EMERGING HEALTH RISKS OF PHARMACEUTICAL POLLUTANTS IN WATER SOURCES: PUBLIC HEALTH PERSPECTIVES AND POLICY RECOMMENDATIONS

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Abstract: Pharmaceutical pollutants are increasingly being detected in natural water sources, raising serious concerns for both environmental integrity and public health. These contaminants originate from human and veterinary drug use, improper disposal, and pharmaceutical manufacturing. Their persistence in the environment and ability to exert biological effects at low concentrations make them pollutants of emerging concern. This review synthesizes recent primary research findings on the environmental pathways, persistence, and health risks associated with pharmaceutical pollutants, highlighting critical gaps in current monitoring and regulatory frameworks, particularly in low and middle-income countries. Furthermore, it offers policy recommendations aimed at strengthening integrated waste management, surveillance systems, and public awareness to mitigate these emerging threats effectively.

Keywords: pharmaceutical pollutants, water contamination, environmental health, antibiotic resistance, public health policy

1. Introduction

The introduction of pharmaceutical pollutants into aquatic environments has become a pressing environmental and public health concern. These substances, which include prescription and over-the-counter medications, are often detected in wastewater, rivers, lakes, and even drinking water supplies. Designed to be stable and biologically active, pharmaceuticals can persist in natural environments and retain their pharmacological effects even at trace concentrations. The presence of these compounds in the environment is alarming due to their potential to cause adverse effects on non-target organisms, notably by promoting antibiotic resistance. The increasing prevalence of pharmaceuticals in the environmental context necessitates a careful examination of how these pollutants arise from pharmaceutical manufacturing processes, human excretion, and improper disposal [1,2].

Citation: M. Muzammal, AIDASCO Reviews 3, 1 (2025) 36-43. DOI: https://doi.org/10.59783/aire.2025.73

 ISSN: 2956-0888 (Online)

Despite increasing awareness, monitoring and regulatory measures remain inadequate, particularly in developing regions where wastewater treatment infrastructure is limited [1]. This review examines the primary sources and environmental behavior of pharmaceutical pollutants, their impacts on human and animal health, and the regulatory gaps that hinder effective management. By integrating findings from primary research studies and case examples, this article aims to provide a comprehensive and evidence-based synthesis to inform future research and policy directions [3].

2. Sources and Pathways of Pharmaceutical Contaminants

Pharmaceutical pollutants reach water bodies through various sources:

Human and veterinary pharmaceutical use: Drug residues are excreted through urine and feces, entering sewage systems. Human and veterinary pharmaceutical use represents a significant pathway through which drug residues enter aquatic environments. When humans or animals consume medications, a significant portion of the active substances is not fully metabolized and is subsequently excreted in urine and feces. These residues enter municipal sewage systems and, depending on the efficiency of wastewater treatment plants, can persist in treated effluents released into rivers, lakes, and groundwater sources

Industrial and hospital waste: Waste from pharmaceutical manufacturing and healthcare institutions often carries high concentrations of active pharmaceutical ingredients. This industrial effluent may sometimes exceed environmental safety thresholds due to insufficient treatment or direct discharge practices. Hospitals and healthcare facilities add to this burden by releasing residues of various drugs through patient excretion and improper disposal of unused medications.

Improper disposal and agricultural runoff: Common practices such as flushing unused medicines or discarding them in household trash contribute significantly to contamination. Discarding medicines in household trash can lead to leaching of active compounds into soil and groundwater, especially in landfills lacking proper containment measures. Agricultural runoff, especially from farms using veterinary pharmaceuticals, transports antibiotics and hormone residues from animal waste and fertilizers into nearby streams and rivers.

Inadequate wastewater treatment facilities in many regions fail to remove these compounds effectively, allowing them to leach into surface and groundwater. In areas lacking proper waste management infrastructure, this pathway is particularly concerning.

