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CHALLENGES OF PHARMACEUTICAL POLLUTANTS: ENVIRONMENTAL IMPACT, LIFE-CYCLE CONCERNS, AND SAFETY STRATEGIES FOR SUSTAINABLE DRUG MANAGEMENT

Santosh Kumar*

*Department of Botany, Maharaja Bijli Pasi Government Post Graduate College, Ashiyana Lucknow-226012 India

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Abstract
Pharmaceutical pollutants have emerged as a critical environmental and public health concern due to their continuous release into ecosystems through manufacturing effluents, improper disposal of expired drugs, hospital waste, and incomplete removal during wastewater treatment. These drug residues persist in water, soil, and biota, causing ecological imbalance, development of antimicrobial resistance, endocrine disruption, and potential long-term toxicity in humans. The life-cycle of pharmaceuticals, from production and consumption to disposal, plays a significant role in determining their environmental footprint. This study reviews the sources, fate, and impacts of pharmaceutical contaminants, emphasizing both conventional and modern drugs, including expired medications. It highlights the challenges associated with inadequate regulatory frameworks, limited public awareness, and inefficiencies in existing treatment technologies. Furthermore, the manuscript discusses the toxicological effects of drug pollutants on aquatic organisms and humans, stressing the need for integrated waste management and green pharmaceutical practices. Emphasis is placed on safety precautions such as proper drug disposal programs, advanced wastewater treatment methods, eco-pharmacovigilance, and the development of environmentally benign drugs. The study underscores the importance of sustainable strategies to minimize pharmaceutical pollution and protect ecosystem integrity and human health. Overall, this work contributes to a better understanding of pharmaceutical life-cycle impacts and provides a foundation for policy formulation and future research aimed at achieving environmental sustainability in healthcare systems.

Keywords
Pharmaceutical pollutants, Environmental contamination, Drug life-cycle assessment, Expired drug disposal, Ecotoxicity and human health, Sustainable pharmacy.

INTRODUCTION

Pharmaceutical pollutants have emerged as a significant class of environmental contaminants due to their continuous and uncontrolled entry into ecosystems through human and veterinary use, industrial discharges, improper disposal of unused or expired medicines, and hospital effluents. Unlike conventional pollutants, pharmaceutical compounds are biologically active, persistent, and specifically designed to interact with living systems, making them potentially hazardous even at very low concentrations (Daughton & Ternes, 1999; Kümmerer, 2009). Over the past two decades, traces of antibiotics, analgesics, antidepressants, hormones, antidiabetics, and anticancer drugs have been frequently detected in surface water, groundwater, soil, and even drinking water supplies, raising serious concerns about environmental safety and public health (WHO, 2019).

The life cycle of a pharmaceutical product, from manufacturing and consumption to excretion and disposal, plays a crucial role in environmental contamination. A

CONTACT *Corresponding author: herbalsantosh5@gmail.com, *Orcid id: 0009-0000-4372-5691*
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significant proportion of drugs are excreted unchanged or as active metabolites, entering wastewater treatment systems that are often not designed to completely remove these complex compounds (Heberer, 2002). In addition, expired and unused medicines disposed of through household waste or flushing into sewage systems contribute substantially to environmental loading (Daughton, 2003). Modern pharmaceuticals, including targeted therapies, biologics, and sustained-release formulations, further complicate the pollution scenario because of their enhanced stability and prolonged persistence in the environment.

Pharmaceutical pollutants pose diverse ecological and biological risks. They can disrupt aquatic ecosystems, alter microbial communities, promote antibiotic resistance, and cause endocrine and behavioral disturbances in wildlife (Fent et al., 2006; Kümmerer, 2009). Chronic exposure, even at trace levels, may lead to long-term effects on biodiversity and ecosystem functioning. Furthermore, bioaccumulation and trophic transfer of drugs raise concerns regarding indirect human exposure through food and water.

