

Environmental contamination with pharmaceuticals: Ecotoxicology and Public Health Implications

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Abstract

Pharmaceuticals are extensively used both in human and veterinary medicine due to their therapeutic efficacy. Despite their bioactive components and increased medicinal value, pharmaceuticals also exert some sublethal effects on non-target organisms and eventually impact the whole ecosystem. Public health care contributes approximately 4-5% to environmental contamination. However, pharmaceuticals affect the environment from production and consumption to waste disposal. During the 20th & 21st centuries, various quantities of pharmaceuticals were discharged into water. But Africa ranked first in detecting pharmaceuticals in estuarine water. These wastes were mainly from hospitals and pharmaceutical industries in rivers, lakes, soil, and coastal waters. Various treatment techniques can be applied to get rid of this problem. These techniques may include physical, biological, and chemical processes. Wastewater treatment plants are significantly important in removing pollutants from wastewater. Despite all techniques and methodologies, the negative impact of pharmaceuticals has not been significantly eliminated. The

aim is to develop a system that also considers the harmful impacts of pharmaceuticals along with their therapeutic effects. Regulatory authorities such as the European Union recognize pharmaceutical waste as a risk of contamination of water and soil. The EMA and European Commission also take initiatives in assessing the risk of pharmaceuticals. However, persistent research is still required to advance removal techniques and for their complete elimination.

Author Details

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Introduction

According to the literature, public healthcare contributes to 4-5% of greenhouse gas emissions globally, produces large amounts of waste, releases pharmaceuticals into the environment, and results in biodiversity loss. The major focus is on the contribution of pharmaceuticals in treating illness and managing a healthy life (Booth & Shaw, 2025). Irrespective of their bioactive components, their continuous and persistent input into the environment potentiates the ecological risk and exerts sublethal effects on non-target organisms. The widespread use of pharmaceuticals from both human and animal sciences has been detected in the environment due to their improper removal and waste (Ashiwaju et al., 2023). However, pharmaceuticals have contributed to environmental impact from development, production, distribution, storage, use, to the disposal of their waste (Booth & Shaw, 2025). Pharmaceutical discharge in the environment comes from various sources such as wastewater treatment plants, industries that manufacture pharmaceuticals, and other medical and hospital wastes and agricultural facilities (Adedipe et al., 2024). Pharmaceutical wastes that discharge from hospitals can cause lethal diseases, bacterial residues, infectious agents, wastes of antiseptics, antibiotics, and other pharmaceutical residues (Yasir & A., 2017). These wastes are directly discharged into lakes, rivers, soil, estuaries, or coastal waters. Their improper discharge poses risks to the environment and eventually the whole ecosystem (Adedipe et al., 2024).

The European Union recognizes pharmaceutical waste as a risk of contamination of both water and soil with other micropollutants. In 1990, water contamination by pharmaceuticals was identified as an important issue. In 2009, the legal release of 271 million pounds of drugs into the environment by U.S. manufacturers was reported. It was also found that about 250 million pounds of pharmaceuticals and contaminated packaged products were released by hospitals. The issue was raised as a concern, and the term was suggested environmental persistent pharmaceutical pollutants (EPPP) by the International Society of Doctors for Environment (ISDE) as a strategic approach (Yasir & A et al., 2017). Over the past 20 years, Africa ranked first in detecting pharmaceuticals in estuarine water (145,461.86 ng/L). However, pharmaceuticals were also detected in North America (24,316.39 ng/L), South America (20,784.13 ng/L), Asia (5958.38 ng/L), Europe (4691.23 ng/L), and Oceania (2916.32 ng/L) in terms of WACL. Many categories of pharmaceuticals were identified, but the majority included analgesics, antibiotics, and stimulants.

There is a need to pay attention to the pollution caused by pharmaceuticals (Deblonde et al., 2013). Various techniques can be applied for the removal of wastes and pharmaceuticals from wastewater. These techniques may include physical, biological, and chemical processes. However, other techniques can also be combined with these processes, such as gas chromatography-mass spectrometry and liquid chromatography - mass spectrometry, to improve extraction of wastes. Wastewater treatment plants are significantly important in removing pollutants from wastewater (Wang & Wang, 2016).

However, limited data are found in the literature about the fate and ecotoxicity of pharmaceuticals. The purpose is to set up a system that considers the harmful effects of pharmaceuticals along with their benefits. The EMEA and the European Commission also assess the risk of pharmaceuticals. The system of classification for the assessment of pharmaceuticals is limited, but it should be followed by other countries and the European Commission and European Parliament (Deblonde & Hartemann, 2013). Nevertheless, environmental pollution with pharmaceuticals is growing day by day, and complete removal from various strategies has not yet been successful. But continuous and persistent research is required for their complete elimination. For this purpose, complete assessment and management of hospitals and industries is required. Furthermore, various suggestions should be given by civil

engineers, microbiologists, environmental engineers, pharmacists, scientists, and other consultants in order to overcome this global problem (Khan et al., 2022).