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The sources of pharmaceutical contaminants in aquatic environments primarily originate from improper disposal practices, inadequate wastewater treatment processes, and an overall increase in pharmaceutical consumption. One significant pathway for these contaminants is the household disposal of drugs, which often occurs through the flushing of pharmaceuticals down the toilet or their disposal in the trash [4]. This method facilitates their introduction into sewage systems, leading to potential leaching into groundwater or surface waters, especially in areas lacking modern infrastructure and proper waste management practices. Although some pharmaceuticals undergo degradation within the human body and subsequent wastewater treatment processes, a considerable proportion may remain intact, necessitating comprehensive risk assessments that factor in the disposal pathways of these substances [5]. The environmental fate and toxicological properties of many pharmaceuticals are often poorly understood, presenting challenges in mitigating their impact on aquatic organisms and ecosystems. The pharmaceutical use driven by heightened accessibility and demand has led to significant and potentially hazardous levels of pollution in surface waters, elevating the need for both source-directed and control measurements [6]. As pharmaceutical usage is projected to increase substantially in the coming years, it becomes imperative to develop effective management strategies to mitigate their environmental impact and ensure a sustainable balance between pharmaceutical availability and ecological health [7].

3. Environmental Distribution and Persistence

Once in the environment, pharmaceuticals interact in complex ways:

Persistence and Bioaccumulation: Many pharmaceutical compounds resist degradation, persisting for extended periods. Lipophilic drugs can bioaccumulate in aquatic organisms, affecting entire food chains.

Ecological Impacts: Pharmaceuticals have been shown to affect the behavior, reproduction, and survival of fish, amphibians, and aquatic invertebrates. Hormone disruptors, in particular, pose long-term risks to biodiversity.

While monitoring programs exist in some countries, they often focus on a limited number of compounds, leaving gaps in our understanding of the broader ecological consequences.

The behavior of pharmaceuticals in aquatic ecosystems has become an increasingly critical area of study due to the growing recognition of their potential impacts on environmental health and biodiversity. Pharmaceuticals are prevalent contaminants in surface water worldwide. Urban activities exert substantial pressure on water bodies, increasing pollution levels and resulting in significant concentrations of various

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pharmaceutical compounds [8]. While there is extensive monitoring of these substances, it often prioritizes a limited number of compounds, resulting in a knowledge gap regarding numerous pharmaceuticals, their metabolites, and degradation products across different water compartments. The lack of comprehensive data underscores the necessity for systematic reviews that encompass a broader range of therapeutic categories and the impact of pharmaceuticals on ecological integrity [9]

4. Health Impacts on Humans and Animals

Pharmaceutical pollutants can cause both acute and chronic health effects:

Acute Health Effects: Exposure to contaminated water may result in allergic reactions, gastrointestinal symptoms, or organ-specific toxicity, especially in vulnerable populations. Because many pharmaceuticals are designed to be biologically active at low doses, even trace levels in drinking water or recreational water bodies can pose health risks, especially when multiple drugs co-occur and may have additive or synergistic effects.

Chronic Health Effects: Long-term exposure to low concentrations of pharmaceutical mixtures can lead to hormonal imbalances and endocrine disruption. The chronic effects may also extend to neurological impairments, immune system suppression, and metabolic disorders as a result of exposure to diverse pharmaceutical compounds, including antidepressants, antipsychotics, and beta-blockers.

Antibiotic Resistance: Continuous low-level exposure to antibiotics in the environment fosters the development of resistant bacterial strains, threatening global health security. Antibiotic resistance compromises the effectiveness of current medical treatments and increases healthcare costs, morbidity, and mortality worldwide. The environmental dimension of this issue is often overlooked in public health policies, underscoring the need for integrated One Health approaches that address pharmaceutical pollution as a key driver of antibiotic resistance at the human-animal-environment interface.

These health risks are compounded by the lack of comprehensive toxicological data and the complex nature of environmental exposure.