Understanding drug pollutants within the framework of their environmental life cycle is therefore essential for developing sustainable pharmaceutical practices. This includes eco-friendly drug design, improved wastewater treatment technologies, responsible disposal strategies, and stricter regulatory policies. The present manuscript aims to critically review the challenges posed by pharmaceutical pollutants, with special emphasis on modern drugs and expired medicines, their environmental fate, and the safety measures required to minimize their adverse impacts. By integrating pharmaceutical sciences with environmental sustainability, effective solutions can be proposed to protect both ecosystems and public health.

Review Findings: Selection Criteria of Studies

The selection of studies for reviewing pharmaceutical pollutants was based on well-defined inclusion criteria to ensure scientific relevance, reliability, and environmental significance. Peer-reviewed research articles, review papers, and reports published in internationally recognized journals were primarily considered. Studies published in the last 15–20 years were prioritized, as pharmaceutical pollution is a rapidly evolving research field and recent findings better reflect current environmental conditions and analytical technologies (Kümmerer, 2009). Articles focusing on the occurrence, fate, transport, toxicity, and ecological risk assessment of drug pollutants in water, soil, sediment, and biota were included.

Preference was given to studies that investigated widely used drug classes such as antibiotics, analgesics, anti-inflammatory agents, antidepressants, antidiabetics, hormones, and anticancer drugs, as these are most frequently detected in the environment (Daughton & Ternes, 1999). Research addressing modern pharmaceuticals, sustained-release formulations, and expired drug disposal practices was also considered highly relevant. Only studies using validated analytical techniques such as LC-MS/MS, GC-MS, and HPLC for detection and quantification of pharmaceutical residues were included to ensure accuracy and reproducibility of data.

In addition, studies examining environmental pathways, wastewater treatment efficiency, bioaccumulation, and ecological or human health impacts were selected. Reports from regulatory agencies such as WHO, US EPA, and European Medicines Agency were included to provide policy-level insights. Together, these criteria ensured that the selected literature comprehensively represented the life cycle, environmental behavior, and risks of pharmaceutical pollutants while maintaining high scientific quality and relevance.

Review Findings: Rejection Criteria of Studies

Studies were excluded from the review if they did not meet the established standards of scientific quality, relevance, and methodological rigor. Articles lacking peer review, such as unpublished theses, non-scientific reports, opinion pieces, and blog-based content, were not considered, as they may contain unverified or biased information (Kümmerer, 2009). Research with insufficient experimental details, unclear methodologies, or absence of validated analytical techniques for pharmaceutical detection was also rejected. Studies that did not employ standard instruments such as LC-MS/MS, HPLC, or GC-MS for quantification of drug residues were excluded due to concerns regarding data accuracy and reproducibility.

Older studies published before 2000 were generally excluded unless they provided historically significant insights into pharmaceutical pollution, as early investigations often lacked advanced analytical sensitivity and environmental risk frameworks (Daughton & Ternes, 1999). Articles focusing solely on industrial chemical pollutants, pesticides, or heavy metals without addressing pharmaceutical compounds were not included, since the scope of this manuscript is restricted to drug pollutants.

Studies reporting contradictory results without adequate statistical validation, small sample sizes, or non-representative sampling locations were also rejected. Research limited to laboratory simulations without environmental relevance, or studies that failed to link pharmaceutical contamination to ecological or health outcomes, were excluded. Furthermore, articles that did not address the life cycle perspective of drugs—including production, usage, disposal, and environmental fate—were not considered. These rejection criteria ensured that only high-quality, reliable, and environmentally meaningful studies contributed to the manuscript.

Drug Pollutants and Modern Drugs in the Environment

Drug pollutants, also referred to as pharmaceutical contaminants or pharmaceutically active compounds

(PhACs), are an emerging class of environmental pollutants that originate from the widespread and continuous use of modern medicines. These compounds include prescription drugs, over-the-counter medications, veterinary pharmaceuticals, personal care products, and biologics. After administration, a significant proportion of drugs are excreted unchanged or as active metabolites through urine and feces, which enter wastewater treatment systems and eventually reach surface water, soil, and groundwater (Daughton & Ternes, 1999; Kümmerer, 2009). Conventional wastewater treatment plants are not specifically designed to remove pharmaceutical residues completely, resulting in their persistent presence in the environment.

