temperature, salinity, and pH, which can affect their stability and interaction with other contaminants [20,80]. Bioaccumulation of nanoplastics in aquatic organisms poses significant risks, particularly for species at lower trophic levels. Research has demonstrated that organisms such as Daphnia and Artemia can accumulate nanoplastics in their tissues, leading to potential toxicological effects [81,82]. The bioaccumulation process is further complicated by the ability of nanoplastics to adsorb harmful chemicals from the surrounding environment, which can then be transferred through the food web [83]. This phenomenon raises concerns about the potential for biomagnification, where higher trophic-level organisms, including fish and marine mammals, may experience increased exposure to both nanoplastics and the associated contaminants [84]. The implications of such bioaccumulation extend to human health, particularly through seafood consumption, as humans may inadvertently ingest nanoplastics and their associated pollutants [7,85].

The interaction of antibiotics with aquatic environments is another critical area of concern. Antibiotics are often introduced into water bodies through agricultural runoff, wastewater discharge, and pharmaceutical waste, leading to their persistence in aquatic ecosystems [86]. The solubility of antibiotics in water can vary significantly based on their chemical structure, which influences their bioavailability and potential for environmental persistence. Factors such as temperature, pH, and the presence of organic matter can affect the degradation rates of antibiotics in aquatic environments, thereby influencing their ecological impacts [87]. The persistence of these compounds raises concerns about their potential to contribute to the development of antibiotic-resistant bacteria in aquatic ecosystems, posing risks to both environmental and human health. The uptake of antibiotics by aquatic organisms is a critical pathway through which these contaminants can enter the food chain. Various aquatic species, including fish and invertebrates, can absorb antibiotics from their environment, leading to potential toxicological effects and alterations in reproductive and developmental processes. The accumulation of antibiotics in aquatic organisms can also affect their interactions within the food web, potentially leading to shifts in community dynamics and ecosystem functioning [88]. Furthermore, the presence of antibiotics in aquatic environments can influence the behavior and physiology of organisms, potentially altering their susceptibility to diseases and environmental stressors [86,87].

Environmental factors play a significant role in the transport and fate of antibiotics in aquatic systems. Temperature, for instance, can influence the solubility and degradation rates of antibiotics, affecting their persistence and bioavailability. Similarly, pH levels can impact the ionization state of antibiotics, which in turn affects their adsorption to sediments and uptake by aquatic organisms [80]. The presence of organic matter can also influence the transport of antibiotics, as it can either enhance or inhibit their bioavailability depending on the specific interactions involved [86,87]. Understanding these environmental factors is crucial for predicting the behavior of antibiotics in aquatic ecosystems and assessing their potential ecological impacts. The combined effects of nanoplastics and antibiotics in aquatic environments represent a complex challenge for ecosystem health. The presence of nanoplastics can enhance the transport and bioavailability of antibiotics, as they can adsorb these contaminants and facilitate their uptake by aquatic organisms [78]. This interaction may lead to increased exposure of organisms to both nanoplastics and antibiotics, potentially exacerbating the toxicological effects associated with each contaminant [7,80]. Furthermore, the combined effects of these contaminants may result in synergistic interactions that could have unforeseen consequences for aquatic ecosystems and human health [85,87].

6. Synergetic Interactions Between Nanoplastics and Antibiotics

The increasing prevalence of nanoplastics in aquatic environments has raised significant concerns regarding their interactions with antibiotics and their potential implications for microbial communities. The adsorption of antibiotics onto nanoplastics can enhance their persistence in the environment, leading to increased exposure of microbial communities to these pharmaceuticals. This phenomenon is particularly concerning as it may contribute to the development of antimicrobial resistance (AMR), a pressing global health issue [89,90]. Table 2 shows an overview of the synergistic effects of nanoplastics and antibiotics in aquatic environments .

The adsorption process is influenced by several factors, including the physicochemical properties of both the nanoplastics and the antibiotics. For instance, the surface charge, hydrophobicity, and size of nanoplastics can significantly affect the extent of antibiotic adsorption [94]. Studies have shown that cationic nanoplastics exhibit a higher affinity for negatively charged antibiotics, thereby facilitating their accumulation in aquatic environments [95]. This accumulation can lead to altered degradation pathways for antibiotics, as the presence of nanoplastics may inhibit the activity of microbial communities responsible for breaking down these compounds [96,97]. Consequently, the transport of antibiotics in wastewater systems may be enhanced, leading to their increased bioavailability and potential ecological impacts. Furthermore, the interaction between nanoplastics and antibiotics can have profound implications for microbial communities. The presence of nanoplastics can alter the composition and function of these communities, potentially leading to shifts in microbial diversity and metabolic activity [80]. For example, the introduction of nanoplastics into aquatic ecosystems has been shown to disrupt the balance of microbial populations, favoring the growth of antibiotic-resistant strains [89]. This shift can exacerbate the problem of AMR, as resistant bacteria may proliferate in environments where antibiotics are present, leading to the emergence and spread of resistant genes. Figure 2 illustrates the multifaceted interactions between nanoplastics (NPs) and bacterial cells, highlighting the mechanisms by which NPs affect bacterial physiology and ecological outcomes [98]. Nanoplastics, influenced by their charge, size, and the structure of bacterial cell membranes, can increase membrane permeability and, in severe cases, cause membrane rupture. This facilitates NP penetration and the release of intracellular components such as enzymes and riboflavin.

