**Frontiers in Environmental Research**
**Print ISSN: 2960-0251**
**Online ISSN: 2960-026X**
**DOI: https://doi.org/10.61784/fer3040**

# ENVIRONMENTAL RISKS AND ECOTOXICOLOGY OF ANTIBIOTIC POLLUTION IN WATER ENVIRONMENTS AND COMPREHENSIVE PREVENTION AND CONTROL STRATEGIES

ZhiJiang Nan
*Qinghai Institute of Technology, Xining 810016, Qinghai, China.*
*Corresponding Author Email: zjnan@qhit.edu.cn*

**Abstract:** The widespread detection of antibiotics in aquatic environments has become a global environmental issue, posing huge potential threats to ecosystems and human health. This paper systematically reviews research progress on antibiotic pollution in aquatic environments, focusing on its environmental behavior, ecotoxicological effects, and comprehensive prevention and control strategies. Firstly, an overview of the global and Chinese pollution status, major sources, and occurrence characteristics of antibiotics in aquatic environments is provided. Secondly, the migration and transformation laws, environmental fate, and ecological risk assessment methods of antibiotics in aquatic environments are explored in depth. Then, the ecotoxicological effects of antibiotics on aquatic organisms are elaborated in detail, including impacts on microbial community structures, the generation and spread of antibiotic resistance genes (ARGs), toxic effects on aquatic animals and plants, and potential risks to human health. Finally, comprehensive prevention and control strategies are proposed from four levels: source control, process interception, end-of-pipe treatment, and system management. Future research directions are also outlined to provide a scientific basis for the risk management of antibiotic pollution in aquatic environments.

**Keywords:** Antibiotic pollution; Aquatic environment; Environmental risk; Ecotoxicology; Antibiotic resistance genes (ARGs); Comprehensive prevention and control

## 1 INTRODUCTION

The discovery and application of antibiotics is a milestone in the history of human medicine, having drastically reduced the mortality rates of infectious diseases. However, with the widespread application of antibiotics in medical, livestock breeding, and aquaculture fields, large quantities of antibiotics and their metabolites have entered aquatic environments through various pathways, forming a new class of pollutants[1-2]. These substances are ubiquitous in the environment; even at extremely low concentrations (ng/L–μg/L), they may exert adverse effects on aquatic ecosystems and induce the generation and spread of resistant bacteria and antibiotic resistance genes (ARGs), thereby threatening human health[3-4].

Over the past two decades, with advancements in analytical techniques—particularly the popularization of high-sensitivity detection methods such as High-Performance Liquid Chromatography-Tandem Mass Spectrometry (HPLC-MS/MS)—the detection frequency and concentration ranges of antibiotics in aquatic environments have continuously expanded[5]. Research indicates that antibiotics have been detected in global surface water, groundwater, drinking water, and even polar environments. As a major producer and consumer of antibiotics, China faces particularly prominent problems regarding antibiotic pollution in aquatic environments, which has attracted widespread attention from the government, academia, and the public. This paper aims to systematically review the research progress on environmental risks and ecotoxicology of antibiotic pollution in aquatic environments. Based on the systematic thinking of "source-process-end", it proposes comprehensive prevention and control strategies to provide a reference for the scientific management and control of antibiotic pollution in aquatic environments[6-7].

## 2 POLLUTION STATUS AND SOURCES OF ANTIBIOTICS IN AQUATIC ENVIRONMENTS

### 2.1 Pollution Levels and Distribution Characteristics in Global and Chinese Aquatic Environments

According to existing literature reports, antibiotic pollution in aquatic environments globally presents obvious spatiotemporal differences and species specificity[5].

Global Overview: In developed regions such as Europe and North America, due to strict regulations and perfect sewage treatment facilities, antibiotic concentrations in surface water are usually at the ng/L level. However, in developing countries in Asia, Africa, and Latin America, due to relatively lax regulations and low sewage treatment rates, surface water antibiotic concentrations can reach the μg/L level. High concentrations of fluoroquinolones and macrolides are frequently detected in rivers in India, Pakistan, and other countries[7].

Current Status in China: China is the world's largest producer and consumer of antibiotics, with an annual usage of tens of thousands of tons. Consequently, the problem of antibiotic pollution in China's aquatic environment is particularly prominent. The main characteristics are as follows:

Uneven Spatial Distribution: Pollution levels show a trend of being higher in the eastern coastal and densely populated areas than in the western regions. The Pearl River Delta, Yangtze River Delta, and Beijing-Tianjin-Hebei regions are hotspots for antibiotic pollution. Studies indicate that the concentration of sulfamethoxazole in the Guangzhou section of the Pearl River can reach hundreds of ng/L, and quinolone antibiotic concentrations in the Tianjin section of the Haihe River are also at a relatively high level[8].

Diverse Species: A wide variety of antibiotic species are detected in China’s aquatic environments, mainly including Sulfonamides (SAs), Quinolones (FQs), Macrolides (MLs), Tetracyclines (TCs), and β-Lactams. Among them, fluoroquinolones (e.g., norfloxacin, ciprofloxacin) and sulfonamides (e.g., sulfamethoxazole) are the two classes with the highest detection frequency and most prominent concentrations[9-11].

Differences in Water Body Types:

Surface Water:* Rivers, lakes, and reservoirs are generally polluted by antibiotics. River sections receiving sewage treatment plant effluent, aquaculture wastewater, and runoff pollution have the highest antibiotic concentrations[10].

Groundwater:* Affected by soil leaching and septic tank leakage, antibiotics are also detected in groundwater in some areas, but concentrations are usually lower than in surface water[12].

Drinking Water:* Conventional water treatment processes struggle to completely remove antibiotics. Trace amounts have been detected in drinking water in some areas. Although far below therapeutic doses, the health risks of long-term low-dose exposure cannot be ignored[12-14].

