Pharmaceutical Wastewater and Environmental Contamination: Challenges, Innovations, and Future Directions

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Abstract

Pharmaceutical pollution has emerged as a critical environmental issue, impacting water quality, aquatic ecosystems, and public health globally. Increasing pharmaceutical consumption and inadequate wastewater treatment have led to the persistence of active pharmaceutical ingredients (APIs) in natural water bodies, raising concerns over ecotoxicological effects and the proliferation of antibiotic resistance. This challenge is particularly pronounced in emerging economies, where rapid industrialization and limited regulatory frameworks exacerbate the problem. While advanced treatment technologies like nano-adsorbents and advanced oxidation processes (AOPs) show promise, challenges remain in terms of scalability, cost, and regulatory acceptance. Policy efforts often focus on end-of-pipe solutions, failing to address the full lifecycle of pharmaceutical pollutants. This review synthesizes current knowledge on pharmaceutical contamination, emphasizing the interplay of innovative technologies, policy frameworks, and socioeconomic factors. By integrating contemporary research, the article aims to guide stakeholders toward effective and sustainable mitigation strategies.

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Keywords: *Pharmaceutical pollution, APIs, water contamination, ecotoxicology, antibiotic resistance, AOPs, nano-adsorbents, wastewater treatment, environmental policy, sustainable solutions*.

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1. INTRODUCTION

Pharmaceutical pollution has rapidly emerged as a front-and-center environmental concern over the past few decades, with ramifications for water quality, aquatic organisms, and public health. The rise in consumption and production of pharmaceuticals—spanning antibiotics, painkillers, hormones, psychiatric medications, and personal care products—has led to a proliferation of contaminants in

waterways (Khalidi-Idrissi et al., 2023). In many instances, existing wastewater treatment infrastructures do not sufficiently remove all pharmaceutical residues (Bankole et al., 2023). Consequently, active pharmaceutical ingredients (APIs) or their metabolites linger in effluents, eventually making their way into natural ecosystems and even sources of drinking water (Abdullahi Haruna Birniwa et al., 2023).

In emerging economies, the situation is compounded by rapid industrial growth, inadequate regulatory oversight, and limited wastewater treatment capacity (Sapkota & Pariatamby, 2023). Even in regions with advanced treatment technologies, traces of pharmaceutical contaminants remain a persistent issue (Hussain et al., 2023). This global predicament has garnered the attention of policymakers, scientists, and the pharmaceutical industry alike, underlining the urgent need for cost-effective, sustainable treatment solutions (Abubakar et al., 2024; Ojha et al., 2024).

A wide range of chemical classes of pharmaceuticals end up in the environment, from common analgesics such as ibuprofen to chemotherapy agents, steroid hormones, and antibiotics (Chakraborty et al., 2023). Not only do these compounds exert ecotoxicological effects by altering aquatic ecosystems and harming non-target species, but they also raise alarm about the emergence of antibiotic resistance (Singh et al., 2024). Several studies have indicated that subtherapeutic levels of antibiotics in water can foster resistance genes within microbial communities (Barkha Madhogaria et al., 2024).

Addressing this challenge requires a comprehensive, multi-pronged approach: advanced treatment technologies, robust policies, public awareness, and innovations in drug design (Ashraf et al., 2024; Atheena et al., 2024). On the technological front, research has advanced toward novel solutions such as nano-adsorbents, advanced oxidation processes (AOPs), and specialized membrane filtration (Thakur et al., 2023). These emergent methods may offer higher removal efficiencies compared to conventional practices, but challenges persist with regard to scale-up, cost, byproduct formation, and regulatory acceptance (Chen et al., 2024).

From a policy perspective, various frameworks strive to manage pharmaceutical pollutants via end-of-pipe controls, but these often fail to capture the entire lifecycle—from manufacturing and distribution to usage and disposal (Kataria et al., 2023). Environmental

stewardship is often overshadowed by cost and expediency in pharmaceutical manufacturing. Alongside policy shortfalls, there is a pressing need for standardized risk assessment methodologies and a deeper understanding of the synergy between multiple pollutants (Nguyen et al., 2023).

This article seeks to synthesize contemporary knowledge on pharmaceutical contamination, highlighting both conventional and cutting-edge mitigation approaches. We will examine the nature and scope of pharmaceutical pollutants, delve into the synergy between technology and policy, and consider the broader socioeconomic dimensions that shape the efficacy of interventions (Gabson Baguma et al., 2023). By integrating references from recent literature, the goal is to provide a holistic, evidence-based overview that can guide researchers, industry stakeholders, and policymakers toward sustainable solutions.