Sources of pharmaceutical contamination

With the advancement of medicine, the production and consumption of pharmaceutical products have been rapidly increasing (Ortúzar et al., 2022). In addition to these, animal husbandry/veterinary excretion (concentrated pharmaceutical mixtures in effluents), manufacturing effluents, and agricultural runoff are important sources of urban domestic wastewater, which is the largest pathway for pharmaceuticals into the environment (Patel et al., 2019; Zahid et al., 2025). Antibiotics are directly added to the environment via pharmaceutical factory effluent and wastewater treatment plant discharge, while livestock manure and agricultural soils are important reservoirs where antibiotics are also present and can persist (Barathe et al., 2024; Imran et al., 2025). The residues enter the environment by a number of different routes, such as production effluent, incorrect disposal practices, agricultural run-off, excretion, etc., and environmental reservoirs include soil, water, and air (Anbarasu and Yuvarajan 2025). The major sources of pharmaceutical contamination and the major pharmaceutical contaminants are listed in **Figure 1**.

Improper Disposal of Unused/Expired Medicines

According to responders from various nations, one way to get rid of unneeded or expired pharmaceuticals is to flush them into the sewage system or dispose of them in household waste, as shown in Figure 1. Pharmaceuticals that are no longer needed or outdated are burnt, dumped in pit latrines, or disposed of as domestic solid waste. Strong hydrological connectedness between pit latrines and groundwater systems may lead to pharmaceutical pollution of groundwater sources, particularly those utilised for drinking water supply; however, the pollution hazards associated with present disposal methods are not well recognised (Gwenzi, Simbanegavi, and Rzymiski 2023). 88% of the respondents did not know how to get rid of nearly expired or expired medications; as a result, they were either thrown in the garbage or flushed down the sanitary ware (Shoaib et al. 2022). These sources of improper disposal have been shown in **Figure 1**.

Pharmaceutical Manufacturing and Factory Effluent

Thousands of tonnes of pharmaceuticals are manufactured globally every year, which are used in both humans and animals (Baaloudj et al. 2025). Untreated industrial pharmaceutical waste is routinely released, posing a serious hazard to ecosystems and human health, particularly in underdeveloped countries. According to recent data showing that one of the main causes of pharmaceutical pollution in receiving sewersheds is direct point source discharges from pharmaceutical plants (Kleywegt et al. 2019). It has been suggested that pharmaceutical manufacturing facilities (PMFs) are significant antibiotic reservoirs. Wastewater is often treated in PMFs' wastewater treatment facilities before being released. Nevertheless, the current PMF wastewater treatment method is unable to eliminate antibiotic residues as described in **Figure 1** (Liu et al. 2023).

Human and Animal Excretion

A portion of the drugs that are thereby transported onto land will either reach open water through surface runoff or seep into groundwater, creating a dispersed source of pollution. (Wöhler et al. 2020). Medications taken orally, inhaled, or applied topically are released into household wastewater due to the human body's insufficient metabolism. As a result, pharmaceuticals and other pollutants with unknown harmful potential are present in the effluent (Caban and Stepnowski 2021). The primary route of excretion is in the urine and faeces, either in their original form or as metabolites

that may have greater biological activity (Przedpeńska, Witczak, and Pokorska-Niewiada 2025). Some of the main routes for the release into the environment of Veterinary Pharmaceutical Medicines are the excretory products of urine and faeces from medicated animals and manure application to agricultural soils, as illustrated in **Figure 1**.

Wastewater Treatment Plant Discharge

Pharmaceuticals and metabolites are discharged to receiving waters when treated wastewater is discharged, as most WWTPs cannot completely remove these pharmaceuticals (Bavumiragira, Ge, and Yin 2022). Although illegal dumping, urban and agricultural runoff, and landfill leachate may also be sources of these pollutants, the chief concern is from wastewater treatment plants (WWTPs) (Khasawneh and Palaniandy 2021). Particularly, hospital wastewater contains pollutants such as radionuclides, organic solvents, pathogenic germs, disinfectants, and medications; in many underdeveloped nations with lax rules or inadequate infrastructure, it is released untreated into the environment (Adeleye et al. 2022). In addition to antibiotics and NSAIDs, there are hormonal compounds, which are the biggest percentage (30% in one recent review) of pharmaceutical contaminants and are generally found in surface water, groundwater, treated effluent, and agricultural wastewater, as illustrated in **Figure 1** (Fakhri B et al. 2024).

Agricultural Run-off

Veterinary medicines commonly used in modern animal husbandry often end up in animal manures and slurries. These bioactive substances can enter the environment by the application of manures to land as an organic fertiliser (Nightingale et al. 2023). Excess solid and liquid manures in agricultural watersheds are considered nonpoint pollution sources, but at high concentrations, nutrients, heavy metals, and antibiotics, especially veterinary antibiotics (VAs), are present in the manures. The emission of urine and faeces from treated animals and the application of polluted manure to farmland are two common ways that veterinary pharmaceuticals enter the environment. These can then leach into groundwater (Rakonjac et al. 2023). Worldwide, significant increases in antibiotic-resistant genes and antibiotics in the soils of agricultural fields have led to global concerns, but there is a lack of systematic studies to examine links between animal husbandry and the potential environmental impacts of fertilisation, especially with manure-based organic fertilisers (MOFs) (Afzal et al., 2025a; Afzal et al., 2025c; Hong et al. 2023). **Figure 1** demonstrates livestock waste, manure application, and agricultural runoff as sources.



