

RESEARCH ARTICLE

Pharmaceutical Pollution and Environmental Health: Sources, Ecological Impacts, and the Role of Community Pharmacists in Sustainable Medicine Disposal

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ABSTRACT

Pharmaceutical pollution has emerged as an environmental and public health concern due to the increasing detection of active pharmaceutical ingredients and their transformation products in wastewater, surface water, groundwater, and other environmental compartments. These contaminants originate from human and veterinary medicine use, pharmaceutical manufacturing, healthcare facilities, agricultural activities, and the inappropriate disposal of unused or expired medicines. This review examines the principal sources and environmental pathways of pharmaceutical residues, their potential ecological and human health implications, and strategies for reducing pharmaceutical pollution, with particular emphasis on the role of community pharmacists. A narrative review approach was adopted to synthesize relevant scientific literature published from 2011 onward, supplemented by authoritative guidance on pharmaceuticals in drinking water. The literature focuses on pharmaceutical occurrence, environmental fate, ecological effects, wastewater treatment, pharmaceutical waste management, and community pharmacy interventions. Pharmaceutical residues are frequently detected in aquatic environments because conventional wastewater treatment processes do not eliminate all active pharmaceutical ingredients. Environmental exposure may affect aquatic organisms, alter biological processes, and contribute to the selection and dissemination of antimicrobial resistance. However, the magnitude of human health risks associated with exposure to trace concentrations through drinking water remains uncertain and varies according to the substance, exposure pathway, and duration. Medicine take-back programs, public education, improved wastewater treatment, responsible prescribing, and environmentally informed pharmaceutical management represent complementary strategies for reducing contamination. Pharmaceutical pollution requires a coordinated One Health response involving healthcare professionals, environmental authorities, pharmaceutical manufacturers, wastewater operators, policymakers, and the public. Community pharmacists can contribute by educating patients, promoting medicine take-back systems, supporting rational medicine use, and discouraging inappropriate disposal practices.

KEYWORDS

Pharmaceutical pollution, pharmaceutical residues, environmental health, aquatic ecosystems, medicine disposal, community pharmacy, antimicrobial resistance, One Health

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1. Introduction

Pharmaceuticals are essential to modern healthcare, enabling the prevention, diagnosis, and treatment of numerous diseases. Nevertheless, their extensive use has raised concerns about the release of pharmacologically active compounds into the environment. Pharmaceutical residues have been identified in wastewater, rivers, lakes, groundwater, sediments, and other environmental matrices. Their occurrence reflects the combined effects of medicine consumption, excretion, manufacturing emissions, agricultural use, and waste disposal practices (Wilkinson et al., 2022; Wydro et al., 2024).

Pharmaceuticals differ from many conventional environmental contaminants because they are specifically designed to produce biological effects. Some compounds remain biologically active after excretion, while others may be transformed into metabolites or environmental degradation products. Their persistence, mobility, and biological activity depend on their chemical structure, environmental conditions, and interactions with microorganisms, sediments, and organic matter (*Zhang et al., 2022, P.M. Bradley et al. 2021*).

Pharmaceutical pollution is therefore an interdisciplinary issue linking environmental science, pharmacology, public health, and pharmacy practice. Although the detection of a pharmaceutical in water does not automatically indicate a health hazard, the continuous introduction of biologically active substances into ecosystems raises important questions about long-term exposure, ecological effects, and the effectiveness of existing waste-management systems.

Community pharmacists occupy a particularly relevant position in addressing this problem because they interact directly with medicine users and influence medication counseling, responsible medicine use, and the management of unused or expired products. Their contribution should complement, rather than replace, improvements in industrial controls, sanitation infrastructure, environmental monitoring, and public policy.