2. GLOBAL OVERVIEW OF PHARMACEUTICAL WASTEWATER CONTAMINATION

Pharmaceutical compounds and their metabolites are now detected globally in surface waters, groundwater, and sediments—underscoring that no single region or water body is immune. Studies across continents confirm the prevalence of antibiotics, analgesics, and anti-inflammatory drugs at varying concentrations (González-González et al., 2023). This universal presence speaks to the extensive use of pharmaceuticals across human and veterinary medicine, as well as the difficulty in eliminating these pollutants via conventional treatment methods (Daba & Elkhateeb, 2024).

In developing regions, expansion of pharmaceutical manufacturing hubs without parallel improvements in wastewater treatment infrastructure has led to localized pollution hotspots (Iman Salahshoori et al., 2024). For instance, high antibiotic loads have been detected in aquatic systems near industrial parks, raising alarms about antibiotic resistance and broader ecological impacts (Aziz et al., 2024a, 2024b). Meanwhile, in developed nations, better monitoring protocols and advanced treatment plants have led to improved detection capabilities, revealing that even trace levels of certain drugs may disrupt aquatic organisms over time (Kosar et al., 2024).

Additionally, the disposal of expired or unused pharmaceuticals remains a challenge worldwide. Without adequate take-back programs or public awareness, substantial volumes of pharmaceutical waste end up in landfills or are poured down the drain (Uddin

et al., 2024). Over-the-counter (OTC) medications can further exacerbate the problem, as easy access promotes frequent misuse and subsequent disposal. These real-world scenarios underscore how broad the pharmaceutical contamination issue is, necessitating multifaceted and cross-sector solutions (Khan, 2024; Singh et al., 2024).

Though numerous policy frameworks address water pollution broadly, the stringent management of pharmaceutical pollutants remains inconsistent. Some regions have defined permissible discharge levels for selected drugs; others rely on voluntary industry guidelines. The complexity of pharmaceutical residues (including transformation products) and the interplay of multiple contaminants further complicate effective policy-making (Sharma & Arora, 2023). Despite these hurdles, awareness is growing, with global organizations calling for stronger action and collaboration among stakeholders (Mangalam et al., 2024).

3. KEY SOURCES AND PATHWAYS OF PHARMACEUTICAL POLLUTANTS

3.1 Human and Veterinary Pharmaceuticals

A significant fraction of pharmaceuticals administered to humans and livestock is excreted unaltered or partially metabolized (Thakur, Kumar, & Singh, 2023). This excretion route means that municipal sewage and livestock runoff become prime sources of pharmaceutical contamination. Studies documenting high antibiotic residues in manure-amended soils highlight the risk of leaching into nearby waterbodies, posing both ecological and human health concerns (Saeed et al., 2024).

3.2 Hospitals and Healthcare Facilities

Hospitals concentrate large volumes of antibiotics, antivirals, and cytotoxic drugs (Mostafa et al., 2023). The direct discharge of hospital wastewater into municipal systems, often without prior on-site treatment, can overload wastewater treatment plants with diverse pharmaceutical residues (Rehman et al., 2024). Waste streams generated from specialized medical procedures (e.g., chemotherapy) may contain potent substances poorly removed by conventional methods (Abubakar et al., 2024).

3.3 Industrial and Manufacturing Effluents

Pharmaceutical manufacturing plants can release high concentrations of active pharmaceutical ingredients (APIs) into aquatic environments if wastewater treatment is inadequate (Abdullahi Haruna Birniwa et al.,

2023). Bulk drug production typically involves solvents, reagents, and unreacted APIs, all of which can enter wastewater streams. Clusters of manufacturing units near rivers or lakes often create regional hotspots of contamination, as documented in Asia, Africa, and parts of Eastern Europe (Talukder et al., 2023).

3.4 Improper Disposal Practices

Consumer-level disposal of leftover or expired medications into household trash or drains remains a common practice globally (Uddin et al., 2024). This route not only contributes to landfill leachate but also burdens municipal wastewater systems. Improper disposal can be attributed to low public awareness, lack of convenient take-back programs, and insufficient regulations, underscoring the sociocultural components of the pharmaceutical waste puzzle (Sapkota & Pariatamby, 2023).

4. NATURE AND TYPES OF PHARMACEUTICAL POLLUTANTS

4.1 Antibiotics and Antibiotic Resistance Genes

Antibiotic residues are among the most extensively studied pollutants, with far-reaching implications for microbial resistance (Nassri et al., 2023). Sub-lethal concentrations of antibiotics in rivers, lakes, and even drinking water sources can facilitate the emergence and propagation of antibiotic resistance genes (ARGs), threatening the efficacy of life-saving medications. Studies highlight the role of horizontal gene transfer in wastewater environments, exacerbating the public health risks (Nguyen et al., 2023).