Figure1: Sources Of Pharmaceutical Contamination
Occurrence and Distribution of Pharmaceuticals in the Environment

Aquatic occurrence

Pharmaceutical residues have been found in a variety of aquatic compartments, such as wastewater, surface water, groundwater, seawater, and in some instances, even in drinking water source areas, indicating their ubiquitous presence in the environment (Adeleye et al., 2022; Felis et al., 2020; González Alonso et al., 2010; Hernández-Tenorio et al., 2022; Ngqwala & Muchesa, 2020; Nguyen et al., 2024; Pérez-Lucas & Navarro, 2024; Tapera et al., 2026; Wada & Olawade, 2025). The dispersion of pharmaceutical residues outside of aquatic habitats has also been documented in sewage sludge and agricultural soils that receive wastewater or sludge supplements (Barreiro et al., 2022; Camotti Bastos et al., 2020; Madikizela et al., 2020).

Global distribution

Some studies suggest that pharmaceutical and personal-care contaminants have been found in the range of picograms per litre to mg/L, and hundreds of individual pharmaceutical substances have been found throughout the world (Adeleye et al., 2022). Monitoring data from 2018–2019 revealed that environmental concentrations of pharmaceuticals were mostly in the range of ng/L–µg/L, and that antibiotics, psychiatric drugs, stimulants, and β -blockers were commonly found in these samples (Hernández-Tenorio et al., 2022). In repeated monitoring studies of surface water and WWTP, several pharmaceuticals were found, such as sulfamethoxazole (SMX), acetaminophen, carbamazepine, diclofenac, ibuprofen, caffeine, naproxen, and ciprofloxacin (Hernández-Tenorio et al., 2022). Recent investigations have shown that pharmaceuticals are geographically widespread, but that their level of contamination varies between geographical areas depending on pharmaceutical consumption patterns, activities in health care, sanitation infrastructure, and water waste management practices (Wada & Olawade, 2025).

Wastewater, WWTPs and geographical variation

Pharmaceuticals can be discharged to the aquatic environment from human use and wastewater in large quantities via wastewater treatment systems. Human excreta are a major source of pharmaceutical loading in wastewater, but other sources may include hospitals, pharmaceutical production, veterinary practices, and agricultural sources (Adeleye et al., 2022; Felis et al., 2020; Pérez-Lucas & Navarro, 2024; Tapera et al.,

2026). A global assessment for 2018–2019 showed that surface water studies represent about 47% of available monitoring data, while evaluations of WWTPs represent about 30% of monitoring data, with the highest concentrations typically reported for either municipal WWTPs or effluents from pharmaceutical manufacturing (Hernández-Tenorio et al., 2022). A recent global survey of WWTPs identified several different therapeutic classes in both influent and effluent concentrations ranging from 0.001 ng/L to several hundred µg/L (Tapera et al., 2026).

Groundwater, soil, sludge and regional occurrence

Pharmaceutical residues can be found in groundwater, soils, sediments, and in agricultural environments, and contaminate via infiltration and leaching or via wastewater reuse, sewage sludge, and manure application (Matongo et al., 2015; Pérez-Lucas & Navarro, 2024; Tapera et al., 2026; Wada & Olawade, 2025). The contamination of groundwater can occur through infiltration from contaminated surface waters, bank filtration, and leaching from soils contaminated with pharmaceuticals, which is a concern in areas that rely on groundwater for drinking-water supplies (Felis et al., 2020). Sewage sludge has also been found to contain pharmaceutical residues, e.g., caffeine, ibuprofen, and carbamazepine; antibiotic residues, e.g., ciprofloxacin and levofloxacin, have also been reported and may persist in agricultural soils after application (Pérez-Lucas & Navarro, 2024). Overall, the available evidence indicates that pharmaceutical residues can travel through a complex network of interconnected aquatic, terrestrial, and agricultural compartments, and there are several gaps in geographical monitoring and occurrence information.

Environmental Fate And Persistence

Pharmaceutical residues can experience various physical, chemical, and biological reactions once they are released into the environment, affecting their mobility, persistence, transformation, and distribution to the different environmental compartments (Bavumiragira et al., 2022; Zhang et al., 2021). The major processes for the fate of pharmaceuticals in aquatic systems are: sorption, photodegradation, hydrolysis, and biodegradation. Pharmaceuticals such as carbamazepine, diclofenac, sulfamethoxazole, and propranolol can undergo markedly different degradation behaviors (Bavumiragira et al., 2022). Pharmaceutical mobility, bioavailability, degradation, and persistence in the environment can all be impacted by sorption to suspended particles, sediments, and soil organic matter, which can lower the dissolved fraction of pharmaceuticals (Li et al., 2020; Smith et al., 2022).

An experimental study of 13 different soils and sediments with 54 different AIs demonstrated a large diversity in sorption properties (Li et al., 2020). Research with β -blockers such as propranolol and sotalol indicates that interactions at the soil-water and sediment-water interfaces can regulate the availability of the compounds in the environment and affect their concentrations in surface-water and groundwater systems (Smith et al., 2022). However, sorption is particularly important in terrestrial settings due to its potential to control the movement of medicines within soil profiles and towards groundwater (Gworek et al., 2021; Zhang et al., 2021). Biodegradation is another important pathway for pharmacological attenuation that is mediated by microorganisms present in wastewater, soil, sediments, and natural waters (Bavumiragira et al., 2022; Shu et al., 2021).