Table 2. Overview of the synergistic effects of nanoplastics and antibiotics in aquatic environments.

Aspect	Interactions	Resistance Contribution	Environmental Implications	References
Adsorption	Antibiotics adsorb onto nanoplastics.	Nanoplastics carry resistant genes.	Increased antibiotic persistence.	[4]
Degradation Influence	Nanoplastics alter antibiotic degradation.	Enhanced microbial resistance.	Risks to ecosystems and health.	[44][91]
Transport and Bioavailability	Changed antibiotic transport dynamics.	Promotes resistance spread.	Wastewater treatment challenges.	[92]
Microbial Community Dynamics	Impacts microbial community composition.	Increased resistance in aquatic systems.	Long-term ecological challenges.	[93]

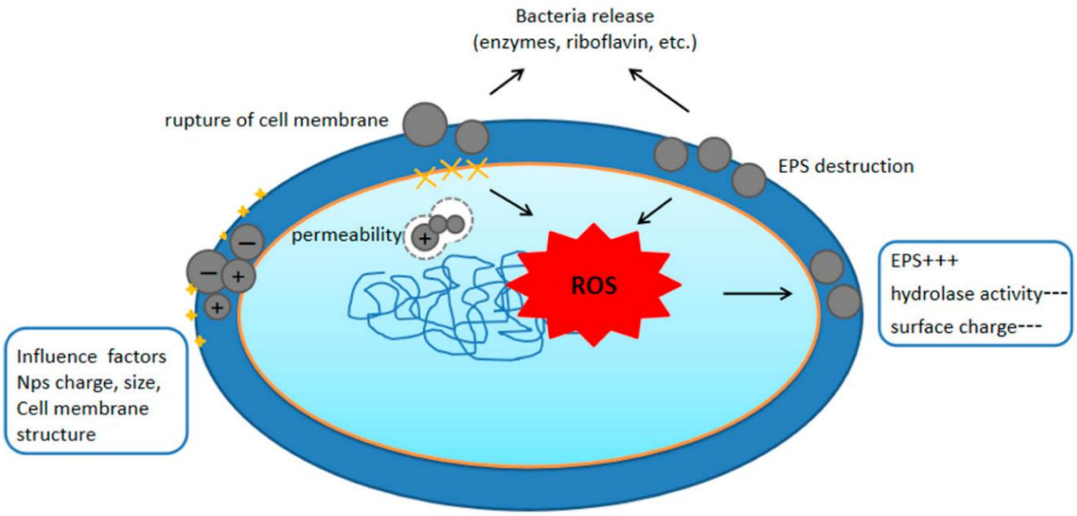

Fig. 2. Interaction between nanoplastics and bacteria. ”+++”implies an increase, “---" implies a reduction. Also, EPs implies extracellular polysaccharides. (Source: Wang et al.[98]. https://creativecommons.org/licenses/by/4.0/)

NPs also modulate extracellular polymeric substances (EPS) production, where “+++” indicates increased EPS and “---” denotes reduced hydrolase activity and altered surface charge, affecting biofilm integrity, bacterial protection, and the potential for horizontal gene transfer (HGT) [98]. Furthermore, NPs induce reactive oxygen species (ROS) generation, causing oxidative stress that damages DNA, proteins, and lipids, which can trigger stress-induced HGT [98]. Collectively, these interactions influence bacterial survival, community composition, and the dissemination of antibiotic resistance genes (ARGs), contributing to the increased abundance of antibiotic-resistant bacteria (ARB) in aquatic environments and impacting overall ecosystem and human health [98].

This interaction between micro- and nanoplastics with antibiotics and the surrounding environment can lead to the formation of a biofilm. However, this has implications for ARG transfer, especially as ultraviolet photoaging increases, which leads to the adsorption of ARGs, bacteria, and plasmids onto micro- and nanoplastics. In addition, the presence of reactive oxygen species is highlighted as a key factor that increases the permeability of bacterial cell membranes, facilitating the horizontal transfer of ARGs. Chemicals leached from aged micro- and nanoplastics can also enhance this transfer. The biofilm surrounding micro- and nano plastics helps protect against excessive ROS, prevents antibiotic degradation, and creates an environment that enriches ARGs. This process exacerbates the potential for antimicrobial resistance development in water bodies contaminated with micro- and nanoplastics, further highlighting the complex ecological and health challenges posed by microplastics in aquatic ecosystems.