4.2 Nonsteroidal Anti-Inflammatory Drugs (NSAIDs)

NSAIDs—like ibuprofen, diclofenac, and naproxen—are widely used for pain management. Even though they are only partially metabolized in the human body, residual quantities can escape treatment systems (Mangalam et al., 2024). Chronic exposure in aquatic fauna has been linked to physiological stress and organ toxicity, emphasizing the subtle but significant impacts of these compounds (Mostafa et al., 2023).

4.3 Personal Care Products and Hormones

Personal care products (PCPs) include cosmetics, soaps, fragrances, and sunscreens containing active chemicals not fully removed by conventional treatments (Chakraborty et al., 2023). Meanwhile, hormones like estrogen from contraceptive pills or livestock feed additives can perturb endocrine systems in fish and other wildlife at very low

concentrations. These disruptions may lead to reproductive anomalies and population-level declines over time (Rehman et al., 2024).

4.4 Other Emerging Contaminants

Beyond the more common classes, emerging pollutants such as psychiatric medications (antidepressants), antiepileptics, and chemotherapy drugs are now receiving growing attention (Hussain et al., 2023). Their complex chemical structures often make them resilient to degradation, posing additional challenges for wastewater treatment facilities. Research is ongoing to identify their metabolites, transformation pathways, and long-term ecological impacts (Kumar et al., 2023).

5. ENVIRONMENTAL AND HUMAN HEALTH IMPLICATIONS

5.1 Ecotoxicity and Bioaccumulation

Aquatic organisms, from algae and plankton to fish and crustaceans, can be adversely affected by trace-level pharmaceutical compounds (Gabson Baguma et al., 2023). Chronic low-dose exposure may impair growth, reproduction, or immunity. Bioaccumulation within aquatic food webs raises alarms about the potential magnification of contaminants up the trophic chain (Chen et al., 2024). Birds or mammals that feed on contaminated prey could experience toxic effects, as documented in large-scale vulture die-offs linked to NSAIDs like diclofenac.

5.2 Antibiotic Resistance and Microbial Community Shifts

Antibiotics exert selection pressure on microbial communities, favoring resistant strains that flourish even in low-concentration environments (Singh et al., 2024). Treated effluents containing residual antibiotics can disseminate resistant bacteria into rivers and streams, eventually intersecting with human and livestock populations (Barkha Madhogaria et al., 2024). The global rise of multidrug-resistant pathogens underscores the magnitude of this threat (Letsoalo et al., 2022).

5.3 Long-Term Human Health Concerns

From a public health standpoint, the presence of pharmaceuticals in drinking water—even at trace levels—raises questions about the cumulative effects of multi-drug mixtures over time (Sharma & Arora, 2023). Hormone mimics, immunosuppressants, and potential carcinogens highlight the need for ongoing toxicological studies. While short-term risk for humans may be low, vulnerable demographics (children, pregnant women,

immunocompromised individuals) may face heightened risks (Nishita Narwal et al., 2023).

6. MONITORING, DETECTION, AND ANALYTICAL METHODS

Effective mitigation strategies hinge on the ability to accurately detect and quantify pharmaceutical pollutants. Analytical advancements have significantly improved detection limits, enabling researchers to trace minute concentrations across diverse matrices (Hameed et al., 2024).

6.1 Chromatographic Techniques

Liquid chromatography-mass spectrometry (LC-MS) remains a gold standard for identifying multiple pharmaceutical classes simultaneously (Hussain et al., 2023). Gas chromatography-mass spectrometry (GC-MS) is also used, though derivatization may be required for polar or thermally labile compounds. These methods provide robust quantitative capabilities, essential for compliance monitoring and fate studies (Bandana Padhan et al., 2024).

6.2 Spectroscopic and Spectrometric Approaches

Ultraviolet-visible (UV-Vis) spectroscopy can provide rapid screening but often lacks specificity. Innovations in Fourier-transform infrared (FTIR) and Raman spectroscopy can identify functional groups of certain contaminants, though quantification can be challenging (Sharma & Arora, 2023). High-resolution mass spectrometry (HRMS) techniques are increasingly used for non-target screening of unknown compounds or transformation products (Mostafa et al., 2023).

