

FLUOROQUINOLONES AS ENVIRONMENTAL CONTAMINANTS: OCCURRENCE, FATE, AND PHYTOTOXICOLOGICAL IMPLICATIONS

Maria Gorea¹, Aura Rusu^{2,*}, Corneliu Tanase^{3,4}

¹George Emil Palade University of Medicine, Pharmacy, Science, and Technology of Targu Mures, 540142 Targu Mures, Romania

²Pharmaceutical and Therapeutical Chemistry Department, Faculty of Pharmacy, George Emil Palade University of Medicine, Pharmacy, Science, and Technology of Targu Mures, 540142 Targu Mures, Romania

³Pharmaceutical Botany Department, Faculty of Pharmacy, George Emil Palade University of Medicine, Pharmacy, Science, and Technology of Targu Mures, 540142 Targu Mures, Romania

⁴Research Center of Medicinal and Aromatic Plants, George Emil Palade University of Medicine, Pharmacy, Science and Technology of Targu Mures, 38 Gheorghe Marinescu Street, 540139 Targu Mures, Romania

*Correspondence:

Aura RUSU

aura.rusu@umfst.ro

Received: 7 May 2026; **Accepted:** 7 June 2026; **Published:** 30 June 2026

Abstract: Fluoroquinolones (FQs) are among the most widely used broad-spectrum antibiotics worldwide, valued for their efficacy against both Gram-positive and Gram-negative bacteria. However, their persistence in the environment has raised significant ecological concerns. Due to incomplete absorption and metabolic transformation in humans and animals, large quantities of FQs are excreted unchanged and subsequently enter aquatic and terrestrial ecosystems via wastewater, agricultural runoff, and biosolids application. This review synthesizes current evidence on the environmental fate of FQs, their phytotoxic effects on aquatic and terrestrial plants, and the potential of phytoremediation as a mitigation strategy. A systematic literature search was conducted for studies published between 2014 and 2025 using major scientific databases, including PubMed, ScienceDirect, Web of Science, and Scopus, to ensure comprehensive coverage of the relevant literature. Studies consistently demonstrate that FQs inhibit plant growth, reduce photosynthetic efficiency, and induce oxidative stress in a dose-dependent manner. Furthermore, FQs promote the dissemination of antibiotic resistance genes in microbial communities, posing an indirect but serious threat to human health. The review also highlights knowledge gaps and areas requiring further research, particularly regarding long-term ecological consequences and the optimization of phytoremediation systems.

Keywords: fluoroquinolones, ciprofloxacin, phytotoxicity, aquatic plants, terrestrial plants, bioaccumulation, antibiotic resistance, phytoremediation

1. Introduction

The global rise in antibiotic consumption has become a growing concern in the scientific community. Residues of antibacterial compounds released into the environment pose

significant ecological and public health challenges. Among these, fluoroquinolones (FQs) are of particular interest due to their widespread use in both human medicine and

veterinary practice, their high stability, and their strong adsorption to soil and sediment particles (Bhatt and Chatterjee, 2022).

Antibiotics, particularly FQs, are widely used to treat bacterial infections by targeting highly conserved enzymes, such as DNA gyrase and topoisomerase IV, which are essential for DNA helix unwinding during replication and transcription. Quinolones are synthetic antibiotics introduced into clinical practice approximately 50 years ago and remain widely used today for the treatment of a broad range of infections caused by both Gram-positive and Gram-negative bacteria (Martinez, 2019; Andriule et al., 2023).

FQs constitute the third largest group of antibiotics by global consumption. They are preferred in clinical practice due to their low allergenic potential, high oral bioavailability, and broad-spectrum antibacterial activity. Their use spans the treatment of urinary tract, respiratory, and gastrointestinal infections, as well as sexually transmitted diseases, and includes prophylactic and therapeutic applications in livestock and aquaculture (Bhatt and Chatterjee, 2022; Hamad, 2010; Collinsworth et al., 2022).