The role of nanoplastics as vectors for antibiotic-resistant genes is a critical area of concern. Research indicates that nanoplastics can facilitate the horizontal gene transfer of resistance genes among bacteria, thereby promoting the spread of AMR [89]. This process is particularly alarming in wastewater treatment plants, where high concentrations of both nanoplastics and antibiotics coexist. The combination of these pollutants can create a selective pressure that favors the survival of resistant bacteria, which may then enter natural water bodies, posing a risk to public health and ecosystems. Moreover, the synergistic effects of nanoplastics and antibiotics on microbial communities can lead to complex interactions that are not yet fully understood. For instance, the presence of nanoplastics may enhance the toxicity of certain antibiotics, leading to increased stress on microbial populations[80]. This stress can result in shifts in community structure, with potential consequences for ecosystem function and resilience [95]. The implications of these interactions extend beyond microbial communities, as they can also affect higher trophic levels, including fish and other aquatic organisms that rely on these microbes for food [80]. In addition to their role in promoting AMR, nanoplastics can also influence the ecological dynamics of aquatic environments. The accumulation of nanoplastics in sediments can alter nutrient cycling and organic matter decomposition, further impacting microbial communities and their interactions with antibiotics. This alteration can lead to changes in the availability of nutrients, which may affect the growth and metabolism of both resistant and susceptible bacterial strains [89]. Consequently, the interplay between nanoplastics, antibiotics, and microbial communities is a multifaceted issue that requires further investigation to fully understand its implications for environmental health and safety. The environmental persistence of nanoplastics is another critical factor that complicates their interactions with antibiotics. Unlike larger plastic debris, which can degrade over time, nanoplastics can remain in the environment for extended periods, continuously interacting with various pollutants, including antibiotics [94]. This persistence raises concerns about the long-term effects of nanoplastics on microbial communities and the potential for chronic exposure to antibiotics, which may further drive the development of AMR. As such, understanding the fate and transport of nanoplastics in aquatic systems is essential for assessing their ecological risks.

The removal of antibiotics and nanoplastics from water systems requires a combination of advanced and traditional treatment methods. Advanced oxidation processes (AOPs), such as ozone, UV, or hydrogen peroxide, are effective for degrading antibiotics and breaking down nanoplastics into less harmful substances. Membrane filtration techniques, including nanofiltration and reverse osmosis, offer high-efficiency physical separation of both contaminants. Activated carbon adsorption and coagulation-flocculation are widely used to capture and remove these pollutants. Biodegradation through microorganisms helps degrade antibiotics, while biofiltration systems trap and potentially degrade nanoplastics. Emerging methods, like electrochemical treatments for antibiotics and magnetic separation for nanoplastics, also show promise. Integrating these approaches optimizes removal efficiency, addressing the persistence of these contaminants in aquatic environments.

7. Impacts on One Health of Antibiotic and Nanoplastics in Wastewater

The proliferation of nanoplastics and antibiotics in aquatic ecosystems has emerged as a significant environmental concern, impacting biodiversity, ecosystem functionality, and water quality. The accumulation of nanoplastics in freshwater and marine ecosystems poses direct threats to aquatic organisms, including fish, invertebrates, and microorganisms. Studies indicate that anthropogenic litter, including plastics, is not only abundant but also mobile within river ecosystems, leading to selective retention and redistribution downstream that ultimately affects marine environments [99]. This mobility facilitates the introduction of pollutants into diverse habitats, disrupting ecological balances and threatening biodiversity. The ecological effects of nanoplastics extend beyond mere physical presence; they can alter the behavior and physiology of aquatic organisms. For instance, ingestion of nanoplastics by fish and invertebrates can lead to bioaccumulation and biomagnification within food webs, ultimately affecting higher trophic levels, including humans.

Furthermore, the presence of nanoplastics can disrupt microbial communities, which are essential for nutrient cycling and energy flow within aquatic ecosystems. Recent research indicates that nanoplastics markedly influence microbial assemblages and ecosystem processes in ways that go beyond the effects of microplastic [4]. For example, nanoplastics have been shown to increase the abundance and horizontal transfer of antibiotic resistance genes in soil microbial communities, shifting the host taxa and functional potential relative to microplastics [3,4]. Nanoplastics also alter wetland soil denitrifier communities and enhance denitrification rates, indicating changes to biogeochemical nitrogen cycling [100]. In engineered environments such as wastewater treatment, chronic nanoplastic exposure reshapes activated sludge microbial networks and suppresses nutrient removal functions [3]. Mechanistically, nanoplastics can adhere to microbial surfaces, impact membrane transport pathways, and induce oxidative stress, leading to shifts in microbial composition and activity [3,4]. These findings suggest that nanoplastic pollution not only alters microbial taxonomic profiles but also affects ecosystem functioning and resilience, posing potential risks to environmental health [3,4,100]. The disruption of these microbial communities can hinder nutrient cycling, which is vital for maintaining the productivity of aquatic habitats.

Antibiotics, often introduced into aquatic systems through agricultural runoff and wastewater discharge, exacerbate the ecological impacts of nanoplastics. The presence of antibiotics in aquatic environments has been linked to the development of antibiotic-resistant bacteria, which poses a significant threat to both environmental and human health. The emergence of these resistant strains can disrupt microbial ecology, leading to altered nutrient cycling and diminished ecosystem services. The interaction between antibiotics and nanoplastics may further complicate these dynamics, as nanoplastics can adsorb antibiotics, potentially increasing their bioavailability and toxicity to aquatic organisms [101]. This interaction underscores the need for comprehensive studies to understand the combined effects of these pollutants on aquatic ecosystems.