The present review explores the sources and environmental pathways of pharmaceutical residues, evaluates their potential ecological and human health consequences, and discusses practical measures for reducing pharmaceutical pollution, emphasizing the contribution of community pharmacy to sustainable medicine management (*Assress, H. A., et al., 2020*)

2. Literature Review

The objectives of this review are to:

- Describe the main sources and pathways through which pharmaceutical residues enter the environment.
- Examine the environmental fate and removal of pharmaceutical compounds in wastewater treatment systems.
- Summarize the potential ecological and public health consequences of pharmaceutical contamination.
- Evaluate approaches to the safe collection, disposal, and reduction of pharmaceutical waste.
- Identify practical interventions that community pharmacists can implement to promote environmental health.

3. Methodology

3.1 Review design

This manuscript is structured as a narrative literature review. The purpose of this approach is to integrate findings from environmental science, pharmaceutical research, public health, and pharmacy practice into a clinically and professionally relevant discussion.

3.2 Literature search strategy

For a publication-ready version, the literature search should be conducted and documented using databases such as PubMed, Scopus, Web of Science, and Google Scholar. Suggested search terms include "pharmaceutical pollution," "pharmaceutical residues in water," "pharmaceuticals in the environment," "wastewater treatment," "environmental health," "medicine take-back programs," "pharmaceutical waste disposal," and "community pharmacists." It may be used to combine search terms, for example: ("pharmaceutical residues" OR "pharmaceutical pollution") AND ("aquatic environment" OR wastewater OR "environmental health").

The proposed publication period was January 2011 to October 2026, with particular attention to peer-reviewed review articles, original environmental monitoring studies, and research examining medicine disposal and healthcare professional practices. Relevant authoritative guidance may be included where appropriate.

3.3 Eligibility and synthesis

Eligible publications should address at least one of the following themes: environmental occurrence, transport and transformation of pharmaceuticals, ecological or human health effects, wastewater treatment, pharmaceutical waste management, or pharmacist-led interventions. Studies should be evaluated according to their relevance, methodological quality, and contribution to the review objectives.

The findings should be synthesized thematically rather than statistically. As a narrative review, this manuscript does not claim a comprehensive systematic search, formal risk-of-bias assessment, or quantitative meta-analysis. The final manuscript should report the actual databases searched, dates, screening process, and number of publications included once these steps have been completed.

4. Findings

Sources and environmental pathways of pharmaceutical pollution

4.1 Human medicine consumption and excretion

One of the major pathways of pharmaceutical entry into the environment begins with medicine use. After administration, medicines undergo absorption, distribution, metabolism, and excretion. Depending on the active ingredient and the patient's physiology, a proportion of the parent compound or its metabolites may be excreted through urine or feces and enter municipal sewage systems.

The extent of environmental release differs among pharmaceutical classes. Analgesics, antibiotics, antidepressants, anticonvulsants, cardiovascular medicines, and other frequently used products have been investigated in wastewater and receiving waters (Thompson, W. A., & Vijayan, M. M., 2022). Environmental concentrations depend on patterns of consumption, population density, pharmaceutical properties, and the capacity of local wastewater treatment systems (Khasawneh & Palaniandy, 2021; Wilkinson et al., 2022).

The presence of pharmaceutical residues in sewage should not be interpreted as evidence of improper patient behavior in every case. Excretion is an expected consequence of appropriate treatment. Therefore, prevention strategies must address both unavoidable emissions from medicine use and avoidable releases caused by inappropriate disposal.

4.2 Improper disposal of unused and expired medicines

Unused and expired medicines may enter the environment when patients dispose of them in sinks, toilets, or household waste without following appropriate local guidance. Flushing medicines into toilets or sinks can introduce pharmaceutical ingredients directly into wastewater systems, while medicines discarded in ordinary waste may reach landfills and potentially contribute to leachate contamination.

The environmental consequences of household pharmaceutical waste depend on the composition of the waste, disposal conditions, landfill management, and the availability of appropriate collection and treatment systems. Medicine take-back programs can provide an alternative route for collecting unwanted products and reducing uncontrolled disposal (World Health Organization [WHO], 2012; Arke et al., 2025).