Coastal Seawater:* Estuaries and coastal waters are increasingly affected by antibiotic pollution due to terrestrial inputs[12].

## 2.2 Major Sources and Input Pathways of Antibiotic Pollution

The pathways for antibiotics to enter aquatic environments are complex and diverse, mainly including point sources and non-point sources.

### *2.2.1 Point source pollution*

Domestic Sewage: About 30–90% of antibiotics consumed by humans are excreted in urine and feces in their original form or as metabolites, entering sewage treatment plants (STPs) through sanitary systems. However, the removal efficiency of traditional activated sludge processes for many antibiotics is limited (ranging from 0 to 90%), resulting in large quantities of antibiotics being discharged into receiving waters with the effluent[7,13,15-17].

Medical Wastewater: Hospitals are the places where antibiotics are most intensively used. Their wastewater is characterized by complex composition, high concentration, and strong biological toxicity. Although some large hospitals have sewage treatment facilities, treatment effects vary, making them important point sources[16].

Pharmaceutical Industrial Wastewater: High-concentration process wastewater generated during antibiotic production. Although enterprises are required to perform pretreatment, accidental incidents or lax supervision may lead to the direct discharge of high-concentration antibiotics[18-20].

Aquaculture Wastewater: The livestock and aquaculture industries use large amounts of antibiotics to prevent diseases and promote growth. Animal feces and aquaculture pond water contain high concentrations of antibiotics and their metabolites. Without effective treatment, they are discharged or applied as fertilizer, eventually entering water bodies through runoff[19].

### *2.2.2 Non-point source pollution*

Agricultural Runoff: Farmland applied with animal manure containing antibiotics can see antibiotics enter nearby water bodies through runoff during rainfall or irrigation[21].

Urban Runoff: Urban surface runoff containing pet feces, landfill leachate, etc., may also carry antibiotics into urban drainage systems or directly into water bodies[18].

Diffusion from Aquaculture Areas: In modes such as cage farming, antibiotics are applied directly to open waters, easily causing widespread pollution in surrounding waters[22-24].

## 2.3 Physicochemical Properties and Environmental Persistence of Typical Antibiotics

The environmental behavior and ecological risks of antibiotics are closely related to their physicochemical properties, with key parameters including the octanol-water partition coefficient (log Kow), acid dissociation constant (pKa), water solubility, and photolysis and biodegradation half-lives[25].

Sulfonamides: Strong polarity, high water solubility, and low log Kow (usually <1). They migrate easily in the water phase and do not easily accumulate in sediments, but their photolysis rate is relatively slow[26].

Quinolones: Mostly amphoteric ions with multiple pKa values, taking different forms in water environments with different pH levels. Water solubility varies significantly. They can form complexes with metal ions and easily adsorb onto sediments and suspended particles; photolysis is an important natural attenuation pathway[27].

Macrolides: Relatively strong hydrophobicity, easy to adsorb onto solid particles, but relatively stable in water[26-28].

Tetracyclines: Prone to forming stable complexes with divalent and trivalent cations (e.g., $Ca^{2+}$, $Mg^{2+}$, $Fe^{3+}$). They strongly adsorb onto soil and sediments. Concentrations in the water phase are usually not high, but they may remain in sediments for a long time.

Most antibiotics belong to “pseudo-persistent pollutants” in the environment. Although they can be partially degraded, continuous input leads to their long-term presence in the environment[25,29-31].

# 3 ENVIRONMENTAL BEHAVIOR AND FATE OF ANTIBIOTICS IN AQUATIC ENVIRONMENTS

After entering the aquatic environment, antibiotics undergo a series of complex migration and transformation processes, including adsorption/desorption, hydrolysis, photolysis, and biodegradation. These processes jointly determine their environmental fate, persistence, and ultimate destination.

### 3.1 Migration and Transformation Processes

#### *3.1.1 Adsorption and desorption*

Adsorption is a key process affecting the distribution of antibiotics between the solid and liquid phases, controlling their distribution in water and sediments/soil. Adsorption mechanisms mainly include:

Electrostatic Interaction: Depends on the charge form of the antibiotic and the charge properties of the solid surface[31].

Hydrophobic Partitioning: For antibiotics with higher log Kow (e.g., some macrolides, fluoroquinolones), hydrophobic interaction is the main adsorption mechanism.

Coordination Complexation: Antibiotics such as tetracyclines and quinolones can form complexes with metal ions or metal oxide surfaces through functional groups like carboxyl and keto groups[32].

Hydrogen Bonding and π-π Interaction: Aromatic antibiotics can interact with aromatic-rich organic matter (e.g., black carbon) through π-π electron donor-acceptor interactions.

Environmental factors such as the organic matter content of sediments, clay mineral types, pH, and ionic strength significantly affect adsorption behavior. Although adsorption can temporarily reduce the aqueous concentration, sediments may become a “sink” and a “secondary source” for antibiotics, releasing them again when conditions change[33].

#### *3.1.2 Hydrolysis*

Hydrolysis is a chemical reaction between antibiotic molecules and water. Its rate is affected by pH, temperature, and ionic strength. The β-lactam ring of β-lactam antibiotics (e.g., penicillin) is unstable and prone to hydrolysis, which is one of their main degradation pathways. In contrast, the hydrolysis rates of sulfonamides and quinolones are usually slow[34].

#### *3.1.3 Photolysis*

Photolysis is an important attenuation pathway for many antibiotics in the surface water layer, including direct photolysis (antibiotics absorb light energy and react) and indirect photolysis (oxidized by photoactive substances such as hydroxyl radicals and singlet oxygen). Quinolones, tetracyclines, and sulfonamides, which contain chromophores, are sensitive to photolysis. Photolysis rates are influenced by light intensity, wavelength, water depth, dissolved organic matter (DOM, which can both sensitize and quench photochemical reactions), pH, and nitrate/nitrite concentrations. Photolysis products may still retain biological activity or toxicity, and their ecological risks deserve attention[34-35].