Water quality is another critical aspect affected by the presence of nanoplastics and antibiotics. The accumulation of pollutants in aquatic environments can lead to significant degradation of water quality, impacting not only aquatic life but also human health and economic activities reliant on clean water sources. This cyclical nature of pollution highlights the importance of monitoring both water and sediment quality to assess the overall health of aquatic ecosystems [102]. Moreover, the economic implications of declining water quality are substantial, affecting fisheries, tourism, and recreational activities, thereby impacting local economies [103]. The impacts of nanoplastics and antibiotics on aquatic biodiversity are profound, with potential long-term consequences for ecosystem stability. The introduction of these pollutants can lead to shifts in species composition and abundance, as sensitive species may decline while more resilient or opportunistic species proliferate. This shift can alter food webs and ecosystem functions, reducing the overall resilience of aquatic systems to environmental changes [104]. Additionally, the entanglement and ingestion of plastic debris by aquatic organisms can lead to direct mortality, further threatening biodiversity. The loss of biodiversity diminishes the capacity of ecosystems to provide essential services, such as water purification, habitat provision, and carbon sequestration.

Microbial resistance development in aquatic systems is a growing concern, particularly in the context of antibiotic pollution. The presence of antibiotics can select resistant strains of bacteria, which can proliferate and spread within aquatic environments, potentially entering human populations through water sources. This phenomenon not only threatens public health but also complicates the management of infectious diseases. The implications of antibiotic resistance extend beyond individual organisms, as resistant bacteria can disrupt microbial communities and nutrient cycling processes, leading to broader ecological consequences. The interaction between antibiotics and nanoplastics may further enhance the persistence and spread of these resistant strains, necessitating urgent research and mitigation strategies.

Table 3 provides a comprehensive comparison of the impacts of antibiotics and nanoplastics on water and sediment quality in aquatic ecosystems. Both pollutants pose significant risks to environmental health, requiring targeted mitigation strategies.

The role of sediment in aquatic ecosystems cannot be overlooked, as it serves as a sink for pollutants, including nanoplastics. Sediments can accumulate contaminants over time, acting as a reservoir that can release pollutants back into the water column under certain conditions [102]. This dynamic can lead to episodic spikes in pollutant concentrations, further complicating the assessment of water quality and ecosystem health. Monitoring sediment quality is crucial for understanding the long-term impacts of pollution on aquatic ecosystems and for developing effective management strategies. The interplay between sediment and water quality emphasizes the need for comprehensive monitoring programs that address both components. The socio-economic implications of pollution in aquatic ecosystems are significant, particularly in regions reliant on fisheries and tourism. The degradation of water quality and biodiversity can lead to declines in fish populations, affecting local livelihoods and food security[103].

Table 3. Impacts of antibiotics and nanoplastics on water and sediment quality in aquatic ecosystems.

Impact area	Antibiotics	Nanoplastics
Water quality		
Disruption of microbial communities	Alters microbial populations.	Disrupts microbial communities.
Antibiotic resistance	Promotes antibiotic-resistant bacteria.	Harbors resistant bacteria.
Toxicity to aquatic organisms	Toxic to aquatic life.	Toxic to aquatic organisms.
Physical properties of water	Indirect effects on ecosystem balance.	Reduces water clarity, increases turbidity.
Chemical interactions	Enhances toxicity of other pollutants.	Adsorbs and transports toxins.
Sediment quality		
Persistence in sediment	Persists in sediments long-term.	Accumulates in sediments.
Impact on sediment-dwelling organisms	Disrupts sediment ecosystems.	Causes physical damage to organisms.
Pollutant transport and release	Gradual release into water.	Releases toxins from sediments.
Bioaccumulation and biomagnification	Spreads resistant bacteria in food chain.	Bioaccumulates, affecting food chain.
Altered nutrient cycling	Disrupts nutrient cycling.	Alters nutrient cycling.

Moreover, the economic costs associated with pollution, such as increased water treatment expenses and loss of recreational opportunities, can strain local economies [103]. Addressing the impacts of nanoplastics and antibiotics on aquatic ecosystems requires collaborative efforts among policymakers, researchers, and local communities to develop sustainable practices and mitigate pollution sources.

The health implications of nanoplastics and antibiotics are increasingly becoming a focal point in environmental health research. One of the primary exposure pathways for humans to nanoplastics is through the consumption of contaminated water and aquatic food sources, such as fish and shellfish. Studies have demonstrated that nanoplastics can accumulate in marine organisms, leading to biomagnification through the food web. For instance, research indicates that polystyrene nanoparticles can be ingested by marine species, including bivalves, which may then transfer these pollutants to higher trophic levels, including humans [83,105]. The ingestion of contaminated seafood poses a direct risk to human health, as these particles can carry toxic substances and pathogens, potentially leading to various health issues. Table 4 provides an overview of the human health implications of antibiotics and nanoplastics in aquatic ecosystems.

Table 4. Health implications of antibiotics and nanoplastics in aquatic ecosystems.