In addition to environmental concerns, retaining unused medicines at home may create risks associated with accidental ingestion, inappropriate self-medication, and diversion. Consequently, medicine disposal programs can support both environmental protection and medication safety (Arke, M. et.al., 2025).

4.3 Hospitals and healthcare facilities

Hospitals and other healthcare facilities may release pharmaceutical residues through patient excretion, cleaning activities, laboratory operations, and the management of pharmaceutical waste. Hospital wastewater can contain a diverse range of medicines, including antibiotics, anticancer agents, analgesics, and contrast agents (Sundararaman, S., et.al., 2022).

Although hospital effluent may contain specific compounds at elevated concentrations, its overall contribution to environmental contamination varies according to the substance, the facility, and the characteristics of the surrounding wastewater infrastructure. It is therefore inappropriate to assume that hospitals are the dominant source of every pharmaceutical pollutant. Environmental monitoring should identify locally important sources and prioritize compounds according to their occurrence, toxicity, and potential for exposure (Wilkinson et al., 2022; Wydro et al., 2024).

4.4 Pharmaceutical manufacturing and veterinary medicine

Manufacturing facilities can release pharmaceutical ingredients during production, cleaning, storage, and waste management if emissions are not adequately controlled. These releases may be especially relevant near manufacturing sites and where wastewater management is insufficient.

Veterinary medicines provide another pathway. Antibiotics, antiparasitic agents, and other compounds used in livestock and aquaculture can enter the environment through animal excretion, manure application, aquaculture discharge, and agricultural runoff. These pathways connect pharmaceutical pollution with soil health, surface-water quality, food production, and antimicrobial resistance (Anand et al., 2022).

A comprehensive assessment should therefore consider pharmaceutical emissions throughout the product life cycle, from manufacturing and distribution to use and final disposal.

5. Environmental Fate and Wastewater Treatment

5.1 Persistence and transformation

Once released, pharmaceutical compounds may undergo biodegradation, photodegradation, hydrolysis, sorption to sediments, or other transformation processes. The relative importance of these processes depends on the compound's chemical characteristics and environmental conditions, including sunlight exposure, temperature, water chemistry, organic matter, and microbial activity (Zhang et al., 2022).

Some compounds degrade relatively rapidly, whereas others persist or are transformed into products whose biological activity and toxicity may differ from those of the original substance. Consequently, measuring only the parent pharmaceutical may not fully characterize environmental exposure (Assress, H. A., et.al., 2020).

Pharmaceuticals may also partition between water, suspended particles, soil, and sediments. This distribution influences their transport, bioavailability, and potential exposure to aquatic organisms (Wasser-Bennett, G., et.al., 2025). Environmental monitoring should therefore consider the properties of individual substances rather than assuming that all pharmaceuticals behave similarly (Bavumiragira, J. P., Ge, J., & Yin, H. 2022; Anand et al., 2022).

The COVID-19 pandemic led to increased consumption of pharmaceutical compounds, resulting in their greater occurrence in surface waters, raw wastewater, and treated wastewater. The presence of these substances in aquatic environments has raised concerns about their potential adverse effects on ecosystem integrity and human health (Vaudin, P., et.al., 2022; Morales-Paredes et al., 2022).

5.2 Limitations of conventional wastewater treatment

Conventional wastewater treatment plants were primarily developed to reduce suspended solids, organic matter, and microbial contamination. They were not necessarily designed to remove the wide range of trace pharmaceutical compounds that enter sewage systems.

Removal efficiency varies substantially according to the pharmaceutical, the treatment process, and operating conditions. Biological degradation and sorption may remove certain compounds effectively, while other substances can pass through treatment plants and be released in treated effluent. The presence of residues in treated wastewater does not mean that treatment is ineffective overall; rather, it reflects the limitations of conventional processes for particular micropollutants (Khasawneh & Palaniandy, 2021).