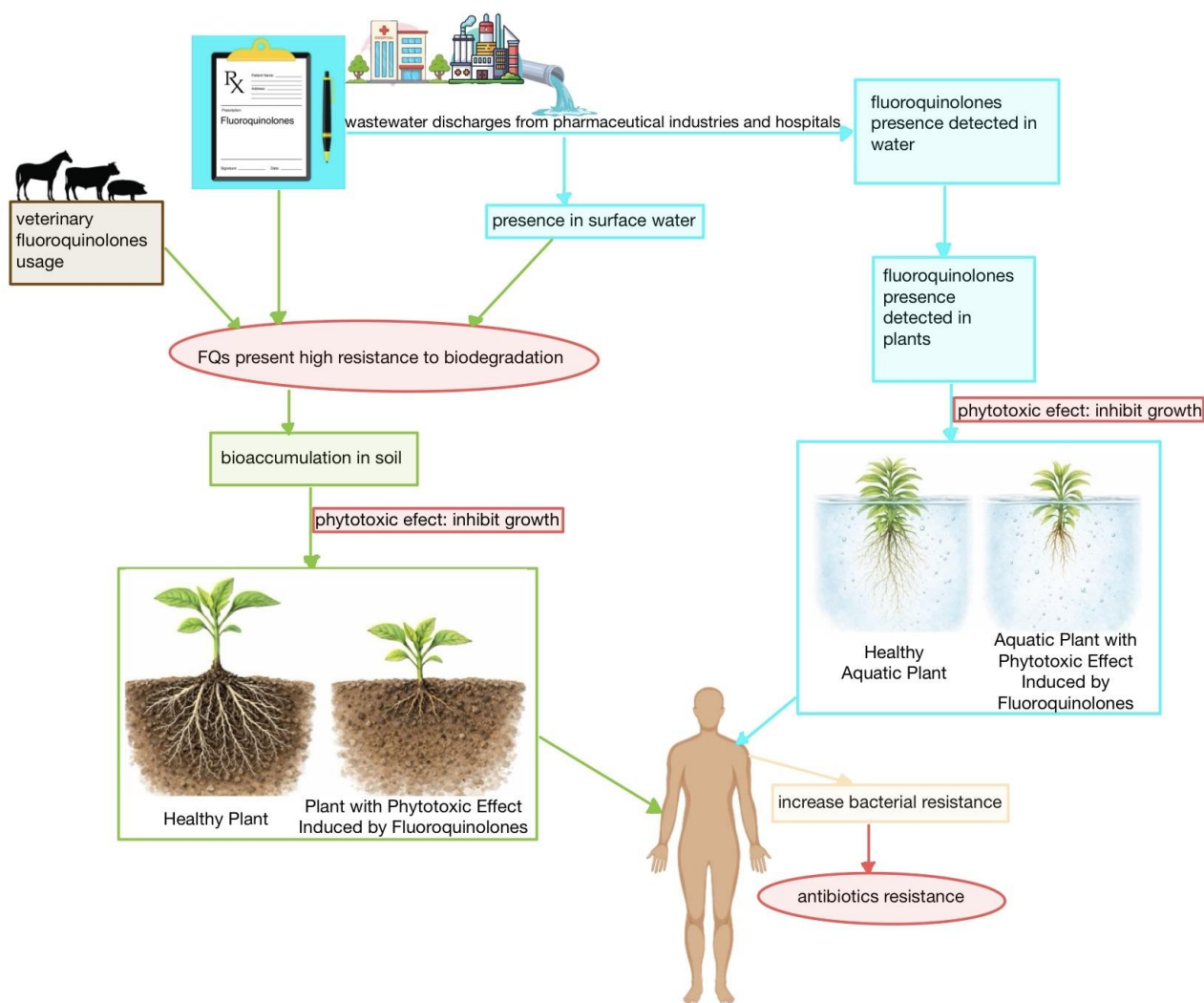


Fig. 1. Environmental pathways and phytotoxic effects of fluoroquinolones (FQs) leading to antibiotic resistance

Given their environmental relevance, this study adopts a systematic review approach to critically evaluate the existing literature on fluoroquinolones in environmental systems. This approach ensures a transparent and reproducible synthesis of available evidence regarding their occurrence, fate, and biological effects.

This situation highlights the importance of assessing and characterizing the phytotoxicity of these antibiotics, with particular attention to their effects on both aquatic and terrestrial plant species. Additionally, since FQs can disrupt basic microbial mechanisms, they can alter the natural balance of soil and aquatic ecosystems, promoting the spread of antibiotic resistance genes (Chen et al., 2024; Zhu et al., 2013).

Figure 1 illustrates the environmental dissemination of FQs from veterinary and pharmaceutical sources, their persistence and bioaccumulation in soil and water systems, and the resulting phytotoxic effects and contribution to the development of bacterial antibiotic resistance.

2. Materials and Methods

This study is presented as a systematic literature review to identify and synthesize peer-reviewed research on the environmental fate and phytotoxic effects of fluoroquinolones (FQs). A structured, reproducible search strategy was used to ensure transparency and consistency in study selection.

A comprehensive bibliographic search was conducted from March to April 2026, covering publications from January 2014 to December 2025. Relevant studies were identified in four major international scientific databases: PubMed, ScienceDirect, Web of Science, and Scopus (Page et al., 2021).

The search strategy employed combinations of the following keywords and Boolean operators: “fluoroquinolones” OR

“ciprofloxacin” OR “norfloxacin” OR “enrofloxacin” AND “phytotoxicity” OR “aquatic plants” OR “terrestrial plants” OR “plant uptake” OR “bioaccumulation” OR “phytoremediation” OR “oxidative stress” OR “environmental contamination” OR “antibiotic resistance”.

Study selection was performed using predefined eligibility criteria. Inclusion criteria comprised peer-reviewed original research articles, systematic reviews, and meta-analyses reporting quantitative or semi-quantitative data on fluoroquinolone occurrence in environmental matrices, plant uptake, or associated phytotoxicological effects. Studies were excluded if they lacked primary experimental or environmental exposure data, focused exclusively on human pharmacokinetics, or did not include environmental or plant-related endpoints.

The selection process involved an initial screening of titles and abstracts, followed by full-text evaluation of potentially relevant studies. Data extraction was conducted in a standardized manner and included information on study design, environmental compartment, plant species investigated, fluoroquinolone compounds evaluated, exposure concentrations, and reported biological and biochemical endpoints such as growth inhibition, oxidative stress markers, and bioaccumulation patterns.

3. Classification and General Properties of FQs

FQs are a subclass of the broader quinolone family, distinguished by the presence of a fluorine atom substituent on the bicyclic ring system. The presence of fluorine in the molecular structure enhances antibacterial potency and broadens the spectrum of activity compared with earlier quinolone antibacterials. Generations of FQs are classified based on their spectrum of

activity and therapeutic use (Hamad, 2010; Collinsworth et al., 2022):

- **first-generation (e.g., norfloxacin)**, primarily active against Gram-negative uropathogens, were characterized by limited systemic distribution (Andriule et al., 2023);
- **second generation (e.g., ciprofloxacin, enrofloxacin)** present extended activity against Gram-negative organisms and some Gram-positive cocci and improved systemic bioavailability (Andriule et al., 2023);

- **third-generation (e.g., levofloxacin)** are characterized by an extended antibacterial spectrum compared to the second generation, mainly a broader Gram-positive spectrum and enhanced activity against *Streptococcus pneumoniae* (Andriule et al., 2023);
- **fourth-generation (e.g., moxifloxacin)** is valuable due to the extended anaerobic spectrum, besides broad-spectrum activity (Andriule et al., 2023).