Health implication area	**Antibiotics**	**Nanoplastics**	**References**
Impact on aquatic organisms			
Toxicity	Toxic to fish, invertebrates, and other aquatic species.	Toxicity due to physical damage and chemical adsorption.	[106] [63]
Reproductive health	Disrupts reproduction in aquatic organisms.	Impairs reproductive processes through physical damage or stress.	[59] [107]
Immune system effects	Weakens immune response, increasing susceptibility to diseases.	Can cause immune suppression in aquatic organisms.	[108] [109]
Growth and development	Inhibits growth and development of juvenile organisms.	Impacts growth, leading to abnormal development.	[110] [111]
Bioaccumulation	Antibiotics accumulate in tissues, affecting food chain.	Nanoplastics bioaccumulate in tissues, transferring toxins up the food chain.	[112][113]
Antibiotic resistance	Contributes to the development of antibiotic-resistant bacteria.	Can harbor antibiotic-resistant bacteria, spreading resistance.	[114][115]
Environmental and ecosystem health			
Disruption of ecosystem functions	Alters microbial communities, disrupting ecosystem processes like nutrient cycling.	Alters ecosystem balance by affecting microbial communities and sediment structure.	[93][116]
Biodiversity loss	Reduces biodiversity due to altered species composition.	Reduces biodiversity by causing physical and chemical harm to organisms.	[117][118]
Food web impacts	Affects the aquatic food web by reducing organism health.	Impacts food webs by transferring toxic materials up the chain.	[106]
Water and sediment quality	Decreases water quality due to accumulation and toxicity.	Reduces water quality, increasing turbidity and pollution.	[119][115]
Human health risks			
Contaminated seafood	Consumption of contaminated seafood can cause human health issues.	Nanoplastics in seafood can pose unknown risks to human health.	[120][121]
Antibiotic-resistant infections	Exposure to resistant bacteria through seafood and water.	Potential for human exposure to resistant bacteria via aquatic food sources.	[122]
Toxin exposure	Direct exposure to antibiotics through water can cause human health risks.	Ingestion of nanoplastics can lead to unknown toxic effects in humans.	[44]
Waterborne diseases	Increases the prevalence of waterborne diseases due to microbial imbalances.	Can lead to an increase in waterborne diseases through contamination.	[123]
Ecological and health monitoring needs			
Need for surveillance	Essential to monitor antibiotic concentrations and resistance patterns.	Need to monitor nanoplastics concentration and their potential effects on health.	[44]
Regulatory measures	Implement tighter regulations on antibiotic use and discharge.	Increase research on nanoplastics and develop regulation standards for aquatic environments.	[124][125]

Inhalation and dermal exposure during recreational activities in contaminated waters represent additional pathways for human exposure to nanoplastics. The small size of nanoplastics allows them to become airborne, particularly in polluted environments, where they can be inhaled or come into contact with the skin [39]. This exposure can lead to systemic absorption, where nanoplastics may enter the bloodstream and affect various organs, including the lungs and gastrointestinal tract [44]. The potential for these particles to penetrate biological barriers raises concerns about their long-term health effects, which are still not fully understood.

Long-term exposure to nanoplastics and antibiotic residues can result in a range of health effects. Research has shown that nanoplastics can induce cellular and molecular toxicity, leading to inflammation, oxidative stress, and even genotoxicity in various organisms [86,126]. In humans, the chronic ingestion of nanoplastics may disrupt gut microbiota and impair metabolic functions, contributing to diseases such as obesity and diabetes [127]. Furthermore, the presence of antibiotic residues in contaminated water can exacerbate these health risks by promoting the development of antibiotic-resistant bacteria, which pose a significant threat to public health [7,39]. The role of contaminated water in spreading antimicrobial resistance is a critical concern in the context of nanoplastics. Antibiotics can adsorb onto the surface of nanoplastics, facilitating their transport through aquatic environments and enhancing the likelihood of exposure to both humans and wildlife[128].

This phenomenon not only increases the risk of antibiotic resistance but also raises questions about the efficacy of current antibiotic treatments, as resistant strains proliferate in environments contaminated with both antibiotics and nanoplastics [89].

The interplay between these contaminants underscores the need for comprehensive strategies to mitigate their impact on human health. Moreover, nanoplastics have the potential to serve as vectors for pathogens and toxic chemicals. Their high surface area allows for the adsorption of various environmental pollutants, including persistent organic pollutants, which can then be transferred to organisms upon ingestion[129]. This bioaccumulation can lead to increased toxicity and adverse health effects, as these contaminants may disrupt endocrine functions and contribute to carcinogenesis [130]. The ability of nanoplastics to carry and enhance the bioavailability of harmful substances presents a significant risk to both aquatic ecosystems and human health.

The interaction between nanoplastics and bacteria is another area of concern, as these particles can influence microbial communities in aquatic environments. Research has shown that nanoplastics can alter bacterial behavior, potentially leading to changes in nutrient cycling and pathogen dynamics[89].