#### *3.1.4 Biodegradation*

Biodegradation is an important transformation process for antibiotics in deep water bodies and sediments. However, since many antibiotics were designed to resist microbial degradation, their biodegradability is generally poor.

Aerobic Degradation: Occurs in aerobic units of sewage treatment plants and oxygen-rich surface water layers, but rates are often limited[32].

Anaerobic Degradation: In sediments and oxygen-deficient water bodies, certain antibiotics (e.g., metronidazole) can be reductively degraded by anaerobic microorganisms, but overall, research on degradation efficiency under anaerobic conditions is insufficient.

Co-metabolism: Many antibiotics cannot serve as the sole carbon and energy source for microorganisms but can be partially transformed through co-metabolism in the presence of other easily degradable organic matter[36].

Microbial community structure, antibiotic concentration, temperature, and nutritional conditions affect biodegradation efficiency. Notably, low concentrations of antibiotics may screen for and enrich microorganisms with degradation potential, but long-term exposure may also inhibit the activity of degrading bacteria[37].

### 3.2 Environmental Fate Models and Multi-Media Simulation

To predict the distribution and persistence of antibiotics in complex environments, researchers have developed various fate models, ranging from simple mass balance models to complex multi-media fugacity models. These models integrate the physicochemical properties of antibiotics, environmental parameters (temperature, pH, hydrological conditions, etc.), and rate constants for various migration and transformation processes. They can be used to simulate the dynamic distribution of antibiotics among water, sediments, and biota; assess long-term exposure concentrations; identify key source and sink areas; and provide decision support for environmental risk management[38].

### 3.3 Ecological Risk Assessment Methods for Antibiotics

Accurately assessing the environmental risks of antibiotics is a prerequisite for formulating control standards. Currently, the Risk Quotient (RQ) method is widely used for preliminary assessment:

Risk Quotient (RQ) = Predicted No Effect Concentration (PNEC) in the environment / Predicted Environmental Concentration (PEC) in the environment

Acquisition of PEC: Can be obtained through actual monitoring (MEC) or estimation based on usage, emission factors, and dilution models[39].

Derivation of PNEC: Usually based on chronic or No Observed Effect Concentrations (NOEC) obtained from laboratory toxicity tests, divided by an assessment factor (usually 10–1000, depending on data quality). Due to the specificity of antibiotic action, it is necessary to consider effects on the most sensitive species (e.g., specific algae, bacteria) and conduct special assessments for microbial resistance risks[35].

Studies show that in hotspots such as sewage treatment plant outlets and downstream of aquaculture areas, the RQ values for multiple antibiotics (e.g., sulfamethoxazole, erythromycin, ciprofloxacin) are greater than 1, indicating medium to high ecological risks. However, the Risk Quotient method has limitations, such as not considering the mixture effects of antibiotics, the chronic effects of long-term low-dose exposure, and the development of resistance. Therefore, higher-level ecological risk assessments need to combine methods such as field community surveys, mesocosm experiments, and effect-directed analysis[33].

## 4 ADVANCES IN ECOTOXICOLOGICAL RESEARCH ON ANTIBIOTIC POLLUTION

Antibiotics are a special class of pollutants with biological activity. Their ecotoxicological effects are reflected not only in traditional acute/chronic toxicity but, more prominently, in the interference with microbial communities and the selection pressure for resistance.

### 4.1 Impact on Aquatic Microbial Communities

Microorganisms are the cornerstone of aquatic ecosystems, driving the biogeochemical cycling of elements such as carbon, nitrogen, and phosphorus. The effects of antibiotics on microorganisms are the most direct and significant.

#### *4.1.1 Community structure and diversity*

Long-term exposure to sub-inhibitory concentrations of antibiotics can significantly alter the composition and diversity of microbial communities in water and sediments. This usually manifests as a decrease in the abundance of sensitive flora (e.g., certain nitrifying bacteria, phosphorus-accumulating bacteria) and an increase in the abundance of tolerant flora or flora with degradation capabilities. Such structural changes may further affect ecologically driven functions, such as organic matter degradation and nitrification/denitrification processes. Research indicates that even at the ng/L level, sulfonamide antibiotics can alter the bacterial community structure in sediments[40].

#### *4.1.2 Functional genes and metabolic pathways*

Metagenomic studies show that under antibiotic stress, the metabolic pathway profiles of microbial communities change. Genes related to stress response, efflux pumps, cell membrane repair, and antibiotic resistance are upregulated, while some genes involved in basic metabolism (e.g., amino acid synthesis, energy metabolism) may be downregulated. This disturbance at the functional level may undermine the stability of microbial ecological services41.

### 4.2 Emergence, Enrichment, and Spread of Antibiotic Resistance Genes (ARGs)

This is one of the most concerning consequences of antibiotic pollution. The aquatic environment is a key site for the generation and spread of ARGs.

#### *4.2.1 Selection pressure and enrichment of ARGs*

The presence of antibiotics exerts strong selection pressure on bacterial communities. Bacteria carrying resistance genes (e.g., genes encoding inactivating enzymes, target site modification, enhanced efflux pumps) have a survival advantage and can reproduce in large numbers, leading to an increase in the abundance and diversity of ARGs in environmental microbial populations. Studies show that in sewage treatment plants, downstream of farms, and in polluted rivers, the abundance of ARGs such as sulfonamides, tetracyclines, and β-lactams is significantly higher than background values[42].