But due to the differences in molecular structure, microbial community, environmental factors, and accessibility of the compounds to the microorganisms, microbial degradation of medicines varies widely. For example, carbamazepine can show very limited biodegradation, whereas diclofenac, sulfamethoxazole, venlafaxine, and desvenlafaxine may undergo greater biological transformation (Muñoz-Vega et al., 2023; Shu et al., 2021). Because of this, the persistence in the environment of different pharmaceuticals could be quite different and vary by

compartment. Some active pharmaceutical ingredients may have longer environmental half-lives and persist in the environment following environmental attenuation or conventional bio-treatment (Honti et al., 2023; Schwarz et al., 2021). From field studies, it can also be concluded that all the processes (sorption, biological degradation, photochemical modification, dilution, hydrological movement) may occur simultaneously, so that the attenuation of pharmaceuticals in natural waters cannot be attributed to any single process (Honti et al., 2023; Zhi et al., 2021). Evaluation of the persistence of pharmaceuticals should, therefore, consider both the disappearance of parent compounds and the transformations that might occur to these compounds, as well as the stability of possible transformation products, and their potential redistribution in soil, water, sediment and biota (Han et al., 2024; Maculewicz et al., 2022). The environmental fate of pharmaceuticals is highly variable, depending on the type of pharmaceutical compound and environmental compartment. Carbamazepine, diclofenac, sulfamethoxazole, NSAIDs, and β -blockers illustrate how different pharmaceutical classes can exhibit distinct patterns, as it is a dynamic interaction between the characteristics of the pharmaceutical and the environmental conditions (Maculewicz et al., 2022; Zhang et al., 2021).

Ecotoxicological Effects

Pharmaceutical pollution in aquatic and terrestrial environments has become an important issue within the field of ecotoxicology, with various types of pharmaceutical drugs affecting organisms from producers to higher trophic levels. This is shown by the impact of pharmaceuticals on the environment even at low concentrations (Bouzas-Monroy et al., 2022), as illustrated in **Figure 2**. Psychoactive pharmaceuticals are among the most common pollutants in aquatic systems. They have negative impacts on the growth, survival, and behavior of the exposed organisms. According to studies, antidepressants cause difficulties in locomotor activity, feeding, and predator avoidance in fish and invertebrates, indicating potential changes in ecological interactions (Słoczyńska et al., 2023). Aquatic plants like *Lemna minor* are affected by psychoactive pharmaceuticals through decreased photosynthetic efficiency and growth, with mixture exposure having higher toxicity than individual exposure (Witt et al., 2026). As a result, there are likely to be disturbances in primary production and trophic interactions in the environment due to psychoactive pharmaceuticals (Argaluz et al., 2021).

Fluoroquinolones like ciprofloxacin are some of the common pollutants that have strong ecotoxicological effects. Anticancer pharmaceuticals represent another group of ecologically harmful substances with unique properties and ecotoxicological effects. The genotoxic, oxidative, and reproductive activities of anticancer drugs have been demonstrated with exposure to cyclophosphamide and methotrexate in fish and invertebrates (Li et al., 2021) as illustrated in **Figure 2**. For example, cyanobacteria and microalgae suffer from reduced photosynthetic activity, growth, and increased oxidative stress in response to exposure to remdesivir and hydroxychloroquine (Marques et al., 2023).

The most common pharmaceuticals in water bodies include non-steroidal anti-inflammatory drugs such as diclofenac, ibuprofen, and aspirin, as well as acetaminophen. Non-steroidal anti-inflammatory drugs prevent the synthesis of prostaglandins, which causes toxic effects on the physiology of crustaceans. Paracetamol (acetaminophen) also causes toxic effects on terrestrial plants. In spinach (*Spinacia oleracea*) exposed to paracetamol, changes in biochemical and molecular parameters were observed, and oxidative stress was reported, which indicates possible risks of toxicity (Badar et al., 2024). These results indicate that pharmaceutical pollution is not only a problem of the aquatic environment but also poses a risk for plants growing in terrestrial ecosystems.

In a study of the toxicity of 35 pharmaceuticals in effluent from wastewater treatment

plants, mixture toxicity exceeded expectations when assessed using a concentration addition method after ozonation and activated carbon treatment (Spilsbury et al., 2024). Similar results of enhanced toxicity due to mixture exposure were obtained in experiments on aquatic plants and algae (Estrada-Almeida et al., 2024). Antidepressants interfere with serotonin pathways in fish and cause behavioral changes (Słoczyńska et al., 2023), while non-steroidal anti-inflammatory drugs prevent prostaglandin synthesis in crustaceans (Singh & Pflugmacher, 2026). In terrestrial plants and algae, pharmaceuticals reduce the chlorophyll content and photosynthetic activity, which means reduced primary production (Marques et al., 2023; Witt et al., 2026). Overall, risks associated with pharmaceutical contamination are related to food web disruptions, biodiversity losses, and impaired functioning of ecosystems (Bouzas-Monroy et al., 2022), as illustrated in **Figure 2**.