This disruption can have cascading effects on ecosystem health and resilience, further complicating the relationship between environmental contaminants and human health. The potential for nanoplastics to facilitate the spread of pathogenic bacteria raises alarms about food safety and public health, particularly in regions reliant on contaminated water sources for agriculture and aquaculture. In addition to the direct health implications, the environmental persistence of nanoplastics poses long-term risks. These particles can remain in ecosystems for extended periods, continuously interacting with organisms and accumulating in food webs [131].

The slow degradation of plastics means that the health risks associated with their presence in the environment will likely persist, necessitating ongoing research and monitoring to understand their full impact on human health and the environment [132].

8. Environmental Factors Influencing Nanoplastic–Antibiotic Interactions

Environmental conditions can profoundly shape the behavior, interactions, and combined ecological risks of nanoplastics and antibiotics in aquatic systems.

Figure 3 provides an overview of how environmental factors influence the fate, behavior, and interactions of nanoplastics and antibiotics in aquatic systems.

Major factors such as pH, salinity, organic matter, temperature, and microbial activity modulate nanoplastic surface properties, antibiotic speciation, and their mutual interactions, including co-corona formation and binding. These processes can, in turn, affect NP mobility, antibiotic persistence, and bacterial stress responses (ROS, EPS, membrane disruption), as well as the spread of ARGs.

pH variations influence both the surface charge of nanoplastics and the ionization state of antibiotics, which, in turn, could affect their adsorption, binding affinity, and bioavailability. Acidic or alkaline conditions may either enhance or inhibit nanoplastics–antibiotic complex formation, thereby altering microbial exposure and antibiotic activity across diverse aquatic environments [133, 134].

Salinity and ionic strength further affect nanoplastics–antibiotic interactions by promoting nanoplastics aggregation and sedimentation, thereby concentrating both pollutants in benthic zones and altering dispersal patterns in the water column. Ionic strength also impacts antibiotic speciation and solubility, influencing how antibiotics interact with nanoplastics and potentially modifying their toxicity and environmental transport [133 - 135].

Natural organic matter (NOM) plays a critical role in mediating nanoplastics–antibiotic interactions. NOM can adsorb onto nanoplastic surfaces, forming eco-coronas that alter nanoplastic surface properties and modify antibiotic binding. These interactions can reduce the bioavailability of antibiotics to microorganisms while stabilizing nanoplastics in suspension, thereby affecting their environmental fate and persistence [134, 136]. Similarly, temperature and light influence nanoplastics and antibiotic interactions. Elevated temperatures could accelerate chemical reactions, increasing nanoplastics mobility and enhancing antibiotic degradation rates. UV radiation can photodegrade antibiotics while simultaneously modifying nanoplastic surfaces, affecting both their stability and potential to interact with antibiotics [135, 137].

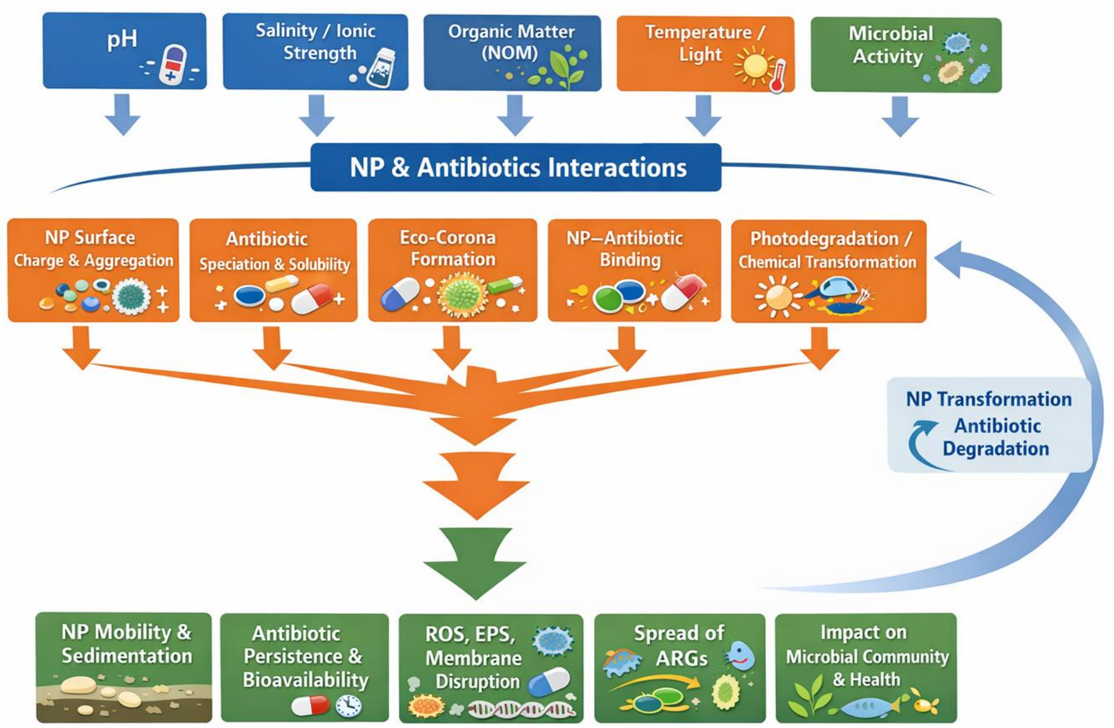

Fig. 3. Overview of the environmental factors influencing nanoplastic–antibiotic interactions.