#### *4.2.2 Horizontal Gene Transfer (HGT)*

HGT is the primary mechanism for the diffusion of ARGs among environmental bacteria, mainly including conjugation (via plasmids), transformation (uptake of free DNA), and transduction (via phages). Many factors in the aquatic environment can promote HGT:

Antibiotics themselves: Sub-inhibitory concentrations of certain antibiotics (e.g., fluoroquinolones) can act as inducers, stimulating the bacterial SOS response and increasing mutation rates and gene transfer frequencies[43].

Co-selection: Other pollutants such as heavy metals (e.g., Cu, Zn) and disinfection by-products may exert co-selection pressure with antibiotics, promoting the spread of plasmids or integrons carrying multiple resistance genes[44].

Mobile Genetic Elements (MGEs): Plasmids, transposons, and integrons are “vehicles” for ARGs. They are widely present in environmental microorganisms and can transfer ARGs between different species or even different bacterial phyla.

#### *4.2.3 Environmental resistome and human health risks*

Environmental ARGs and antibiotic-resistant bacteria (ARB) may spread to humans directly or indirectly through drinking water, recreational water, and consumption of contaminated aquatic products. Even more concerning is that environmental bacteria can serve as a “reservoir” and “incubator” for ARGs, where novel resistance genes may evolve and subsequently transfer to human pathogens. Therefore, controlling antibiotic pollution and the spread of ARGs in the environment is a crucial link in addressing the global public health crisis of antibiotic resistance[45].

### 4.3 Toxic Effects on Aquatic Animals and Plants

#### *4.3.1 Aquatic animals*

Acute and Chronic Toxicity: High concentrations of antibiotics can cause acute toxicity to fish, crustaceans, shellfish, etc., affecting survival. More common are chronic toxicity effects caused by long-term low-dose exposure, including:
*Growth Inhibition:* Affecting feeding, digestion, and energy metabolism.
*Reproductive and Developmental Toxicity:* Interfering with the endocrine system, affecting gonad development, gametogenesis, reproductive capacity, and offspring survival rates. For example, certain antibiotics have estrogenic or anti-androgenic activity.
*Oxidative Stress and Tissue Damage:* Inducing the production of reactive oxygen species (ROS), leading to lipid peroxidation and DNA damage, causing pathological changes in organs such as the liver, gills, and kidneys[46].
*Immunotoxicity:* Inhibiting immune cell function and reducing disease resistance.
*Behavioral Changes:* Affecting swimming ability, foraging behavior, and social interaction.
Species Sensitivity Differences: Sensitivity to the same antibiotic varies significantly among different species and life stages. Usually, juvenile stages are more sensitive.

#### *4.3.2 Aquatic plants and algae*

Algae (especially cyanobacteria and green algae) are sensitive groups to antibiotics. Antibiotics can inhibit algae growth by inhibiting chlorophyll synthesis, interfering with the photosynthetic system, and destroying cell division, thereby altering the algae community structure (e.g., causing a decrease in sensitive algae species and making resistant or tolerant species dominant). This may destroy the primary productivity of aquatic ecosystems and produce cascading effects through the food web. Macrophytes (e.g., submerged plants) may also suffer from growth inhibition and physiological interference[47].

### 4.4 Potential Risks to Human Health

The general public is exposed to trace amounts of antibiotics and their ARGs/ARB in the environment over long periods through drinking water and consuming aquatic products. The health risks are not yet fully clear, but potential threats include:
Direct Toxicity: The concentration of antibiotics in drinking water is extremely low, so the risk of direct toxicity alone is very small, but the “cocktail effect” of long-term co-exposure to multiple antibiotics and other pollutants needs attention[48].
Allergy and Hypersensitivity: A very small number of sensitive individuals may have allergic reactions to trace amounts of antibiotics (e.g., penicillin).
Gut Microbiota Disturbance: Antibiotics in drinking water may affect the balance of human gut microorganisms.
Increased Risk of Resistant Bacterial Infection: This is the most significant risk. Environmental ARB or ARGs may enter the human body through various pathways, colonize the gut or skin, or, if pathogens acquire these ARGs, lead to refractory infections.

## 5 COMPREHENSIVE PREVENTION AND CONTROL STRATEGIES FOR ANTIBIOTIC POLLUTION

Addressing the complex problem of antibiotic pollution in aquatic environments requires comprehensive strategies combining “source reduction, process control, end-of-pipe treatment, and system management” to build a whole-process prevention and control system covering production, consumption, and discharge[49].

### 5.1 Source Control Strategies

Source control is the most fundamental and economical way to solve pollution problems.

#### *5.1.1 Regulating and reducing antibiotic use*

Medical Field: Strengthen the management of clinical antibiotic application, implement prescription review, hierarchical management, and usage monitoring, and reduce unnecessary prophylactic and therapeutic use. Strengthen public education to put an end to self-purchasing and abuse.
Livestock Breeding Industry:
Strictly enforce the “antibiotic ban”, prohibiting the addition of antibiotics for growth promotion to feed.
Therapeutic antibiotics must be used with a veterinary prescription and comply with withdrawal period regulations.
Promote “antibiotic-free farming” and “antibiotic-reduction farming” modes, improve breeding environments, and enhance animal immunity.
Research and apply antibiotic alternatives, such as probiotics, prebiotics, antimicrobial peptides, plant extracts, and phages.
Aquaculture Industry: Optimize farming modes (e.g., ecological integrated farming) to reduce disease occurrence; promote vaccine immunization and green fishery drugs.
Pharmaceutical Industry: Encourage the development and production of new, environmentally friendly (easily degradable, low ecotoxicity) antibiotics and improve production processes to reduce the loss of raw materials.