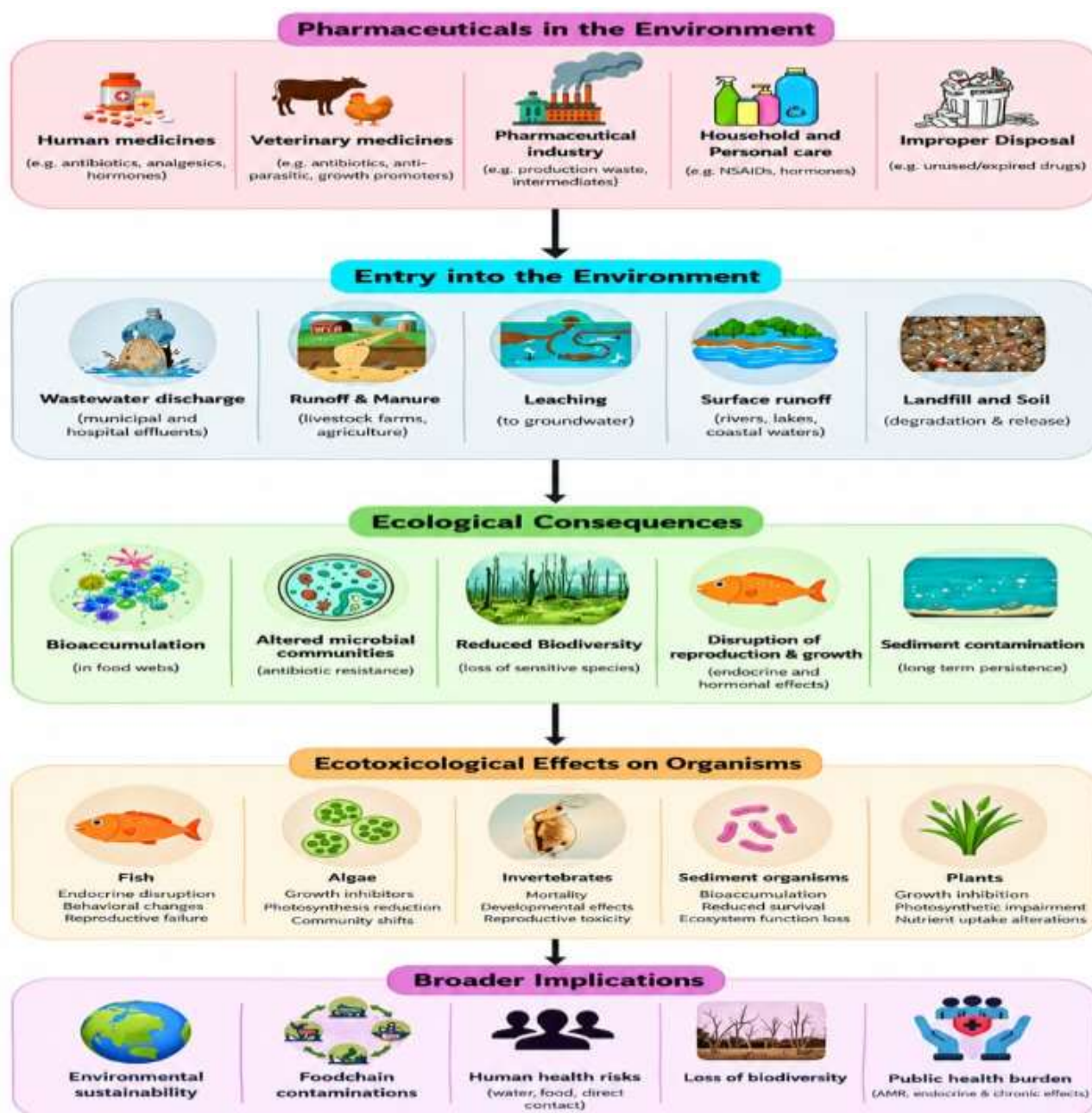


Figure 2: Ecotoxicological Effects

Public Health Implications

Pharmaceutical residues have been detected in distinct water compartments, including raw source water, treated drinking water, tap water, and even bottled water. Systematic reviews indicate that antibiotics, analgesics, antidepressants, and endocrine-disrupting pharmaceuticals have been detected in drinking-water supplies across the globe (Zanni et al., 2024). Similar detections have been reported in rivers, groundwater, and wastewater (Anbarasu & Yuvarajan, 2025; Sharma et al., 2022), as illustrated in **Figure 3**. The most likely exposure route for humans is the consumption of drinking water, either from public supply or bottled water (Smalling et al., 2023; Zanni et al., 2024). Exposure is also possible from the food chain, as antibiotic residues have been detected in foodstuffs and aquatic organisms (Afzal et al., 2025b; Akhter et al., 2024; Bacanlı, 2024). Improper disposal of pharmaceuticals down the toilet or into waterways contributes to environmental pollution and provides an indirect exposure route for communities (Arke et al., 2025).