Table 1. Chemical structures and IUPAC names of selected fluoroquinolones (FQs) used in human and veterinary medicines (Gao and Pedersen, 2005)

FQs	IUPAC Name	Therapeutic application
Ciprofloxacin	1-cyclopropyl-6-fluoro-4-oxo-7-piperazin-1-ylquinoline-3-carboxylic acid	Broad-spectrum: UTI, respiratory, GI infections
Danofloxacin	1-cyclopropyl-6-fluoro-7-[(1 <i>S</i> ,4 <i>S</i>)-5-methyl-2,5-diazabicyclo[2.2.1]heptan-2-yl]-4-oxoquinoline-3-carboxylic acid	Veterinary medicine
Enrofloxacin	1-cyclopropyl-7-(4-ethylpiperazin-1-yl)-6-fluoro-4-oxoquinoline-3-carboxylic acid	Veterinary medicine (metabolised to ciprofloxacin)
Levofloxacin	(<i>S</i>)-9-fluoro-2,3-dihydro-3-methyl-10-(4-methylpiperazin-1-yl)-7-oxo-7H-pyrido[1,2,3- <i>de</i>]-1,4-benzoxazine-6-carboxylic acid	Respiratory infections, community-acquired pneumonia
Norfloxacin	1-ethyl-6-fluoro-4-oxo-7-piperazin-1-ylquinoline-3-carboxylic acid	Urinary tract infections, veterinary use
Marbofloxacin	7-fluoro-2-methyl-6-(4-methylpiperazin-1-yl)-10-oxo-4-oxa-1,2-diazatricyclo[7.3.1.0 ^{5,13}]trideca-5(13),6,8,11-tetraene-11-carboxylic acid	Veterinary medicine
Moxifloxacin	7-[(4 <i>aS</i> ,7 <i>aS</i>)-1,2,3,4,4 <i>a</i> ,5,7,7 <i>a</i> -octahydropyrrolo[3,4- <i>b</i>]pyridin-6-yl]-1-cyclopropyl-6-fluoro-8-methoxy-4-oxoquinoline-3-carboxylic acid	Respiratory, urogenital, skin and soft-tissue, intra-abdominal, gynaecological, and ocular bacterial infections (Rusu et al., 2021)
Orbifloxacin	1-cyclopropyl-7-[(3 <i>S</i> ,5 <i>R</i>)-3,5-dimethylpiperazin-1-yl]-5,6,8-trifluoro-4-oxoquinoline-3-carboxylic acid	Veterinary medicine
Pradofloxacin	7-[(4 <i>aS</i> ,7 <i>aS</i>)-1,2,3,4,4 <i>a</i> ,5,7,7 <i>a</i> -octahydropyrrolo[3,4- <i>b</i>]pyridin-6-yl]-8-cyano-1-cyclopropyl-6-fluoro-4-oxoquinoline-3-carboxylic acid	Veterinary medicine

All FQs share a zwitterionic character at physiological pH, which influences their solubility, adsorption behavior, and uptake by organisms. Their amphoteric nature, with pK_a values typically between 5.7 and 9.3, results in complex interactions with soil organic matter and mineral surfaces, particularly clay minerals and metal cations such as Fe^{3+} , Al^{3+} , and Ca^{2+} (Bhatt and Chatterjee, 2022; Gao and Pedersen, 2005) (**Table 1**).

Currently, systemic FQs are classified as agents requiring restricted use due to their high ecological impact, rising resistance among Gram-negative pathogens, and safety concerns highlighted by international health authorities (Olivieri et al., 2023).

FQs currently used in veterinary practice comprise a limited group of compounds specifically approved for animal use by major regulatory authorities. The veterinary FQs include enrofloxacin, which is widely authorized for use in companion animals and food-producing species; marbofloxacin and orbifloxacin, both commonly employed in small-animal medicine; pradofloxacin, a later-generation FQ approved for cats in the United States and for both dogs and cats in the European Union; and danofloxacin, which is restricted primarily to cattle for defined indications. Notably, many human FQs are not approved for veterinary use and are discouraged due to antimicrobial stewardship and resistance concerns (Papich and Riviere, 2009).

4. Environmental Sources and Fate of FQs

The environmental presence of FQs originates from multiple sources. In human medicine, oral FQs are incompletely absorbed, and a significant portion is excreted as unchanged parent compounds or active metabolites through urine and feces. It is estimated that up to 70% of administered FQs

may be excreted unchanged and enter municipal wastewater systems. Conventional wastewater treatment plants (WWTPs) are not specifically designed to remove antibiotics and typically achieve only partial elimination of FQs, with removal efficiencies ranging from 14% to 80%, depending on treatment configuration and compound properties (Bhatt and Chatterjee, 2022; Chen et al., 2024).

In veterinary and agricultural settings, FQs are administered to livestock and aquaculture species, and residues enter the environment through manure application, effluent discharge from fish farms, and direct excretion into water bodies. Enrofloxacin, widely used in poultry and swine production, is metabolized in part to ciprofloxacin, extending the range of FQs present in agricultural soils and sediments (Chen et al., 2024; Zhang et al., 2019).

Once in the environment, FQs strongly adsorb to soil particles and sediments due to their zwitterionic character and tendency to form stable complexes with multivalent metal cations. This high sorption capacity, combined with low biodegradability under aerobic conditions, leads to the accumulation of FQs in soils and sediments over time. Studies have detected FQs in soils from Asia, Europe, and the Americas, with concentrations varying greatly by region. For instance, six different FQs were quantified in soils from Beijing and Shanghai at concentrations up to $2160 \mu\text{g kg}^{-1}$, significantly higher than those recorded in Chennai, India ($126.29 \mu\text{g kg}^{-1}$) (Chen et al., 2024; Gao and Pedersen, 2005).