#### *5.1.2 Improving laws, regulations, and standard systems*

Include more high-risk antibiotics in the list of priority controlled pollutants. Research and timely formulate environmental quality standards for antibiotics and their ARGs in aquatic environments. Increase indicators related to antibiotics in the discharge standards for wastewater from industries such as pharmaceuticals and farming.

## 5.2 Process Blockade and End-of-Pipe Treatment Technologies

For wastewater containing antibiotics that has already been generated or is unavoidable, efficient treatment is required.

### *5.2.1 Strengthening traditional sewage treatment processes*

Optimizing Operating Parameters: Extending the sludge retention time (SRT) helps enrich slow-growing microorganisms and may improve the biodegradation efficiency of certain antibiotics.

Combined Processes: Processes such as $A^2/O$ and MBR have better removal effects on some antibiotics than the traditional activated sludge process. Combining biochemical treatment with advanced treatment units (e.g., ozone, activated carbon adsorption) can enhance overall removal efficiency.

### *5.2.2 Advanced Oxidation Processes (AOPs)*

AOPs can effectively degrade or even mineralize refractory antibiotics by generating strongly oxidizing hydroxyl radicals (·OH), etc., making them a promising depth treatment technology.

Ozone Oxidation: Effective in removing antibiotics containing unsaturated bonds or aromatic rings (e.g., sulfonamides, fluoroquinolones), often used in combination with $H_2O_2$ ($O_3/H_2O_2$) to enhance ·OH yield.

Fenton and Fenton-like Technologies: Using the $Fe^{2+}/H_2O_2$ system to generate ·OH has low costs but requires a narrow pH range (~3). Heterogeneous Fenton, photo-Fenton, and electro-Fenton technologies have improvements in broadening the pH application range and reducing iron sludge.

Photocatalytic Oxidation: Semiconductor catalysts represented by $TiO_2$ generate electron-hole pairs under ultraviolet irradiation, subsequently generating oxidizing species. Developing visible-light responsive catalysts (e.g., doped modified $TiO_2$, g-$C_3N_4$) is a current hotspot.

Persulfate Advanced Oxidation: Oxidation technology based on $SO_4^{\cdot -}$ has advantages such as high oxidation potential, long half-life, and wide pH adaptation range, showing excellent degradation effects on some antibiotics.

AOPs need to address energy consumption, cost, by-product toxicity, and the quenching effect of actual water matrices (e.g., DOM, carbonate).

### *5.2.3 Adsorption technology*

Adsorbent materials such as activated carbon, biochar, carbon nanotubes, graphene, and metal-organic frameworks (MOFs) can be used to remove antibiotics from water. Biochar has attracted much attention due to its wide source of raw materials, low cost, and environmental friendliness. Its adsorption capacity and selectivity can be enhanced through physical and chemical modification. Adsorption is the concentration and transfer of pollutants; saturated adsorbents need to be properly handled to avoid secondary pollution.

### *5.2.4 Membrane separation technology*

Nanofiltration (NF) and Reverse Osmosis (RO) membranes can effectively intercept antibiotics with larger molecular weights and produce good water quality, but problems such as concentrate treatment, membrane fouling, and high operating costs exist[37].

### *5.2.5 Natural and ecological treatment systems*

Ecological engineering measures such as constructed wetlands, stabilization ponds, and riparian filtration zones remove antibiotics through synergistic effects of plant absorption, substrate adsorption, and microbial degradation. They have the advantages of low cost and good landscape and ecological benefits, making them suitable for the deep purification of tail water from sewage treatment plants or the interception of non-point source pollution. However, they require large land areas, and treatment efficiency is affected by seasons and climate.

### *5.2.6 Removal and control of antibiotic resistance genes*

Controlling the spread of ARGs is a deeper challenge. Some AOPs (e.g., UV, ozone, advanced oxidation) can destroy cell structures and free DNA, effectively reducing the abundance of ARB and ARGs. Disinfection processes (chlorine, UV) have a certain inactivating effect on ARB, but it is necessary to be alert to the possibility of inducing bacterial stress responses and gene transfer. Research shows that Membrane Bioreactors (MBR) have better removal effects on certain ARGs than traditional activated sludge processes[37-43].

## 5.3 System Management and Policy Recommendations

### *5.3.1 Establishing lifecycle management and multi-department collaborative mechanisms*

Establish a management system covering the entire lifecycle of antibiotics "R&D-production-circulation-use-disposal-emission". Strengthen communication and collaboration among environmental protection, health, agriculture, drug administration, and science and technology departments to form regulatory synergy, achieve information sharing, and conduct joint law enforcement.

### *5.3.2 Improving environmental monitoring networks and risk assessment systems*

Incorporate antibiotics and representative ARGs into national and local water environment monitoring or special survey plans to grasp their spatiotemporal distribution and trends. Develop rapid, sensitive, high-throughput on-site monitoring and screening technologies. Develop more refined ecological and health risk assessment models that incorporate mixture effects, long-term chronic effects, and resistance risks[48].

### *5.3.3 Promoting green pharmaceutical manufacturing and circular economy*

Encourage the pharmaceutical industry to adopt green synthesis routes to reduce the use and generation of toxic and hazardous substances from the source. Explore reduction technologies for antibiotics and ARGs in aquaculture waste (feces, litter) and, based on safety assessment, achieve resource utilization (e.g., composting after harmless treatment for field application).

**5.3.4 Strengthening public participation and international cooperation**

Raise public awareness of the harm and environmental consequences of antibiotic abuse, advocating for green consumption and healthy lifestyles. Antibiotic pollution and resistance are global challenges; we should actively participate in international conventions and cooperative projects, sharing data, technologies, and experiences to respond together[38].