The antibiotics are among the most frequently detected pharmaceuticals that have

been consistently reported from numerous studies on wastewater, rivers, and drinking water (Akhter et al., 2024; Kotwani et al., 2021). Analgesics and non-steroidal anti-inflammatory drugs (NSAIDs) have also been detected in drinking water (Zanni et al., 2024). Hormonal pharmaceuticals and drugs that interfere with endocrine function, including contraceptive compounds, have also been detected in surface water, raising concerns over potential endocrine disruption (Lunghi et al., 2025). Anticancer and psychiatric pharmaceuticals have been reported as contaminants in some studies, albeit less frequently (Oritsemuelebi et al., 2026). However, for pharmaceutical effluents, the concentrations of antibiotics could be in the range of milligrams per liter (Kotwani et al., 2021). Chronic exposure via drinking water and the food chain could potentially accumulate to hazardous levels despite low individual concentrations (Sharma et al., 2022).

Endocrine and reproductive problems are a significant health concern associated with pharmaceutical contamination of the environment. Studies on humans and animals suggest that exposure to pharmaceutical and personal care product (PPCP) contaminants may be associated with changes in pubertal development. Pregnant women, newborns, children, elderly people, and Individuals with weak immune systems should be given special attention, as they can be more susceptible to the negative effects of environmental pharmaceutical exposure (Oritsemuelebi et al., 2026), as illustrated in **Figure 3**.

The risk assessment reports for pharmaceutical contamination of drinking water concluded that the detected concentrations of pharmaceutical compounds are below the minimum concentrations used in clinical therapy, as illustrated in **Figure 3**. However, they note the uncertainties regarding chronic exposure to low concentrations of such pollutants and the potential physiological effects (Ifedinezi et al., 2024; Salam et al., 2023). Most of the studies on pharmaceutical pollution are environmental and toxicological, with fewer epidemiological investigations (Oritsemuelebi et al., 2026). There is also a need for more research on the health risks of mixtures and the physiological responses, particularly in vulnerable groups (Snapkow et al., 2024). The negative effects include healthcare expenditure resulting from exposure to environmental pharmaceuticals as well as the consequences of antimicrobial resistance; nevertheless, the methods for assessing the former are currently inadequate (Ashraf et al., 2025; Kurnianto et al., 2026). Indeed, 33 pharmaceuticals commonly used in the population were assessed in terms of consumption and excretion data and revealed that nine of them were high-risk priority pollutants while 24 were of concern, thus confirming the effectiveness of such surveillance within the framework of wastewater-based modeling (Pang et al., 2024). Thus, the importance of public health prevention through proper pharmaceutical waste management, medication disposal practices, advanced wastewater treatment, and extensive environmental monitoring must be emphasized (Kurnianto et al., 2026; Oritsemuelebi et al., 2026), as illustrated in **Figure 3**.

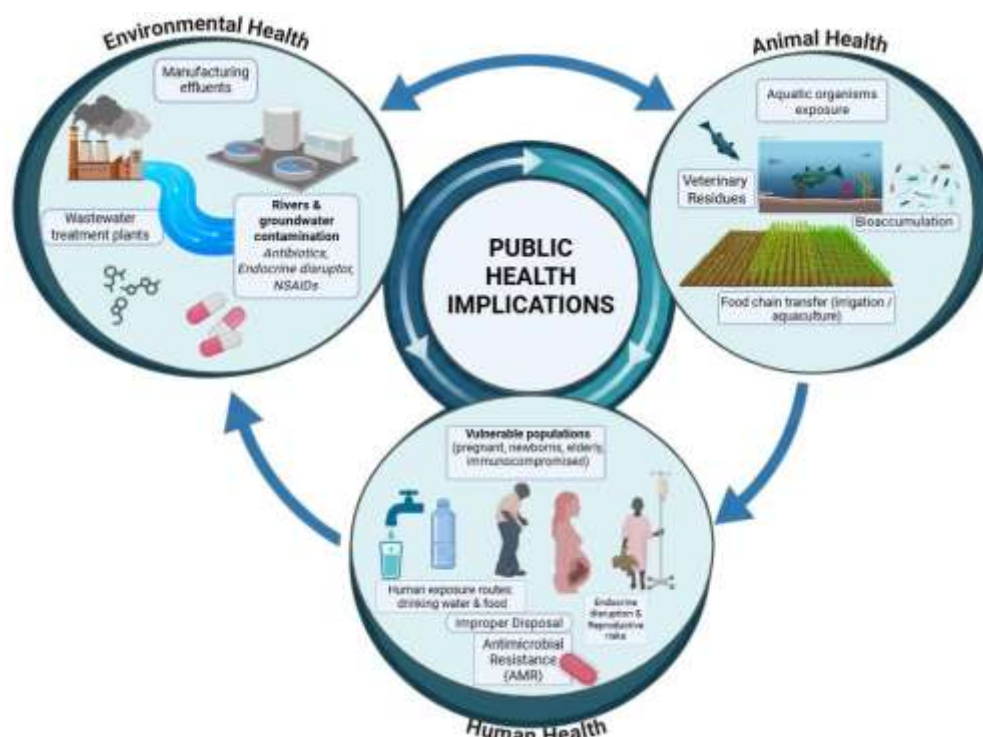


Figure 3. Public Health Implications

Analytical Detection & Remedial Strategies

Strong analytical workflows are essential for measuring trace contaminants and establishing remediation baselines.