Photolysis is considered the primary degradation pathway for FQs in aquatic systems under sunlight, generating transformation products that may exhibit antibiotic activity or toxicity. Under anaerobic conditions, such as in waterlogged soils or sediments, biodegradation is even slower, further contributing to environmental persistence. FQs have also been detected in

surface waters and groundwater, posing risks to both aquatic organisms and water quality (Bhatt and Chatterjee, 2022; Van Boeckel et al., 2014).

5. Phytotoxic Effects: Dose-Response Relationships

The phytotoxic effects of FQs depend strongly on their concentration in the growth medium or soil. A dose-response framework is essential for understanding the spectrum of responses observed across different plant species and experimental conditions (Martins et al., 2012; Calouro et al., 2020).

At low, environmentally relevant concentrations (typically below $1 \mu\text{g}\cdot\text{L}^{-1}$), the effects of FQs on plants are often subtle, primarily involving biochemical and metabolic changes. These include shifts in antioxidant enzyme activity, altered secondary metabolite profiles, and, in some cases, a hormetic response, in which low doses transiently stimulate plant growth or protective enzyme activity. Hormesis has been described in several FQ-plant pairs and reflects the activation of adaptive stress-response mechanisms as a form of plant defense (Martins et al., 2012; Lin et al., 2025).

At moderate concentrations (ranging from 1 to $100 \mu\text{g}\cdot\text{L}^{-1}$), the most frequently reported effects include inhibition of seed germination, reduced root and shoot elongation, decreased chlorophyll and carotenoid content, impaired photosynthetic efficiency, and increased markers of oxidative stress such as malondialdehyde (MDA) accumulation and elevated reactive oxygen species (ROS) levels. The degree of inhibition is species-specific and depends on the plant's capacity to accumulate and detoxify FQs (Martins et al., 2012; Nunes et al., 2019; Mravcová et al., 2024).

At high concentrations (above $100 \mu\text{g}\cdot\text{L}^{-1}$ or $5 \text{ mg}\cdot\text{kg}^{-1}$ in soils), ciprofloxacin and other

FQs cause significant phytotoxic effects, including severe growth suppression, major metabolic disruptions, structural damage to plant tissues, including root necrosis and chloroplast disorganization, and, in some cases, plant death. At these concentrations, plant antioxidant defense systems are overwhelmed, and cellular damage becomes irreversible (Chen et al., 2024; Zhao et al., 2024).

6. Bioaccumulation of FQs and Absorption in Aquatic and Terrestrial Plants

Bioaccumulation refers to the process by which organisms accumulate substances from the environment at concentrations exceeding ambient levels. In the context of FQs, plants can take up these antibiotics from contaminated soil or water through their roots, with subsequent translocation to aboveground tissues. The general pattern of FQ distribution in plant tissues follows the gradient: root > stem > leaf, suggesting that roots are the primary site of accumulation, and translocation to shoots and leaves is more limited (Chen et al., 2024; Chen et al., 2023).

Bioaccumulation in plants has direct consequences for food safety, as residues in edible plant parts may enter the human food chain. Moreover, it contributes to antibiotic resistance in soil microbial communities. The selective pressure exerted by even sub-inhibitory concentrations of antibiotics in soils promotes the selection of resistant bacterial strains and the horizontal transfer of resistance genes, leading to the emergence and spread of multidrug-resistant bacteria that significantly threaten effective treatment of human diseases (Bhatt and Chatterjee, 2022; Martinez, 2019; Zhu et al., 2013).

Compared to other antibiotic classes, FQs exhibit especially strong adsorption and high resistance to biodegradation, leading to their accumulation at elevated concentrations in both

soil and plant tissues. Their amphoteric character allows them to interact with root cell membranes and metal complexes, facilitating uptake even in soils with high organic matter content (Chen et al., 2024; Gao and Pedersen, 2005).

6.1. Aquatic Plants

Plants are essential components of freshwater ecosystems, providing oxygen, habitat, and nutrients. They can also serve as biomonitors and potential bioremediators of chemical contaminants. Since not all administered FQs are fully absorbed by target organisms, a significant amount is excreted into wastewater and subsequently detected in coastal, riverine, and lacustrine environments (Chen et al., 2024; Lin et al., 2025).

Macroalgae are among the most sensitive aquatic organisms to FQ toxicity. Their simple morphology and close contact with surrounding water facilitate direct uptake of dissolved contaminants. Studies have shown that macroalgae can accumulate FQs at concentrations several times higher than those in the surrounding medium. For submerged macrophytes, root uptake from sediment is an additional route of exposure, particularly relevant in contaminated aquaculture systems (Chen et al., 2023; Lin et al., 2025).

6.2. Terrestrial Plants

When FQs enter the soil, a series of physicochemical and biological processes govern their availability for plant uptake. The fraction that remains dissolved in soil pore water (the bioavailable fraction) is determined by the equilibrium between adsorption to soil particles and dissolution. Root exudates can influence this equilibrium by modifying soil pH or chelating metal ions that form complexes with FQs (Chen et al., 2024; Gao and Pedersen, 2005).

Studies have shown that root uptake of FQs is generally passive and directed by concentration gradients, though active transport mechanisms may also contribute. Translocation from roots to shoots is more limited, particularly for FQs that form stable metal complexes in the apoplast. In hydroponic systems, where FQs are dissolved directly in the nutrient solution, uptake and translocation are typically higher than in soil-based systems, where adsorption reduces bioavailability. Research indicates that FQs can both enhance growth and exhibit toxicity for terrestrial crops at higher concentrations ($5 \text{ mg}\cdot\text{L}^{-1}$), consistent with the hormesis framework described above (Chen et al., 2024; Mravcová et al., 2024).