## 6 FUTURE RESEARCH PROSPECTS

Despite a large amount of research, there are still many scientific gaps and challenges regarding antibiotic pollution in aquatic environments that urgently need to be addressed:

Identification and Risk of New Antibiotics and Transformation Products: With the development and market launch of new antibiotics, their behavior and risks in the environment are unknown. At the same time, the identification, toxicity, and resistance development potential of complex transformation pathways and products of antibiotics in the environment need to be strengthened.

Ecological Effects of Long-Term Low-Dose Combined Exposure: Real environments often involve the coexistence of multiple antibiotics and other pollutants (e.g., heavy metals, nanomaterials, microplastics). Research on the joint effects and mechanisms of this type of long-term, low-dose, multi-component combined exposure on aquatic ecosystems (from molecular to community levels) is at the forefront of ecotoxicology.

Transmission Mechanisms and Control of Resistance Genes in the Environment: There is a need to reveal the transmission dynamics, key driving factors, and barriers of ARGs in different environmental media more deeply, and to develop specific control technologies targeting MGEs and HGT processes.

Research and Development of High-Efficiency, Low-Carbon Treatment Technologies and Integration: Develop new removal technologies (e.g., novel catalysts, functional materials) with low cost, high efficiency, low energy consumption, and few by-products, and optimize combined processes of different technologies to deal with complex and variable actual wastewater[38-41].

Risk-Based Precise Control and Standard Formulation: Accumulate more comprehensive toxicity data for native species and environmental exposure data, develop risk assessment methods suitable for China’s national conditions, and provide a basis for scientifically formulating environmental quality standards, discharge standards, and ecological restoration goals.

Systematic Research under the “One Health” Framework: Conduct interdisciplinary and cross-media comprehensive research under the integrated health framework of “Human-Animal-Environment”, tracing the complete chain of antibiotics and ARGs from the source to the human body, to provide a scientific basis for formulating systematic solutions[42-45].

## 7 CONCLUSION

Antibiotic pollution in aquatic environments is a complex environmental problem accompanying the development of modern society. Its environmental risks are reflected not only in the direct toxicity to aquatic organisms but, more profoundly, in the disturbance of microbial ecological functions and the accelerated spread of antibiotic resistance, posing long-term threats to ecosystem security and public health. This paper systematically reviews research progress in this field, revealing the widespread existence and locally severe pollution status of antibiotics in global and Chinese aquatic environments, and elucidating their complex migration and transformation behaviors and multiple ecotoxicological effects, especially the driving role in the development of resistance. Facing this challenge, single technologies or management measures are unlikely to be effective; comprehensive governance strategies must be adopted. This requires us to not only regulate source use and strengthen process and end-of-pipe treatment but also focus on building long-term prevention and control mechanisms from multiple dimensions, including laws and regulations, standard systems, monitoring and assessment, technological innovation, and public education. Future research should pay more attention to deep-seated scientific issues such as combined pollution effects, transformation product risks, and resistance gene transmission control, and commit to developing efficient and practical pollution control technologies. Only through continuous scientific research, strict regulation, and the joint efforts of the whole society can we effectively curb antibiotic pollution in aquatic environments and its cascading risks, protecting aquatic ecological security and human health to achieve sustainable development.

## COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

## REFERENCES

[1] Xie X, Liu W, Zhang J, et al. Enhanced adsorption and photocatalytic degradation performance of lomefloxacin by C60/CNTs composite under LED light irradiation. Journal of Materials Science: Materials in Electronics, 2025, 37 (1): 30-30. DOI:10.1007/S10854-025-16443-X.

[2] Böckmann M, Axtmann K, Bierbaum G, et al. Pulsed antibiotic release into the environment may foster the spread of antimicrobial resistance. FEMS microbiology ecology, 2025. DOI:10.1093/FEMSEC/FIAF128.

[3] Celano R M, Pinho D V J, Azevedo E O D F M S, et al. Environmentally relevant concentrations of the antibiotic azithromycin enhance the toxicity of the cyanobacterium Microcystis aeruginosa on the water flea Daphnia similis. Harmful Algae, 2026, 152: 103040-103040. DOI: 10.1016/J.HAL.2025.103040.

[4] Chen P, Huang F, Kou X, et al. Portable hierarchical MXene-graphene hybrid sensor for ultrasensitive multiplex antibiotic detection in aquatic environments. Chemical Engineering Journal, 2026, 527: 171523-171523. DOI: 10.1016/J.CEJ.2025.171523.

[5] Yalcin S, Cebeci T. Prevalence, antibiotic resistance, and heavy metal resistance genes of Raoultella species in marine fish from coastal districts in Türkiye: Potential health risk and environmental implications. Regional Studies in Marine Science, 2026, 93: 104712-104712. DOI: 10.1016/J.RSMA.2025.104712.

[6] Oluwakoya M O, Okoh I A. Antibiotic resistance profile of Campylobacter species recovered from some freshwater milieu in the Eastern Cape Province, South Africa.. BMC microbiology, 2025. DOI: 10.1186/S12866-025-04557-5.

[7] Li X, Han M, Shen S, et al. Exposure to Evironmentally Relevant Concentrations of Antibiotics Increases N2O Emissions and Delays Nitrate Removal: New Insights into Bacteriostatic Antibiotics at the Cellular Level. Environmental science & technology, 2025. DOI: 10.1021/ACS.EST.5C09865.

[8] Zhang M, Feng M, Zhou M, et al. Environmental Drivers and Source Apportionment of Antibiotic Pollution in Shichuan River Basin, China. Water, Air, & Soil Pollution, 2025, 237(4): 232-232. DOI: 10.1007/S11270-025-08902-2.

[9] Meireles N A, Sandahl M, Turner C, et al. Environmental fingerprinting of recent strategies for detection of macrolides and fluoroquinolones in environmental and food matrices based on green analytical chemistry indexes. Green Analytical Chemistry, 2026, 16: 100313-100313. DOI: 10.1016/J.GREEAC.2025.100313.