Sample Preparation and Extraction Methodologies

Key optimization conditions for matrix processing involve pH adjustment of the sample, avoiding particulate blockage by filtration, centrifugation, sample concentration, and the careful selection of the elution solvent (Y. Zhang et al., 2020). Solid-Phase Extraction (SPE) is still regarded as the ultimate method for the extraction of specific drug classes from liquid matrices. Analytes are retained and eluted using solvents during SPE, which involves passing samples through sorbents that are contained in cartridges or syringes. For primary separation, ion exchange chromatography (IC) along with reversed-phase chromatography (RP) are used. Microwave-Assisted Extraction (MAE) is a green solvent extraction technique that lowers extraction time and solvent use by using ionic conduction and dipole rotation to directly impact the molecules. The effectiveness of extraction has been further enhanced by recent developments, including MAE-HF-L/SME methods along with single-step microwave-assisted headspace solid-phase microextraction (SPME). Other extraction methods include ultrasound-assisted extraction (UAE). Supercritical fluid extraction (SFE) is noted for its rapid processing and reduced matrix interference. However, during the extraction process of active compounds from the sample, oxidation is likely to occur. Combining extraction and analysis via an online system hinders air from entering. Supercritical fluid (SF) maintains characteristics of both liquid and solid simultaneously at high temperature and pressure. Whereas, Pressurized Liquid Extraction (PLE) provides automated, high-recovery extraction of pharmaceutical residues from complex solid matrices like sludge and sediments (Alqarni, 2024)

Chromatographic and Mass Spectrometric Identification of Pharmaceuticals

The selection of the analytical methods and techniques has a significant impact on the

identification and quantification of PhACs in a sample. Two popular methods for analyzing and identifying PhACs in the environment are liquid chromatography (LC) and gas chromatography (GC) (Sapingi et al., 2023). Liquid Chromatography coupled with Mass Spectrometry (LC-MS or LC-MS/MS or tandem MS2) is the most widespread instrumental technique available for the analysis of PPCPs since it allows direct analysis of a wide variety of polar, non-volatile, and thermally labile compounds without prior chemical derivatization (Richardson, 2018). On the contrary, Gas Chromatography (GC-MS / GC-MS/MS) is suitable for non-polar, volatile compounds (e.g., phenolic compounds, musk fragrances, UV filters down to sub-ng/g levels. In order to increase their volatility, polar PPCPs must undergo derivatization (by means of silylation or acylation) so that they can be ionized using Electron Impact (EI) ionization for matching against the spectrum library (Alqarni, 2024).

Advanced Oxidation Methodologies for Pharmaceutical Remediation

Advanced oxidation processes (AOPs) have been utilized to eliminate active pharmaceutical ingredients (APIs) from pharmaceutical or drug products because they are efficient at degrading newly discovered APIs (Kanakaraju et al., 2025). A comprehensive comparative assessment of their mechanisms, target compounds, advantages, and operational limitations is detailed in **Table 7.1**.

Remediation Technology	Mechanism of Removal	Target Pharmaceuticals (Examples)	Major Advantages	Key Limitations	References
Fenton	hydroxyl radical (H ₂ O ₂ + Fe ²⁺ → 2OH· + 2H ⁺) generation via reaction	Diclofenac, ibuprofen, cefazolin, imipenem, vancomycin, Carbamazepine, NSAIDS, Paracetamol, Amoxicillin	High oxidation efficiency, stable storage, low selectivity, and a broad pH range for heterogeneous persulfate and Fenton-like reactions	Sludge formation, pH dependence in conventional Fenton processes, high catalyst separation, reactivation costs,	(Hama Aziz et al., 2025; Kanakaraju et al., 2025; Quang et al., 2022)
Ozonation	Direct oxidation of organic compounds by ozone	Carbamazepine, amoxicillin, ciprofloxacin, acetaminophen, iohexol, bezafibrate, lamotrigine, valsartan, cyclophosphamide, sulfamethoxazole	>95% mineralization rate, effective at near-neutral pH, quick reaction speeds, oxidizing capacities	Low ozone solubility, potential formation of toxic oxidation by-products (bromate), pH dependence,	(Anjali Shanthakumar, 2022; Hama Aziz et al., 2025; Kanakaraju et al., 2025; Q. Zhang et al., 2024)

				low mineralization, high energy consumption	
UV Photolysis	Direct photon cleavage (UV) or radical generation (UV/H ₂ O ₂ , UV/chlorine)	Atenolol, bezafibrate, metoprolol, analgesics, anti-inflammatories, antibiotics, psychiatrics	High quantum yield, inexpensive, very efficient, eco-friendly	Incomplete mineralization, high energy cost, sluggish reaction rates, stability, and reusability	(Hama Aziz et al., 2025; Kanakaraju et al., 2025; Ravinder & Golder, 2025)
Sonolysis (Ultrasound)	Acoustic cavitation generates localized high heat and (HO·) radicals	Paracetamol, amoxicillin, acetaminophen, ciprofloxacin, norfloxacin, diclofenac, sulfamethoxazole	Chemical-free process, operating expense	High power consumption, high operational costs, incomplete mineralization	(Hama Aziz et al., 2025; Kanakaraju et al., 2025; Pirsheh et al., 2023)
Electrochemical Oxidation	Direct electron transfer at the anode (direct) or electro-generated active species (indirect)	Sulfamethoxazole, propranolol, carbamazepine, sulfadiazine	Recalcitrant APIs, Persistent synthetic	High degradation efficacy, reduces	(Donoso et al., 2021; Hama Aziz et al., 2025; Kanakaraju et al., 2025)
			steroids, Eco-friendly, requires	pollutants and sludge without added chemicals, high application cost	