5.3 Advanced treatment technologies

Several technologies have been investigated to improve pharmaceutical removal, including activated carbon adsorption, ozonation, advanced oxidation processes, membrane filtration, and enhanced biological treatment. These approaches can improve the removal of selected pharmaceutical compounds, but their effectiveness depends on the target substances, system design, and operating conditions (Adeoye et al., 2024; Wydro et al., 2024).

Advanced treatment may also involve increased energy consumption, chemical requirements, operating costs, or the production of residual waste streams. In some cases, treatment can generate transformation products that require additional evaluation. Decisions about implementation should therefore consider overall environmental performance, cost, feasibility, and the characteristics of local wastewater systems.

A practical strategy is to combine source reduction with appropriately selected treatment technologies. Preventing unnecessary pharmaceutical releases can reduce the burden on wastewater infrastructure, while improved treatment can help manage residues that cannot be avoided (Anand et al., 2022).

6. Potential Ecological and Human Health Effects

6.1 Effects on aquatic organisms

Pharmaceuticals are designed to interact with biological targets, and some may affect non-target organisms when exposure is sufficient. Potential effects include changes in growth, reproduction, behavior, development, and physiological function (Vaudin, P., Augé, C., et.al., 2022). The magnitude of these effects depends on the compound, concentration, duration of exposure, species sensitivity, and environmental conditions (Hejna, M., Kapuścińska, D., & Aksmann, A., 2022).

Research on pharmaceutical pollution has identified the aquatic environment as an important setting for evaluating exposure and ecological risk. Large-scale monitoring has demonstrated that pharmaceutical contamination occurs in rivers across different geographic regions, although concentrations and mixtures vary substantially among locations (Wilkinson et al., 2022).

Detection alone does not establish ecological damage. Environmental risk assessment requires comparison of measured or predicted exposure with appropriate toxicity data and consideration of chronic exposure, mixtures, and sensitive species (Assress, H. A., et.al., 2020).

6.2 Antimicrobial resistance

Antibiotics entering wastewater and natural environments may contribute to conditions that favor the selection of resistant microorganisms, depending on exposure concentrations, microbial communities, and other environmental factors. Wastewater can also carry resistant bacteria and antibiotic resistance genes, creating opportunities for their movement between human, animal, and environmental settings.

The relationship between environmental pharmaceutical residues and antimicrobial resistance is complex. Antibiotic contamination is one relevant pressure among several, alongside antibiotic use in humans and animals, sanitation conditions, and the movement of resistant organisms. Environmental monitoring and responsible antimicrobial use should therefore be integrated into broader antimicrobial resistance prevention strategies (Anand *et al.*, 2022).

6.3 Human health considerations

Human exposure to pharmaceutical residues may occur through drinking water, food, or contact with contaminated environmental media (Wang, Y. Q., *et al.*, 2022). However, the presence of a pharmaceutical in a water sample does not automatically imply a clinically significant risk (Sundararaman, S., *et al.*, 2022).

The WHO has reviewed the occurrence of pharmaceuticals in drinking water and emphasized the need to assess these substances within the broader framework of drinking-water safety (WHO, 2012, Zanni, S., *et al.*, 2025). Risk assessment should consider the identity of the compound, its concentration, toxicity, exposure frequency, and the vulnerability of potentially exposed populations.

Current evidence does not justify treating all trace pharmaceutical detections as equivalent health threats. Uncertainty remains for certain substances, mixtures, and long-term low-level exposures. Research should prioritize compounds with relevant toxicological properties, plausible exposure pathways, and evidence of environmental persistence or biological effects.

7. Strategies to Reduce Pharmaceutical Pollution

7.1 Responsible prescribing and medicine use

Reducing avoidable pharmaceutical waste begins before a medicine reaches the household. Appropriate prescribing, medication review, patient education, and adherence support can help reduce unnecessary use and the accumulation of unused products.