[10] Group I C C, Nofal R M, Rwamatwara A, et al. Strengthening surgical antibiotic stewardship in low-resource settings: a multicentre, prospective, quality improvement study.. The British journal of surgery, 2025, 112 (Supplement_15): xv65-xv67. DOI: 10.1093/BJS/ZNAF241.

[11] Choi U, Son E J, Han G, et al. Identification of Genetic and Environmental Factors Suppressing the Lethality and Antibiotic Susceptibility Mediated by Depletion of LptD, a Lipopolysaccharide Transport Protein. Journal of microbiology and biotechnology, 2025, 35: e2509011. DOI: 10.4014/JMB.2509.09011.

[12] Dilxat D, Zhang W, Wang J L, et al. Click chemistry-empowered multi-channel biosensing for highly-efficient detection of antibiotic resistance genes in aquatic environments. Water research, 2025, 290: 125121. DOI: 10.1016/J.WATRES.2025.125121.

[13] Liu X, Liu Y, Wo Y, et al. Synergistic application of photocatalysis and biocatalysis in antibiotic degradation: emerging strategies for sustainable environmental remediation. Chemical Papers, 2025(prepublish): 1-14. DOI: 10.1007/S11696-025-04541-3.

[14] Gong Z, Yu M, Jiang Y, et al. Emerging Transition Metal Sulfides for Sensing of Antibiotics in Environmental, Food and Biological Samples. Journal of Analysis and Testing, 2025(prepublish): 1-22. DOI: 10.1007/S41664-025-00414-6.

[15] Huang H, Wei L, Li L, et al. Microbial interactions as the key to understanding and controlling environmental spread of antibiotic resistance genes. npj Antimicrobials and Resistance, 2025, 3(1): 97-97. DOI: 10.1038/S44259-025-00174-4.

[16] Kumari H, Singh M, Chakrawarti K M, et al. Distribution and antibiotic resistance patterns of airborne staphylococci in urban environments of Delhi, India. Scientific Reports, 2025, 15(1): 43026-43026. DOI: 10.1038/S41598-025-95462-4.

[17] Lai J, Su J, Li Z, et al. Impact of extracellular polymeric substances from Skeletonema costatum on the combined toxicity of microplastics and antibiotics in estuarine environment.. Marine pollution bulletin, 2025, 223: 119077. DOI: 10.1016/J.MARPOLBUL.2025.119077.

[18] Shi C, Yang J, Yang L, et al. Micro and macro interaction behaviors analysis between microplastics and antibiotics in complex hydrodynamic environment. Journal of Environmental Chemical Engineering, 2025, 13(6): 120341-120341. DOI: 10.1016/J.JECE.2025.120341.

[19] Sundar S, Jayaprakash N, Govindaraj D. Carbon-based nanomaterials in the remediation of antibiotics from aquatic environments: Advances, mechanisms, and future perspectives. Environmental Pollution and Management, 2026, 3: 99-116. DOI: 10.1016/J.EPM.2025.11.002.

[20] Pizzol D L J, Lubschinski L T, Mohr B T E, et al. Future Trends in Antibiotic Concentrations and Risk Assessment of Selection Pressure Based on Reported Antibiotic Concentrations in Brazil's Aquatic Environments.. Integrated environmental assessment and management, 2025. DOI:10.1093/INTEAM/VJAF177.

[21] Tateno B K, Ricchizzi E, Latour K, et al. Infections and antibiotic treatment in long-term care facilities: results from 1-year cross sectional study in three Polish settings.. Antimicrobial resistance and infection control, 2025, 14 (1): 142. DOI: 10.1186/S13756-025-01659-7.

[22] Chen W, Li L, Dai X, et al. Health risk and benefit assessment methods for antibiotic resistance bacteria/genes in the environment: A critical review. Journal of environmental management, 2025, 396: 128071. DOI: 10.1016/J.JENVMAN.2025.128071.

[23] Borah P, Roy S, Ahmaruzzaman M. Environmental fate of complex antibiotics in aquatic systems and its degradation by electrochemical advanced oxidation process: A holistic review of process variables, mechanistic insights, and implications. Journal of Environmental Chemical Engineering, 2025, 13(6): 120267-120267. DOI: 10.1016/J.JECE.2025.120267.

[24] Wang J, Tao Y. Effects of Antibiotics at Environmental Concentrations on Cyanobacteria and its Mechanisms: A Review Focusing on Hormesis. Current Pollution Reports, 2025, 11(1): 61-61. DOI: 10.1007/S40726-025-00390-6.

[25] Yi X, Cai H, Liu H, et al. Environmental exposure augments the abundance and transferability of antibiotic resistance genes in the respiratory tract. Cell reports, 2025: 116517. DOI: 10.1016/J.CELREP.2025.116517.

[26] Diabil J M H G, Jalali A, Komijani M. Metagenomic analysis of antibiotic resistance and pathogens in landfill leachates: Environmental implications.. Journal of hazardous materials, 2025, 500: 140365. DOI: 10.1016/J.JHAZMAT.2025.140365.

[27] Hamdi S, Issaoui M, González M A, et al. Agro-waste materials: A low-cost approach to ionophore antibiotics mitigation in aquatic environment. Bioresource Technology Reports, 2025, 32: 102412-102412. DOI: 10.1016/J.BITEB.2025.102412.

[28] Wang H, Guo J, Chen X. Comparative Profiling of Antibiotic Resistance Genes and Microbial Communities in Pig and Cow Dung from Rural China: Insights into Environmental Dissemination and Public Health Risks. Biology, 2025, 14(11): 1623-1623. DOI: 10.3390/BIOLOGY14111623.