Hybrid-AOPs	Synergistic combination of chemical oxidation, photolysis, and physical energy mineralization.	Carbamazepine, ciprofloxacin	Higher mineralization efficiency, reduced chemical consumption, Increased generation	Complex operational control, higher initial capital cost, requires careful optimization.	(Hama Aziz et al., 2025; Kanakaraju et al., 2025; Krishnan et al., 2023)
Non-thermal plasma	Electrical discharge without external chemicals.	Diclofenac, Ibuprofen, Propranolol, Enrofloxacin, Dexamethasone, Sulfamethoxazole, Tetracycline, Chloramphenicol, Carbamazepine	Chemical-free operation, operates	H ₂ O ₂ saturation limits over time; performance is highly dependent cost, high energy usage	(Hama Aziz et al., 2025; Savić et al., 2024)

Challenges and Future Perspectives

As new bioassay methods and analytical tools become available, new pollutants are identified. Chronic exposure, even at trace concentrations, may contribute to the development of antimicrobial resistance or disrupt hormonal systems in humans and wildlife. (Y. Zhang et al., 2020). Key degradation pathways, including photolysis, microbial biotransformation, and chemical oxidation, heavily influence the mobility and toxicity of aquatic residues. Numerous investigations have demonstrated that PPCP pollutants pose health concerns to humans (Alqarni, 2024). Wastewater treatment plants (WWTPs) are also important hubs for antimicrobial resistance (AMR) as they allow a wide variety of bacterial communities to grow and interact directly with mobile genetic elements and leftover antimicrobials. The environment creates a selective pressure that speeds up horizontal gene transfer. As a result, resistant strains and genes spread into the soil, sediment, and water through biosolids and treated effluent, re-exposing humans through crops, water, direct contact, or insect vectors (Osińska et al., 2020). Addressing the growing threat of pharmaceutical contamination calls for a comprehensive strategy like the Dutch chain approach proposed by Moermond and de Rooy. It deals with pharmaceutical pollution in water by integrating the health and water sectors throughout the whole drug lifecycle. Since most pharmaceuticals enter water via patient excretion, the strategy includes green innovations at the source, such as creating biodegradable 'Green Pharmacy' drugs, especially using special urine collection bags for stubborn X-ray contrast agents, advising people on the correct way to dispose of drug waste, and encouraging environmentally friendly prescribing practices such as preferring paracetamol to NSAIDs (Moermond & de Rooy, 2022). These campaigns highlight the health and environmental dangers of improper medication disposal. In the pharmaceutical sector, the aim is to create a "greener pill" that maintains therapeutic effectiveness while being environmentally friendly (TOMA & CRIŞAN, 2018).

To overcome some of these analytical gaps, there is a need to develop automated non-targeted analysis workflows and high-throughput screening tools to enable efficient

traceability of unknown transformation products and metabolites in complex environmental matrices in the future (Alqarni, 2024; Fatima et al., 2026). Before introducing new drugs, the effects of long-term, low-concentration exposure to pharmacological mixes on humans, wildlife, and aquatic ecosystems should be studied. It should include studies on microbiome effects, sub-lethal effects, and possible connections to human chronic disorders. Additionally, studies on how the environment contributes to the emergence and spread of AMR, as well as methods for reducing this risk, are required.

Conclusion

Pollution of the environment by pharmaceutical compounds is a large and increasingly complex environmental and public health problem. Pharmaceutical residues are likely to become present in aquatic and terrestrial environments at biologically relevant levels if they originate from human and animal use, production, hospital use, agriculture, discharge of wastewater, and improper disposal. Even though many pharmaceuticals are found in trace amounts, long-term exposure to them can have sublethal effects on non-target organisms. These impacts might be widespread and lead to ecological dysfunction at different trophic levels. From the public health perspective, medicines in the environment are of concern due to the possibility of chronic exposure, resistance to these medicines, impacts on ecosystem functions, and potential for transfer through drinking water and the food chain. Because conventional wastewater treatment plants are not specifically designed to remove all pharmaceutical chemicals, there is a need for improved treatment technologies and for source-control measures. Accordingly, an integrated approach with pharmaceutical stewardship, appropriate disposal practices, advanced wastewater treatment, environmental monitoring, risk assessment, and a more stringent regulatory framework is required for good management. An interrelated approach, known as One Health, which brings together environmental, animal, and human health, is particularly important to address interrelated effects of pharmaceutical pollution. Future research should seek to study emerging pollutants, environmental antimicrobial resistance, susceptible ecosystems and communities, long-term and mixed effects, and standardized monitoring. To ensure environmental integrity and public health, reducing pharmaceutical pollution ultimately requires action along the entire pharmaceutical lifecycle, from the manufacture to the disposal of pharmaceuticals.

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