This does not mean withholding clinically indicated medicines for environmental reasons. Decisions about treatment must remain based on patient needs and established clinical evidence. Environmental considerations should complement safe, effective, and rational pharmacotherapy.

7.2 Medicine take-back programs

Medicine take-back programs provide designated collection points for unused or expired medicines and direct the collected waste toward authorized disposal routes. Community pharmacies may serve as accessible collection locations where national regulations and local infrastructure permit.

For these programs to succeed, the public needs clear information about where medicines can be returned, which products are accepted, and how collected waste is handled. Programs should also be evaluated according to accessibility, participation, cost, and the effectiveness of the final disposal process (Arke, M. *et al.*, 2025).

Collection programs should not be assumed to be universally available. In areas without formal take-back services, pharmacists should direct patients to the official guidance provided by local health or environmental authorities.

7.3 Public education on safe disposal

Public education is central to improving pharmaceutical waste management. Patients may retain unwanted medicines because they are uncertain about disposal procedures, lack access to collection facilities, or are unaware of potential environmental consequences.

Pharmacists can explain the importance of not flushing medicines or pouring them into drains unless specific official instructions require this method. They should also avoid giving overly broad instructions about placing medicines in household waste, because recommendations differ by jurisdiction and by product.

Education can be incorporated into prescription dispensing, medication reviews, pharmacy posters, printed leaflets, and community health campaigns. Clear, practical instructions are more likely to support behavior change than general messages about environmental responsibility (Assress, H. A., et.al., 2020).

7.4 Sustainable pharmaceutical manufacturing and wastewater management

Manufacturers, healthcare facilities, and wastewater operators share responsibility for reducing pharmaceutical emissions. Measures may include improved process controls, monitoring of industrial effluent, appropriate handling of concentrated pharmaceutical waste, and implementation of treatment technologies suited to the substances involved.

Environmental stewardship should extend throughout the pharmaceutical life cycle. Product design, manufacturing, distribution, prescribing, use, and disposal can all influence the amount of pharmaceutical material released into the environment (Anand et al., 2022).

7.5 Policy and interdisciplinary collaboration

Effective pharmaceutical pollution prevention requires coordination between health authorities, environmental agencies, pharmacists, prescribers, manufacturers, water utilities, and the public.

Policies may establish collection systems, define responsibilities for pharmaceutical waste, improve wastewater monitoring, and provide guidance for the management of high-risk products. Public health campaigns should be supported by practical infrastructure; education alone cannot ensure safe disposal when suitable collection services are unavailable (Arke, M. et.al., 2025).

A One Health approach is particularly relevant because pharmaceutical pollution connects human health, animal health, environmental quality, and antimicrobial resistance.

8. The Role of Community Pharmacists in Environmental Health

Community pharmacists are well positioned to translate environmental health recommendations into everyday practice. Their accessibility and frequent contact with patients make them important participants in medicine stewardship.

First, pharmacists can educate patients about the appropriate management of unused and expired medicines. Counseling should include the location of authorized collection points and the disposal instructions applicable to the specific medicine and jurisdiction.

Second, pharmacists can support rational medicine use by promoting adherence, encouraging appropriate medication review, and helping patients understand treatment duration and storage requirements. These activities may reduce avoidable accumulation of unused medicines while maintaining treatment effectiveness.

Third, pharmacists can participate in public health campaigns that explain how pharmaceutical residues enter wastewater and why medicine disposal matters. Information should be evidence-based and proportionate, avoiding unnecessary alarm about trace concentrations in drinking water (Wang, Y. Q., et.al., 2022; Sundararaman, S., et, al.,2022).

Fourth, pharmacies may collaborate with local authorities to establish or promote medicine collection programs where permitted. Pharmacists can also help identify practical barriers to participation, such as inconvenient collection locations or limited public awareness.