[29] Hao W, Zhang H, Wang K, et al. Determination of quinolone antibiotic residues in surface water environments by THB-Salen-COFs combined with UPLC−MS/MS. Microchemical Journal, 2025, 219: 116059-116059. DOI: 10.1016/J.MICROC.2025.116059.

[30] Sun J, Xu C, Wang D, et al. Comprehensive Review on the Distribution, Environmental Fate, and Risks of Antibiotic Resistance Genes in Rivers and Lakes of China. Water, 2025, 17(22): 3228-3228. DOI: 10.3390/W17223228.

[31] Jiménez G M D, Matias F M, Paiva I, et al. Antibiotic–Cyclodextrin Interactions: An Effective Strategy for the Encapsulation of Environmental Contaminants. Molecules, 2025, 30(22): 4359-4359. DOI: 10.3390/MOLECULES30224359.

[32] Li B, Gao H, Li R, et al. Characteristics of regionalized distribution of antibiotics and ARGs in Daliao River-Liaodong Bay waters and their environmental impact factors. Journal of Environmental Sciences, 2026, 160: 722-731. DOI: 10.1016/J.JES.2025.04.060.

[33] Wäfler N, Knüsli J, Lhopitallier L, et al. Screening for antibiotics residues among adults with respiratory infections in primary care in Switzerland: evaluating over-the-counter use and environmental exposure. Clinical microbiology and infection: the official publication of the European Society of Clinical Microbiology and Infectious Diseases, 2025. DOI: 10.1016/J.CMI.2025.10.024.

[34] Malik S S, Sadaiappan B, Hassan A A, et al. Environmental Footprint of Antibiotics: A Multi-Source Investigation of Wastewater Systems in UAE. Antibiotics, 2025, 14(11): 1105-1105. DOI: 10.3390/ANTIBIOTICS14111105.

[35] Shu Q, Sun J, Li H, et al. Environmental safety evaluation of organic fertilizer produced from spiramycin fermentation residue via thermally activated persulfate integrated with aerobic composting: Effects on antibiotic resistance genes, microbial communities, and soil quality. Environmental Technology & Innovation, 2025, 40: 104596-104596. DOI: 10.1016/J.ETI.2025.104596.

[36] Wen L, Dai J, Ma J, et al. Comprehensive Profiling of Quinolone Antibiotics in the Bohai Sea: Occurrence, Source Apportionment, and Environmental Risks.. Environmental pollution (Barking, Essex : 1987), 2025, 387: 127338. DOI: 10.1016/J.ENVPOL.2025.127338.

[37] Nian Q, Zhang H, Wang K, et al. MOF-801 and polydopamine dual-modified PAN nanofiber membranes for simultaneous removal of multiple antibiotic classes from environmental water. Journal of Environmental Management, 2025, 395: 127706-127706. DOI: 10.1016/J.JENVMAN.2025.127706.

[38] Manzoor I, Vijayaraghavan R. Ag-Capped Zinc Peroxide (Ag–$ZnO_2$) Nanocomposite: An Efficient Heterostructure Photocatalyst for the Environmental Remediation of Organic Dyes and Pharmaceuticals Antibiotics Under UV and Sunlight Irradiation. International Journal of Environmental Research, 2025, 19(6): 272-272. DOI: 10.1007/S41742-025-00952-Y.

[39] Chi T, Liu Z, Zhang B, et al. Risk assessment of the spread of antibiotic resistance genes from hospitals to the receiving environment via wastewater treatment plants. Ecotoxicology and environmental safety, 2025, 306: 119264. DOI: 10.1016/J.ECOENV.2025.119264.

[40] Pandey K N, Simon M, Vishwakarma K R, et al. Exploring Microbial Diversity, Antibiotic Resistance, and their Environmental Drivers in Urban and Peri-Urban Riverbed Sediments of Sub-tropical River Basins.. Environmental research, 2025, 288 (P1): 123174. DOI: 10.1016/J.ENVRES.2025.123174.

[41] Wang Y, Wu H, Lou X, et al. Sustainable and microwave-assisted extraction of tetracycline antibiotics from environmental water via magnetic pH-responsive block copolymer.. Talanta, 2025, 298(PB): 129034. DOI: 10.1016/J.TALANTA.2025.129034.

[42] Zhang J, Chang X, Ma Y, et al. Environmentally relevant concentrations of representative aquatic compounds promote the conjugative transfer of antibiotic resistance genes. Journal of Water Process Engineering, 2025, 79: 108936-108936. DOI: 10.1016/J.JWPE.2025.108936.

[43] Zhang X, Liu J, Zhan T, et al. Environmental concentrations of benzalkonium chloride promote the horizontal transfer of extracellular antibiotic resistance genes via natural transformation. Process Safety and Environmental Protection, 2025, 203 (PB): 108003-108003. DOI: 10.1016/J.PSEP.2025.108003.

[44] Hammerton G J C, Hooton P S, Sands K, et al. Sublethal concentrations of antibiotics enhance transmission of antibiotic resistance genes in environmental Escherichia coli. Frontiers in Microbiology, 2025, 16: 1675089-1675089. DOI: 10.3389/FMICB.2025.1675089.

[45] Guo Y, Zhang Z, Wang J, et al. Microplastic-mediated interactions with antibiotics and antibiotic resistance genes in sludge: combined effects and environmental implications.. Environmental geochemistry and health, 2025, 47 (11): 506. DOI: 10.1007/S10653-025-02811-3.

[46] Wang W, Duan L, Sun Y, et al. Occurrence forms and transformation mechanisms of typical antibiotics in the aquatic environment of the Zaohe-Weihe River estuary. Environmental geochemistry and health, 2025, 47(11): 502. DOI: 10.1007/S10653-025-02816-Y.