Acute health effects of pharmaceuticals in humans are a complex issue, often compounded by the multifaces nature of exposure pathways. Pharmaceuticals enter water systems primarily through human excretion, improper disposal, and agricultural runoff. Moreover, the challenge in assessing acute health effects is magnified by the reality that humans are often not exposed to single pharmaceuticals but rather to complex mixtures [10]. This exposure could lead to unforeseen cumulative or synergistic effects that remain poorly understood. For instance, while individual studies have investigated specific drugs,

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the interactions between multiple pharmaceuticals, alongside other present environmental pollutants, could enhance their persistence and toxicity, thereby complicating risk assessments. The National Research Council's recommendation for future risk assessments emphasizes the need for a holistic approach, integrating multiple exposure pathways, to yield a more accurate appraisal of the health risk posed by pharmaceuticals in the environment [3].

Chronic health effects in humans associated with pharmaceuticals, particularly those found in the environment, have attracted increasing attention from researchers. Although the primary focus has often been on acute exposure to specific drugs, evidence is mounting that long-term exposure to low levels of a mixture of pharmaceutical pollutants may pose significant health risks [11]. The mixing of varying substances may lead to cumulative or synergistic effects, which remain understudied but raise concerns about their potential health impacts [12].

Antibiotic resistance has emerged as a critical public health challenge driven by the misuse and overuse of pharmaceutical compounds. The phenomenon wherein the use of antimicrobial drugs can lead to the selection of resistant strains not only complicates treatment regimens but also facilitates the emergence of resistance against other antimicrobial classes [13]. As bacteria evolve in response to these pressures, the timeframe from drug application to resistance emergence can vary significantly, but it often becomes irretrievable. This emphasizes that effective management of antibiotic usage is vital in both human and veterinary medicine [14].

5. Case studies and regional burdens

South Asia and Sub-Saharan Africa. The lack of pharmaceutical waste regulation and insufficient treatment infrastructure lead to severe contamination of water bodies.

Eastern Europe and the Balkans. Studies report the presence of antibiotics, painkillers, and psychotropic drugs in rivers, often exceeding recommended limits.

These cases highlight the global nature of the problem and the need for international cooperation [12].

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6. Monitoring and Regulatory Gaps

Lack of Standardized Methods: There is no universal standard for testing pharmaceutical residues in water. The absence of clear guidelines for sampling frequency, target compounds, and reporting units further exacerbates these challenges, calling for coordinated international efforts to establish reliable and universally accepted testing frameworks.

Weak Enforcement: Where regulations exist, enforcement is often lacking. Strengthening enforcement requires updating legislation and improving transparency, accountability, and cooperation among stakeholders, including government agencies, industry players, and the public.

Data Deficiency: Inadequate surveillance leads to underreporting and delays effective responses. Existing datasets often cover only a limited range of compounds or geographic areas, failing to capture the full extent of pharmaceutical pollution and its temporal variability.

Policy recommendations and solutions

1. Integrated pharmaceutical waste management

2. Strengthening surveillance systems

3. Regulation and accountability

4. Public awareness and stewardship

5. Global collaboration

7. Conclusions

Pharmaceutical pollutants represent a growing threat at the nexus of environmental sustainability and public health. Their persistence, biological activity, and widespread distribution demand urgent attention. Addressing this complex challenge requires a comprehensive strategy that integrates effective regulatory policies, enhanced and standardized environmental surveillance systems, cutting-edge technological innovations in wastewater treatment and pollution control, as well as proactive public engagement and education initiatives. Through such a holistic and collaborative approach, we can successfully mitigate the risks posed by pharmaceutical contaminants and foster a more

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responsible, equitable, and sustainable framework for pharmaceutical production and consumption.

Acknowledgments: I would like to express my sincere gratitude to Dr. Maria Savanović for her valuable insights, suggestions, and encouragement throughout the development of this article.

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