Modern drugs such as antibiotics, analgesics, antidiabetics, antidepressants, antiepileptics, hormones, and anticancer agents are frequently detected in aquatic ecosystems. Antibiotics like ciprofloxacin and amoxicillin contribute to the development of antimicrobial resistance in environmental microorganisms. Hormonal drugs such as ethinylestradiol disrupt endocrine function in aquatic organisms, leading to feminization of fish and reproductive abnormalities (Fent et al., 2006). Antidiabetic drugs like metformin and dapagliflozin, as well as cardiovascular drugs such as beta-blockers and statins, have also been increasingly reported in river waters and sediments, indicating the growing burden of chronic disease medications on ecosystems.

Expired and unused drugs represent a significant yet often neglected source of pharmaceutical pollution. Improper disposal practices, such as flushing medicines down toilets or throwing them into household garbage, lead to the direct release of high concentrations of active pharmaceutical ingredients into the environment. In many developing countries, including India, awareness and infrastructure for safe drug disposal are limited, intensifying the problem. Expired drugs can still retain substantial biological activity, and their degradation products may be equally or more toxic than the parent compound (Bound & Voulvoulis, 2005).

Veterinary pharmaceuticals further aggravate environmental contamination. Drugs used in livestock, aquaculture, and poultry farming enter soil and water through manure, runoff, and direct excretion. Antiparasitic agents such as ivermectin and antibiotics like tetracyclines persist in soil and adversely affect non-target organisms, including beneficial insects and soil microbes. This disrupts ecological balance and nutrient cycling.

The life cycle of modern drugs—from synthesis and formulation to consumption and disposal—plays a crucial role in environmental contamination. Manufacturing effluents, hospital wastewater, pharmaceutical packaging waste, and improper disposal of expired drugs all contribute to environmental loading. With the increasing consumption of modern medicines due to population growth and chronic disease prevalence, pharmaceutical pollution is expected to intensify unless strict regulatory control and sustainable waste management practices are implemented (Boxall et al., 2012).

Thus, both active modern drugs and expired pharmaceuticals act as persistent environmental pollutants, posing serious threats to aquatic life, soil ecosystems, and potentially human health through bioaccumulation and contamination of drinking water resources.

Table 1: Persistent environmental pollutants, posing serious threats to aquatic life, soil ecosystems, and potentially human health.

Drug Pollutant Category	Example Drugs	Major Source in Environment	Effect on Aquatic Life	Possible Effect on Human Body	References
Antibiotics	Ciprofloxacin, Amoxicillin, Tetracycline	Hospital effluents, domestic sewage, livestock waste	Development of antibiotic-resistant bacteria; toxicity to algae and microorganisms	Reduced antibiotic efficacy, gut microbiota disturbance, increased resistant infections	Kümmerer (2009); Larsson et al. (2007); aus der Beek et al. (2016)
Analgesics / NSAIDs	Diclofenac, Ibuprofen, Paracetamol	Household disposal, pharmaceutical wastewater	Kidney and gill damage in fish, reproductive toxicity	Long-term liver and kidney dysfunction	Oaks et al. (2004); Fent et al. (2006); Vieno & Sillanpää (2014)
Hormones	Ethinylestradiol, Estradiol	Contraceptive use, sewage effluents	Endocrine disruption, feminization of male fish, reproductive failure	Hormonal imbalance, infertility, cancer risk	Jobling et al. (1998); Kidd et al. (2007); Caldwell et al. (2012)
Antidiabetic Drugs	Metformin, Dapagliflozin	Domestic sewage, hospital discharge	Altered metabolism and growth in aquatic metabolic organisms	Potential disruption and unknown chronic toxicity	Niemuth & Klaper (2015); Trautwein & Kümmerer (2011); aus der Beek et al. (2016)
Antidepressants	Fluoxetine, Sertraline	Domestic wastewater	Behavioral changes in fish, impaired	Neurological and endocrine	Brooks et al. (2003); Schultz