7. Effects of FQs on Aquatic Plants

Multiple studies confirm that FQs can harm a broad range of aquatic organisms, including marine bacteria, algae, crustaceans, and fish. The mechanisms of phytotoxicity in aquatic plants include direct inhibition of prokaryotic-type plastid division (targeting the FtsZ protein, a structural analog of bacterial tubulin), impairment of chloroplast electron transport chains, and induction of oxidative stress through ROS overproduction (Chen et al., 2024; Lu et al., 2025; Sun et al., 2021).

7.1. *Gracilariopsis heteroclada*

Recent evidence shows that FQs inhibit the growth of aquatic plants in a dose-dependent manner. Norfloxacin, enrofloxacin, and lomefloxacin have been shown to affect the growth of the red macroalga *Gracilariopsis heteroclada*, a thermotolerant species mainly found in the Northern South China Sea. This alga is commercially important for its high agar content (approximately 29.8% by dry weight) and its applications in the food, cosmetics, and pharmaceutical industries. Other recent studies have also identified its capacity to decrease the relative abundance of antibiotic resistance

genes in its surrounding environment (Lin et al., 2025).

The dose-response pattern of *G. heteroclada* to the three FQs was non-linear. At low concentrations, fluoroquinolones stimulated algal growth, whereas at higher concentrations they exerted inhibitory effects, a pattern consistent with hormesis. Importantly, at most tested concentrations, the FQs did not cause complete inhibition, and a 50% reduction in growth was not observed within 96 hours, suggesting a relatively high tolerance of this species to FQ exposure. Sorption of FQs by algal biomass was also quantified, indicating that *G. heteroclada* can serve as a sorbent for these contaminants (Lin et al., 2025).

7.2. *Hydrilla verticillata*

Ciprofloxacin, one of the most frequently detected FQs in aquatic environments, causes phytotoxicity in the submerged macrophyte *Hydrilla verticillata*, a widespread species in tropical and subtropical freshwater systems. The phytotoxic mechanisms include growth inhibition, decreased photosynthetic efficiency (as measured by the Fv/Fm ratio), and induction of oxidative stress. Antibiotics can disrupt photosynthetic processes by impairing electron transport at photosystem II, leading to an overproduction of reactive oxygen species (ROS) that cause lipid peroxidation and cellular membrane damage (Lu et al., 2025).

A notable finding in *H. verticillata* is the significant increase in anthocyanin levels following ciprofloxacin exposure. Anthocyanins, belonging to the flavonoid family, function as non-enzymatic antioxidants and UV-screening pigments. At lower ciprofloxacin concentrations, elevated ROS signaling activated transcriptional pathways for anthocyanin biosynthesis, representing a protective response. At high ciprofloxacin concentrations, this biosynthetic capacity was

suppressed, indicating overwhelmed defense mechanisms (Lu et al., 2025).

7.3. *Lemna minor* and *Lemna gibba*

The duckweeds *Lemna minor* and *Lemna gibba* are standardized test organisms frequently used in ecotoxicological assessments due to their rapid growth, simple morphology, and sensitivity to environmental contaminants. Studies evaluating the effects of ciprofloxacin on these species measured catalase activity as a marker of antioxidant response and lipid peroxidation as an indicator of oxidative damage (Nunes et al., 2019; Harpaz et al., 2021).

Ciprofloxacin treatment increased catalase activity, indicating an active antioxidant response to oxidative stress. Paradoxically, lipid peroxidation levels decreased, suggesting the antioxidant defense system effectively scavenged ROS before lipid peroxidation could occur. Chlorophyll a and b contents did not differ significantly between treated and control groups. However, carotenoid levels were significantly reduced, potentially impairing the photoprotective function of the photosynthetic apparatus and increasing susceptibility to photoinhibition (Martins et al., 2012).

8. Effects of FQs on Terrestrial Plants

Fluoroquinolones (FQs), especially ciprofloxacin, are commonly detected in agricultural soils as antibiotic residues resulting from the application of sewage sludge, animal manure, or irrigation with treated wastewater. In experimental studies, plants are often exposed to concentrations that exceed those typically reported in the environment, which may amplify observed phytotoxic effects compared with environmentally relevant exposure scenarios. Exposure to sub-lethal concentrations of FQs has been shown to induce a range of physiological and biochemical changes in terrestrial plants,

including alterations in germination rate, root growth, photosynthetic pigment content, and the activity of antioxidant enzymes such as superoxide dismutase and catalase (Martins et al., 2012; Carée et al., 2021).

FQs can also interfere with plant secondary metabolism, affecting the biosynthesis of phenolic compounds and flavonoids, which play key roles in plant antioxidant defence and have broader ecological and pharmacological relevance. Consequently, changes in their levels may have implications beyond individual plant physiology, potentially affecting plant–microbe interactions and ecosystem-level processes. However, the magnitude and direction of these responses vary considerably depending on plant species, FQ compound, exposure concentration, and duration, as well as the experimental system used (e.g., hydroponic versus soil-based conditions), which can further influence contaminant availability and uptake (Martins et al., 2012; Zhao et al., 2024).

8.1. *Lactuca sativa*

Lettuce (*Lactuca sativa*) is a widely consumed leafy vegetable commonly used in phytotoxicity studies due to its sensitivity to contaminants and its relevance to food safety. Exposure of *L. sativa* to seven ciprofloxacin concentrations (0–500 $\mu\text{g}\cdot\text{L}^{-1}$) over 35 days under hydroponic conditions revealed progressive phytotoxic effects. By the end of the exposure period, plant mortality increased in a concentration-dependent manner, accompanied by visible changes in root morphology, including shortened, discolored roots, and a significant decrease in root length. (Mravcová et al., 2024).

The obtained evidence highlights the risks associated with irrigating lettuce with

ciprofloxacin-contaminated water or growing it in FQ-contaminated soils, which are realistic scenarios in regions where reclaimed wastewater is used for agricultural irrigation. Lettuce is particularly vulnerable due to its leafy structure and high water content, which favor uptake and accumulation of soluble contaminants (Mravcová et al., 2024; Carée et al., 2021).