Finally, pharmacy professionals can advocate for sustainable medicine management within professional organizations and healthcare institutions. Environmental responsibility should be integrated into professional education, pharmaceutical waste procedures, and discussions of medicine stewardship.

These responsibilities must be implemented within local legal and professional requirements. Pharmacists should not accept pharmaceutical waste unless authorized and equipped to do so, and they should not replace established hazardous-waste procedures with informal disposal practices (Arke, M. et.al., 2025).

9. Challenges and Future Research Directions

Despite progress in analytical methods and environmental monitoring, several challenges remain.

First, pharmaceutical occurrence data are unevenly distributed across countries and regions. Differences in wastewater infrastructure, medicine consumption, industrial activity, and monitoring capacity limit direct comparisons between locations.

Second, many environmental studies focus on individual compounds, whereas aquatic organisms may encounter complex mixtures. Future research should improve the assessment of mixture toxicity, chronic exposure, transformation products, and interactions between pharmaceuticals and other contaminants (Hejna, M., Kapuścińska, D., & Aksmann, A., 2022; Zaidi, N., et.al., 2025).

Third, the relationship between measured environmental concentrations and human health outcomes remains uncertain for many substances. Research should distinguish hazard identification from actual risk and prioritize realistic exposure scenarios.

Fourth, the implementation of medicine take-back programs varies among jurisdictions. Comparative studies are needed to determine which collection systems are most accessible, cost-effective, and successful in reducing inappropriate disposal.

Finally, additional research should evaluate the contribution of community pharmacists to public awareness, patient behavior, and pharmaceutical waste reduction. Intervention studies could examine whether pharmacist-led counseling improves knowledge, increases participation in collection programs, and reduces the inappropriate disposal of medicines (Arke, M. et.al., 2025).

10. Recommendations for Community Pharmacy Practice

The following practical recommendations may be considered by community pharmacies, subject to local law and available services:

- Provide patients with clear information about local medicine take-back and disposal options.
- Display educational materials explaining the environmental pathways of pharmaceutical residues.
- Encourage patients to consult pharmacists before disposing of unused or expired medicines.
- Promote appropriate prescribing, adherence, and medication review to reduce avoidable medicine waste.
- Collaborate with authorized collection services and public health authorities.
- Follow specific instructions for hazardous medicines, cytotoxic products, controlled medicines, and other regulated pharmaceutical waste.
- Participate in local environmental health campaigns and evaluate their impact on patient knowledge and disposal practices.

These measures can help integrate environmental stewardship into routine pharmacy practice without compromising patient safety or access to necessary treatment.

11. Conclusion

Pharmaceutical pollution is an important environmental health issue arising from the use, production, and disposal of medicines. Pharmaceutical residues can enter aquatic ecosystems through human and animal excretion, healthcare and manufacturing effluents, agricultural runoff, and the inappropriate disposal of unused products (Hejna, M., Kapuścińska, D., & Aksmann, A., 2022). Their environmental fate depends on chemical properties, environmental conditions, and the effectiveness of wastewater treatment (Bavumiragira, J. P., Ge, J., & Yin, H. 2022; Anand et al., 2022).

Although the detection of pharmaceutical residues does not automatically indicate a significant human health risk, ecological effects and the potential contribution of antibiotic contamination to antimicrobial resistance warrant continued monitoring and prevention. Improved wastewater treatment, responsible medicine use, appropriate pharmaceutical waste management, and evidence-based public education should be implemented as complementary strategies.

Community pharmacists can make a meaningful contribution by counseling patients, supporting medicine take-back programs, promoting rational pharmacotherapy, and collaborating with public health and environmental authorities. However, lasting progress requires coordinated action across the pharmaceutical life cycle, supported by suitable infrastructure, effective policies, and further research. Integrating environmental stewardship into community pharmacy practice offers a practical opportunity to connect medication safety with environmental protection and the broader principles of One Health.

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