			predator response	disturbances	et al. (2011); Fent et al. (2006)
Antiepileptics	Carbamazepine, Valproate	Sewage treatment plants	Persistent bio-accumulation, developmental toxicity	Possible neuro-developmental effects	Zhang et al. (2008); Ferrari et al. (2003); aus der Beek et al. (2016)
Cardiovascular Drugs	Atenolol, Propranolol, Statins	Domestic and hospital wastewater	Altered heart rate and metabolism in fish	Cardiovascular and metabolic disturbances	Huggett et al. (2002); Fent et al. (2006); Kümmerer (2009)
Anticancer Drugs	Cyclophosphamide, Methotrexate	Hospital effluents	Genotoxicity and growth inhibition in aquatic organisms	Mutagenic and carcinogenic risks	Kümmerer (2009); Johnson et al. (2008); Parrella et al. (2018)
Veterinary Drugs	Ivermectin, Sulfonamides	Animal excreta, agricultural runoff	Toxicity to insects, soil microbes, aquatic fauna	Indirect toxicity via food chain contamination	Boxall et al. (2004); Monteiro & Boxall (2010); Kümmerer (2009)
Expired / Unused Medicines	Mixed pharmaceutical residues	Improper disposal in garbage or toilets	Acute toxicity, ecosystem bioaccumulation	Exposure to degraded or toxic drug products	WHO (2011); Daughton & Ruhoy (2009); Tong et al. (2011)

Challenges and Safety Precautions in Managing Drug Pollutants

The management of pharmaceutical pollutants in the environment faces multiple scientific, technological, regulatory, and societal challenges. One of the primary difficulties is the continuous introduction of drugs into aquatic systems through domestic sewage, hospital effluents, agricultural runoff, and improper disposal of expired or unused medicines. Conventional wastewater treatment plants are not specifically designed to remove complex pharmaceutical compounds, resulting in their persistence in surface water, groundwater, and soil (aus der Beek et al., 2016). Moreover, many drugs and their metabolites exhibit chemical stability and resistance to biodegradation, increasing the risk of bioaccumulation and long-term ecological toxicity (Kümmerer, 2009).

Another major challenge is the lack of comprehensive monitoring systems and standardized regulatory limits for pharmaceutical residues in environmental matrices. In developing countries, limited infrastructure and poor public awareness further aggravate improper disposal practices, leading to uncontrolled contamination (Patel et al., 2019). Additionally, the combined effects of multiple drug residues (cocktail effect) are poorly understood, making accurate risk assessment difficult (Mezzelani et al., 2018).

To mitigate these risks, several safety precautions should be implemented. Public awareness programs should educate communities on safe drug disposal methods, such as returning unused medicines to pharmacies or designated collection centers. Healthcare institutions must adopt strict waste management protocols to prevent direct discharge of active pharmaceutical ingredients into sewage systems. Advanced wastewater treatment technologies, including ozonation, activated carbon adsorption, membrane filtration, and advanced oxidation processes, should be integrated to enhance drug removal efficiency (Michael et al., 2013).

Furthermore, regulatory authorities should establish clear environmental guidelines for pharmaceutical emissions and promote eco-pharmacovigilance, encouraging the development of biodegradable and environmentally safer drugs. Strengthening interdisciplinary collaboration between environmental scientists, pharmacologists, policymakers, and industry stakeholders is essential to ensure sustainable pharmaceutical use while protecting ecosystems and human health.

Conclusion

Pharmaceutical pollutants have emerged as a critical environmental concern due to their continuous release, persistence, and potential to disrupt ecological balance and human health. The presence of active drug compounds, metabolites, and expired medicines in water, soil, and biota highlights the urgent need for improved waste management and regulatory control. Conventional treatment systems remain inadequate to completely remove these contaminants, emphasizing the necessity for advanced remediation technologies. Sustainable drug design, public awareness on safe disposal, and stricter environmental policies are essential strategies to minimize pharmaceutical pollution. Addressing this issue holistically will ensure environmental protection while maintaining the therapeutic benefits of modern medicines.

Conflict of interest

Author declare no conflict of interest

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