8.2. *Brassica parachinensis*

Exposure of plants to ciprofloxacin can cause markedly different effects depending on each variety's capacity to accumulate and tolerate the antibiotic. Studies on Chinese flowering cabbage (*Brassica parachinensis*) compared varieties with different levels of ciprofloxacin accumulation. Varieties with lower ciprofloxacin accumulation paradoxically experienced greater inhibition of growth and photosynthesis than those accumulating higher amounts, indicating that tolerance is not simply a function of exclusion, but also of the plant's ability to compartmentalise and detoxify accumulated compounds (Zhao et al., 2024).

Further transcriptomic and proteomic analyses revealed that, in sensitive varieties, genes and proteins involved in essential metabolic processes, including protein synthesis, carbon metabolism, and energy production, were more strongly downregulated than in tolerant varieties. The results explained in **Table 2** suggest that ciprofloxacin phytotoxicity depends not only on its concentration but also on the plant's capacity to regulate molecular networks involved in stress responses and secondary metabolism (Zhao et al., 2024).

Table 2. Summary of phytotoxic effects of fluoroquinolones (FQs) on selected plant species

FQs	Tested species	Observed effects
Norfloxacin, enrofloxacin, lomefloxacin	<i>Gracilariopsis heteroclada</i>	Hormetic response: growth stimulation at low doses, inhibition at high doses; FQ sorption by algal biomass (Lin et al., 2025)
Ciprofloxacin	<i>Hydrilla verticillata</i>	Growth inhibition, decreased Fv/Fm, increased oxidative stress; elevated anthocyanins at low concentrations (Lu et al., 2025)
Ciprofloxacin	<i>Lemna minor</i> and <i>Lemna gibba</i>	Increased CAT activity, decreased lipid peroxidation; no change in chlorophylls a and b; reduced carotenoids (Nunes et al., 2019)
Ciprofloxacin	<i>Lactuca sativa</i>	Increased plant mortality, altered root morphology, decreased root length, concentration-dependent over 35 days (Mravcová et al., 2024)
Ciprofloxacin	<i>Brassica parachinensis</i>	Growth and photosynthesis inhibition; variety-dependent tolerance; downregulation of metabolic pathways in sensitive varieties (Zhao et al., 2024)

9. FQs and the Spread of Antibiotic Resistance

Beyond their direct phytotoxic effects, FQs exert a profound indirect impact on ecosystems by promoting antibiotic resistance. Even at sub-inhibitory concentrations, FQs can exert selective pressure on soil and aquatic microbial communities, favouring the proliferation of resistant bacterial strains and the horizontal transfer of resistance genes via mobile genetic elements such as plasmids, transposons, and integrons (Martinez, 2019; Zhu et al., 2013).

Studies have consistently demonstrated positive correlations between FQ concentrations in soil and the abundance of FQ-resistance genes, such as *qnr* (plasmid-mediated quinolone resistance), and mutations in *gyrA* and *parC* (encoding the target enzymes DNA gyrase and topoisomerase IV). The concentration of FQs in agricultural soils, estimated at ng to $\mu\text{g}\cdot\text{kg}^{-1}$, is sufficient to select for resistance (Martinez, 2019; Zhu et al., 2013; Liu et al., 2022).

Resistant bacteria in environmental reservoirs can colonise the gastrointestinal tracts of animals and humans through the food

chain, creating a difficult-to-break cycle of resistance dissemination. The World Health Organization (WHO) has listed FQ-resistant bacteria, including fluoroquinolone-resistant *Enterobacteriaceae* and *Pseudomonas aeruginosa*, among the critical priority pathogens requiring urgent development of new antibiotics (World Health Organization, 2017).

10. Phytoremediation as a Strategy to Reduce FQs Pollution

Phytoremediation is an environmentally friendly, cost-effective, and publicly acceptable technology that uses living plants and their associated rhizosphere microorganisms to remediate contaminated soil, sediment, and water. The mechanisms involved include phytoextraction (uptake and accumulation of contaminants in plant tissues), phytodegradation (enzymatic transformation by plant enzymes), rhizodegradation (microbial degradation in the rhizosphere), and phytostabilization (immobilization of contaminants in the root zone) (Chen et al., 2023; MacDonald et al., 2019).

Numerous studies have demonstrated that plants can effectively reduce FQ concentrations in contaminated environments. The general pattern of FQ distribution in plant tissues (root > stem > leaf) is advantageous for phytoremediation, since harvesting root biomass can remove accumulated FQs from the site (Chen et al., 2024; Chen et al., 2023).

10.1. *Vallisneria spiralis*

Studies on the submerged macrophyte *Vallisneria spiralis* have demonstrated its potential for phytoremediation of FQ-contaminated aquaculture sediments. Under controlled conditions, the presence of *V. spiralis* in enrofloxacin-contaminated sediment significantly accelerated the elimination of enrofloxacin and its metabolite ciprofloxacin. This effect was attributed to two complementary mechanisms: direct uptake of antibiotics by plant roots and modification of the sediment microbial community by the plant, which favoured the activity of antibiotic-degrading microorganisms (Zhang et al., 2019).

Vallisneria spiralis demonstrated considerable tolerance to enrofloxacin. At low and moderate concentrations, leaf growth and total biomass were maintained or even stimulated, and nutrient uptake was not significantly hindered. At high concentrations, slight negative effects on root development were observed, but the plant continued to survive, demonstrating a high capacity for chemical stress resistance (Zhang et al., 2019).