Microbial activity adds another layer of complexity. Microorganisms colonizing nanoplastic surfaces can mediate antibiotic adsorption [138], degradation, and bioavailability. These interactions may facilitate horizontal gene transfer and influence the spread of ARGs, highlighting the interplay between nanoplastics, antibiotics, and microbial communities in shaping aquatic ecosystem dynamics [134, 139].

9. Discussion

From the perspective of linking synergistic interactions, AMR, and one health risks, this review highlights that nanoplastics and antibiotics act as interacting stressors in wastewater systems, in addition to occurring independently. Their co-occurrence in WWTPs could create conditions that enhance contaminant persistence, microbial disruption, and antimicrobial resistance, thereby posing risks to aquatic ecosystems and human health within a One Health framework [19,20,39]. Nanoplastics could serve as vectors for antibiotics and antibiotic resistance genes (ARGs), thereby increasing their environmental mobility and bioavailability [7,53,90]. This interaction strengthens the linkage between wastewater contamination, ecosystem exposure, and downstream human health risks through food chains and water use [39,40].

Given wastewater treatment limitations and contradictory information, the evidence consistently indicates that conventional wastewater treatment processes are insufficient for removing nanoplastics and residual antibiotics, particularly at the nanoscale [20,38]. While advanced methods, such as membrane filtration, adsorption, and ionic liquid-assisted extraction, have shown improved removal efficiencies, their effectiveness varies widely depending on contaminant properties and operational conditions[45,48,50]. Some studies report enhanced nanoplastic removal through coagulation and adsorption [28,29], whereas others document incomplete removal, membrane fouling, and secondary contamination risks [38,49]. These contradictions highlight the absence of standardized performance metrics and limit direct comparison across treatment technologies.

Regarding microbial community disruption and AMR development, a central finding across studies is the role of nanoplastics in altering microbial community dynamics and promoting AMR. Nanoplastics can increase bacterial membrane permeability, induce oxidative stress, and facilitate horizontal gene transfer, particularly in biofilm-rich wastewater environments [89,98]. However, reported outcomes differ; some studies indicate microbial inhibition and toxicity [80], while others show selective enrichment of resistant bacterial populations without immediate ecosystem collapse [93]. These inconsistencies likely reflect differences in nanoplastic size, surface chemistry, aging state, and antibiotic class [94,95]. Outstandingly, most of the available data are derived from short-term laboratory studies, limiting insight into long-term resistance evolution under environmentally realistic conditions.

Several critical gaps remain. Firstly, long-term and chronic exposure studies examining the combined effects of nanoplastics and antibiotics across multiple trophic levels, including bioaccumulation and trophic transfer, are scarce [85]. Such studies should incorporate realistic environmental concentrations and extended exposure durations to better reflect ecological conditions. Secondly, standardized and validated analytical methods for detecting and quantifying nanoplastics in complex wastewater, sludge, and sediment matrices remain inadequate, creating uncertainty in risk assessment and regulatory monitoring [53]. Future research should prioritize the harmonization of sampling, extraction, and characterization protocols to improve comparability across studies. Thirdly, although adsorption mechanisms are relatively well established, the environmental fate of antibiotic–nanoplastic complexes, particularly during bioaccumulation, digestion, and trophic transfer, remains poorly understood [73].

In parallel, research into biodegradable and environmentally benign plastic alternatives, as well as strategies to reduce antibiotic inputs at source, should be advanced to mitigate long-term environmental loading. Addressing these gaps through coordinated experimental, methodological, and material-innovation research will strengthen risk assessments and support more effective wastewater management and policy decisions.

From the perspectives of biodiversity and human health, the reviewed evidence indicates that nanoplastics and antibiotics jointly threaten aquatic biodiversity by disrupting microbial processes, nutrient cycling, and food web stability [104]. Human exposure occurs primarily through contaminated water and seafood, with emerging evidence linking nanoplastics to disruption of the gut microbiota, oxidative stress, and chronic health effects [43,44]. Of particular concern is the role of nanoplastics in facilitating the environmental spread of AMR, reinforcing the connection between wastewater pollution and public health challenges [89,114]. However, the relative contribution of nanoplastics compared to other resistance drivers remains uncertain.

Overall, the literature demonstrates that synergistic interactions between nanoplastics and antibiotics amplify ecological and health risks beyond their individual effects, while existing wastewater treatment and monitoring frameworks remain inadequate. Addressing these challenges requires harmonized methodologies, long-term field-based studies, and integrated One Health approaches that explicitly account for co-contaminant dynamics. Strengthening this evidence base is essential for improving wastewater management strategies and informing effective environmental and public health policies.