10.2. Wetland Plants and Multi-Species Systems

Beyond individual species, constructed wetland systems employing multiple plant species have shown promise for reducing antibiotic concentrations in contaminated effluents. Macrophytes such as *Phragmites australis*, *Typha latifolia*, and *Iris pseudacorus* have been investigated for their capacity to take

up and transform FQs. The combination of direct plant uptake, rhizosphere microbial degradation, and photolysis in surface-flow wetland systems can achieve substantial FQ removal rates, with studies reporting removal efficiencies of over 90% for ciprofloxacin under optimised conditions (Chen et al., 2023; MacDonald et al., 2019).

Dynamic speciation techniques, such as the diffusive gradients in thin films (DGT) method, have been applied to phytoremediation systems to distinguish plant-available FQ fractions from those bound to sediment, providing a more accurate picture of the phytoremediation process and the flux of antibiotics to root surfaces (Chen et al., 2023).

11. Knowledge Gaps and Future Research Directions

Despite the growing body of literature on fluoroquinolone (FQ) phytotoxicity and phytoremediation, several important knowledge gaps remain. The majority of existing studies have been conducted under controlled laboratory conditions, often using relatively high, experimentally applied concentrations of single FQ compounds and single plant species. In contrast, environmentally relevant concentrations are typically lower and occur within complex mixtures of antibiotics and other co-contaminants. The interactive effects of such mixtures on plant systems remain poorly understood, and synergistic or antagonistic interactions may substantially modify phytotoxic outcomes compared with single-compound exposures (Martins et al., 2012; Calouro et al., 2020).

Long-term ecological studies addressing the cumulative effects of chronic, low-level FQ exposure on plant communities, soil microbial diversity, and overall ecosystem functioning are still scarce. Most available studies are short-term (ranging from days to weeks), which

limits understanding of multigenerational effects under environmentally realistic exposure scenarios. This is particularly relevant given the continuous environmental input of FQs from agricultural, veterinary, and pharmaceutical sources (Bhatt and Chatterjee, 2022; Chen et al., 2024).

In addition, the molecular mechanisms underlying FQ uptake, translocation, and tolerance in plants remain insufficiently characterised. Identifying specific transporter proteins, detoxification pathways, and stress-response signalling networks would provide a basis for developing more efficient phytoremediation systems through plant selection or molecular improvement strategies (Zhao et al., 2024; MacDonald et al., 2019).

Finally, the lack of standardised experimental protocols for assessing FQ phytotoxicity across different plant species and exposure systems limits comparability between studies. The development of harmonised guidelines, similar to OECD or ISO ecotoxicological testing frameworks, would improve reproducibility and strengthen the scientific basis for environmental risk assessment and regulatory decision-making (Calouro et al., 2020; OECD, 2006).

Conclusions

FQs are globally significant antibiotics whose environmental persistence poses considerable ecological risks. Because of their low biodegradability, high excretion rates, and strong adsorption properties, FQs accumulate in soils, sediments, water bodies, and plants. Numerous studies demonstrate that both aquatic and terrestrial plants absorb FQs, with effects depending on concentration. While low doses may enhance growth or activate antioxidant defences through hormetic mechanisms, higher concentrations cause phytotoxic effects, including growth inhibition, reduced photosynthetic efficiency, oxidative

stress, altered secondary metabolism, and structural damage to plant tissues.

Beyond plant-level toxicity, FQs contribute to the dissemination of antibiotic resistance in soil and aquatic microbial communities through selective pressure and horizontal gene transfer, with broader implications for ecosystem stability and public health. At the same time, the reviewed evidence highlights the potential of phytoremediation-based approaches, particularly submerged macrophytes and constructed wetland systems, as promising tools for mitigating FQ contamination in wastewater and aquatic environments.

Overall, this review consolidates current knowledge on the environmental fate, phytotoxic effects, and remediation potential of FQs, providing an integrated perspective on their ecological impact. The findings emphasize the need for improved environmental monitoring of antibiotic residues, stricter regulation of antibiotic use in agriculture and aquaculture, and enhanced wastewater treatment strategies to limit environmental dissemination. From a practical standpoint, integrating phytoremediation into wastewater management systems and environmental monitoring frameworks represents a promising and scalable approach for reducing FQ pollution. Continued research is required to better understand long-term ecological risks and to optimize remediation technologies for real-world applications.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

Conceptualization: C.T.; Data curation: M.G.; Formal analysis: M.G. and C.T.; Investigation: C.T. and M.G.; Methodology: M.G., A.R., C.T.; Project administration: C.T.; Resources: C.T.; Supervision: C.T.; Validation: A.R. and C.T.; Visualization: C.T.; Writing – original draft: M.G., Preparation: M.G.; Writing – review & editing: A.R. and C.T.

Disclaimer/Publisher’s Note

The authors alone are responsible for the content of this article. The validity, accuracy of data and views expressed are solely those of the author(s) and do not necessarily reflect those of their affiliated institutions, the publisher, the editors, or the reviewers. Any product evaluated or claim made by its manufacturer is not guaranteed or endorsed by the publisher.

Generative AI Statement:

During the preparation of this work, the author(s) used Grammarly *to improve language and grammar*. After using Grammarly, the author(s) reviewed and edited the content as needed and are fully responsible for the originality and integrity of the content of the manuscript.

References

- Bhatt S, Chatterjee S (2022) Fluoroquinolone antibiotics: Occurrence, mode of action, resistance, environmental detection, and remediation – A comprehensive review. *Environ Pollut* 315:120440. doi: 10.1016/j.envpol.2022.120440
- Martinez JL (2019) Mechanisms of action and resistance to quinolones. In: *Antibiotic drug resistance*. Wiley, pp 39–55
- Andriule A, Mazur J, Kudlak B (2023) Fluoroquinolones – occurrence, toxicity and remediation. *Chem Ecol* 39:120–145
- Hamad B (2010) The antibiotics market. *Nat Rev Drug Discov* 9:675–676. <https://doi.org/10.1038/nrd3267>
- Collinsworth SM, Alafrizón LI, Greenfield M, Hawkins E, Siddiqui AH (2022) Fluoroquinolone use in veterinary medicine and its contribution to antibiotic resistance. *One Health* 14:100382
- Chen X, Song Y, Ling C, Shen Y, Zhan X, Xing B (2024) Fate of emerging antibiotics in soil-plant systems: A case on fluoroquinolones. *Sci Total Environ* 951:175487
- Zhu YG, Johnson TA, Su JQ, Qiao M, Guo GX, Stedtfeld RD, et al (2013) Diverse and abundant antibiotic resistance genes in Chinese swine farms. *Proc Natl Acad Sci USA* 110:3435–3440. doi: 10.1073/pnas.1222743110
- Gao J, Pedersen JA (2005) Adsorption of sulfonamide antimicrobial agents to clay minerals. *Environ Sci Technol* 39:9509–9516
- Rusu A, Lungu IA, Moldovan OL, Tănase C, Hancu G (2021) Structural characterization of the millennial antibacterial (fluoro)quinolones – shaping the fifth generation. *Pharmaceutics* 13:1289. doi: 10.3390/pharmaceutics13081289
- Olivieri R, Vannini P, Corzani A, Bianco MT, Franchi F, Cusi MG, Scolletta S, Arena F, Basagni C, Gusinu R, et al (2023) Rapid decrease in fluoroquinolones consumption following implementation of a simple antimicrobial stewardship bundled intervention in a university hospital during the COVID-19 pandemic. *Antibiotics* 12:694. <https://doi.org/10.3390/antibiotics12040694>

11. Papich MG, Riviere JE (2009) Fluoroquinolone antimicrobial drugs. In: Veterinary pharmacology and therapeutics, pp 983–1012
12. National Center for Biotechnology Information (n.d.) PubChem Compound Database for Fluoroquinolones. <https://pubchem.ncbi.nlm.nih.gov/#query=f luoroquinolones>
13. Zhang L, Zhang Y, Liu L (2019) Effect of submerged macrophytes *Vallisneria spiralis* L. on restoring sediment contaminated by enrofloxacin in aquaculture ponds. *Ecol Eng* 140:105596
14. Van Boeckel TP, Gandra S, Ashok A, Caudron Q, Grenfell BT, Levin SA, et al (2014) Global antibiotic consumption 2000 to 2010: an analysis of national pharmaceutical sales data. *Lancet Infect Dis* 14:742–750
15. Chen J, Liu SS, Wu Q, Huang WJ, Yang F, Wang YJ, et al (2023) Removal, fate, and bioavailability of fluoroquinolone antibiotics in a phytoremediation system with four wetland plants using dynamic DGT and traditional methods. *Sci Total Environ* 881:163464
16. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 372:n71. doi: 10.1136/bmj.n71
17. Martins N, Pereira R, Abrantes N, Pereira J, Gonçalves F, Marques CR (2012) Ecotoxicological effects of ciprofloxacin on freshwater species: data integration and derivation of toxicity thresholds for risk assessment. *Ecotoxicology* 21:1167–1176. doi: 10.1007/s10646-012-0871-x
18. Calouro S, Sousa JP, Nogueira AJA (2020) Phytotoxicity of antibiotics on plant seedlings. *Arch Environ Contam Toxicol* 79:211–222
19. Lin K, Guo Y, Xin R, Xie E, Wang X, Cui J, et al (2025) Dose-response pattern of marine macroalgae *Gracilariopsis heteroclada* to three fluoroquinolones and the cause-and-effect relationship of dose, growth, toxicity, and sorption. *Algal Res* 90:104133
20. Nunes B, Veiga V, Frankenbach S, Serôdio J, Pinto G (2019) Evaluation of physiological changes induced by ciprofloxacin in *Lemna minor* and *Lemna gibba*. *Environ Toxicol Pharmacol* 72:103242
21. Mravcová L, Urbánová I, Zouhar L, Klápačiková K, Klápáček M (2024) Assessing lettuce exposure to a multipharmaceutical mixture under hydroponic conditions. *ACS Omega*
22. Zhao HM, Du H, Huang HB, Huang YN, Xiang L, Cai QY, et al (2024) Insights into the molecular network underlying phytotoxicity of ciprofloxacin in plants. *Sci Total Environ*
23. Lu L, Huang R, Wan L, Li G, Xu Z, Guo J (2025) Phytotoxic effects and microbial responses to ciprofloxacin and its removal by *Hydrilla verticillata*. *Toxics* 13:882. doi: 10.3390/toxics13100882
24. Sun Y, Guo Y, Shi M, Qiu T, Gao M, Tian S, et al (2021) Effect of antibiotic type and vegetable species on antibiotic accumulation in soil-vegetable system, soil microbiota, and resistance genes. *Chemosphere* 263:128099
25. Harpaz D, Seet LF, Marks RS, Tok AIY, Eltzov E (2021) Whole-organism, whole-cell, and cell-free biosensors for the detection of antibiotics. *Biosensors* 11:265
26. Carée C, Lazerges M, Bedri M, Mao Z (2021) Ciprofloxacin residues in vegetables irrigated with contaminated water: a threat to human health? *Environ Sci Pollut Res* 28:4726–4735

27. Liu M, Zhang Y, Zhao Z, Li C, Du J, Cao H, et al (2022) Quinolone resistance mechanisms in bacteria and the role of the environment. *Front Microbiol* 13:935155
28. World Health Organization (2017) Global priority list of antibiotic-resistant bacteria to guide research, discovery, and development of new antibiotics. Geneva: WHO
29. MacDonald JMF, Hudson D, Asbridge R (2019) Phytoremediation of emerging contaminants in wetlands: A review. *Chemosphere* 236:124376
30. OECD (2006) Test No. 221: Lemna sp. Growth Inhibition Test. OECD Guidelines for the Testing of Chemicals, Section 2. Paris: OECD Publishing