10. Future Research Directions in Addressing the Synergistic Effects of Antibiotics and Nanoplastics in Wastewater

The synergistic effects of antibiotics and nanoplastics in wastewater present a complex challenge to aquatic ecosystems, primarily due to their combined influence on microbial communities and the potential for increased antibiotic resistance. Nanoplastics, generated from the degradation of larger plastic waste, possess unique properties (such as a high surface-to-volume ratio) that enhance their interaction with microorganisms. This interaction can facilitate the horizontal gene transfer of antibiotic resistance genes (ARGs) among bacteria, thereby exacerbating the proliferation of antibiotic-resistant bacteria (ARB) in aquatic environments [3,4,140,141]. The presence of antibiotics in wastewater, originating from agricultural runoff and pharmaceutical discharges, further compounds this issue by creating selective pressure that favors the survival and growth of ARB [142]. Studies have demonstrated that nanoplastics can act as vectors for the attachment and transfer of ARGs, leading to a significant increase in the abundance of ARB in contaminated waters [140,141]. This phenomenon underscores the urgent need for comprehensive research into how nanoplastics influence microbial dynamics and the spread of antibiotic resistance.

Moreover, the ecological implications of the interaction between antibiotics and nanoplastics extend beyond microbial communities, affecting higher trophic levels and overall ecosystem health. The bioaccumulation of nanoplastics in aquatic organisms, such as fish and shellfish, raises concerns regarding the transfer of both nanoplastics and ARB through the food web [143, 144]. For instance, research indicates that nanoplastics can impair reproductive functions in aquatic species, leading to decreased biodiversity and altered ecosystem dynamics [144]. Additionally, the potential for humans to be exposed to these contaminants through seafood consumption underscores the public health risks associated with the co-occurrence of antibiotics and nanoplastics in aquatic environments [145,146]. The implications of these findings necessitate a multidisciplinary approach to address the challenges posed by these emerging contaminants, focusing on ecological and health perspectives.

Innovative detection and remediation strategies are essential to mitigate the risks associated with the synergistic effects of antibiotics and nanoplastics. Advanced technologies such as surface-enhanced Raman spectroscopy (SERS) have been proposed to improve the identification of nanoplastics in complex water matrices, enabling more accurate monitoring of their presence and concentration[147]. While SERS offers high sensitivity and specificity, its practical deployment at large scales remains constrained by instrument cost, operational complexity, and the need for standardized protocols, particularly in routine wastewater monitoring. In parallel, the development of filtration and purification systems capable of simultaneously targeting antibiotics and nanoplastics is critical for reducing their ecological and health impacts [148]. However, the feasibility and scalability of these systems depend on energy demand, maintenance requirements, and integration into existing wastewater treatment infrastructure. Additionally, potential unintended consequences, such as membrane fouling, generation of secondary waste streams, or transformation of contaminants into by-products with unknown toxicity, must be carefully evaluated. Addressing these limitations through pilot-scale validation and life-cycle assessments is essential to ensure that advanced treatment technologies are both effective and environmentally sustainable. Interdisciplinary research integrating toxicology, microbiology, and environmental science will be vital in developing effective strategies to combat the dual threats these contaminants pose and safeguard aquatic ecosystems and human health.

11. Conclusion

The co-occurrence of nanoplastics and antibiotics in wastewater systems represents a significant threat to environmental and human health, driven by their pervasive presence and potential for synergistic interactions. These contaminants not only compromise ecosystem integrity but also exacerbate the spread of antimicrobial resistance through enhanced persistence and bioavailability in aquatic environments. Hence, highlighting the need for targeted and coordinated interventions rather than broad conceptual responses. To address this challenge, we recommend the following:

From a technology perspective, wastewater treatment systems should be upgraded to enable the simultaneous removal of antibiotics and nanoplastics. Integrating membrane filtration with high-affinity nanoadsorbents such as graphene oxide, biochar-based composites, or metal–organic frameworks should be further investigated. Hybrid treatment systems combining membrane bioreactors with advanced oxidation processes (e.g., ozonation or UV/H_2O_2) should also be prioritized, supported by pilot- and full-scale studies to evaluate feasibility, cost-effectiveness, and long-term performance under real wastewater conditions.

Regarding policy and regulation, antibiotics and micro-/nanoplastics must be formally recognized as linked emerging contaminants. Discharge standards for these pollutants should be defined and mandated, with routine monitoring and reporting by wastewater treatment facilities. Strengthened pharmaceutical waste management regulations and enforcement of extended producer responsibility for plastics and pharmaceutical industries, including take-back programs and cleaner production incentives, will help reduce pollutant input at the source.

Finally, in terms of education and public awareness, public campaigns should promote responsible antibiotic use and proper disposal of unused medicines.

Targeted training programs for wastewater operators, healthcare professionals, and environmental regulators can enhance adherence to best management practices. Additionally, community-level education initiatives emphasizing the environmental and health risks of plastic pollution and antibiotic misuse will encourage behavioral changes that support source-level pollution prevention and long-term protection of aquatic ecosystems and human health.

Author’s contribution

Sylvester Chibueze Izah: Conceptualization, Methodology, Investigation, Resources, Supervision, Drafting original draft, Review & editing. Matthew Chidozie Ogwu: Conceptualization, Methodology, Investigation, Resources, Visualization, Drafting original draft, Review & editing. Esther Ugo Alum: Methodology, Investigation, Resources, Validation, Drafting original draft, Review & editing.

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