6.3 Biosensors and Molecularly Imprinted Polymers

Molecularly imprinted polymers (MIPs) offer a selective approach to pre-concentrate and detect target pharmaceuticals in complex matrices (Eissa et al., 2024). Their enhanced specificity and potential for miniaturization make them attractive for field-based or portable testing. Biosensor platforms, including enzymatic or aptamer-based systems, also show promise for real-time monitoring (Rehman et al., 2024).

7. CONVENTIONAL TREATMENT METHODS: EFFICACY AND LIMITATIONS

7.1 Primary and Secondary Treatment

Municipal wastewater treatment plants (WWTPs) typically employ mechanical screening, sedimentation, and biological processes (activated sludge). While effective for reducing organic load and pathogens, these

methods do not specifically target pharmaceutical pollutants (Chauhan et al., 2022). Many pharmaceuticals survive secondary treatment stages, ending up in treated effluents or sludge (Pratap et al., 2022).

7.2 Adsorption and Sorption Approaches

Activated carbon adsorption is commonly used as a tertiary treatment step, offering moderate removal efficiencies for various drugs (Kumar et al., 2023). However, the high costs of activated carbon regeneration and disposal can be prohibitive (Bankole et al., 2023). Low-cost materials such as agricultural byproducts have also been explored, but scale-up remains a challenge.

7.3 Biological Treatment in Constructed Wetlands

Constructed wetlands employ plants, microbial biofilms, and substrates like gravel or soil to degrade or immobilize pollutants (Hameed et al., 2024). They are cost-effective and eco-friendly but often require large footprints and longer residence times. Their removal efficiencies can vary depending on the contaminant class, system design, and operating conditions (Zeba Ali Mumtaj et al., 2024).

8. INNOVATIVE AND ECO-FRIENDLY TREATMENT TECHNOLOGIES

A growing body of research focuses on advanced and eco-friendly methodologies that complement or replace conventional treatments. This section provides a deep dive into the most promising solutions, drawing upon recent literature.

8.1 Advanced Oxidation Processes (AOPs)

AOPs—such as Fenton oxidation, ozonation, photocatalysis, and UV/hydrogen peroxide—generate reactive radicals that degrade stubborn pharmaceuticals into more benign byproducts (Kumar, 2024).

- **Ozonation** can be highly effective but may form toxic bromate byproducts if bromide ions are present (Sharma & Arora, 2023).
- **Fenton and Photo-Fenton Reactions** are cost-effective but produce iron sludge that must be managed (Daba & Elkhateeb, 2024).
- **Photocatalysis**, using semiconductors like TiO_2, can degrade a broad range of contaminants under UV or visible light (Thakur, Kumar, & Singh, 2023).

8.2 Nanotechnology and Nano-Adsorbents

Nanomaterials, including carbon nanotubes, graphene oxide, and magnetic nanoparticles, offer large surface areas and tunable functional groups for adsorption (Farhana Anoob et al., 2024).

- **Graphene-Based Adsorbents**: Graphene derivatives exhibit strong adsorption capacity for antibiotics and hormones but can be expensive (Mangalam et al., 2024).
- **Magnetic Nanoparticles**: Facilitate easy separation via magnetic fields, reducing the complexity of post-treatment handling (Liu et al., 2024).
- **Green Synthesis**: Eco-friendly routes to nanomaterial fabrication are being explored to reduce environmental footprints (Ugoeze et al., 2024).

8.3 Biochar-Based Materials

Biochar, a carbon-rich material derived from pyrolysis of organic waste, has attracted significant attention for pharmaceutical adsorption due to its large surface area and porosity (Aziz et al., 2024a, 2024b; Kosar et al., 2024).

- **Feedstock Selection**: Agricultural residues, wood waste, and organic solid waste from traditional Chinese medicine can be pyrolyzed into specialized biochars (Chen et al., 2024).
- **Modification**: Chemical activation (e.g., acid, base treatment) or doping with functional groups can dramatically improve adsorption capacities (Hama Aziz et al., 2024a, 2024b).
- **Scalability**: Biochar production can be integrated into waste management systems, promoting a circular economy approach where waste is valorized into remediation materials (Kumar et al., 2023).

8.4 Chitosan- and Cellulose-Based Membranes

Biopolymers such as chitosan and cellulose have drawn interest for membrane fabrication due to their biodegradability and functional modifiability (Atheena et al., 2024; Bandana Padhan et al., 2024).

- **Chitosan Membranes**: Effective for adsorbing heavy metals, dyes, and certain antibiotics due to amino and hydroxyl groups that chelate pollutants (Ashraf et al., 2024).

- **Cellulose Membranes**: Widely available from natural sources; chemical modifications can impart selective permeability for improved separation of pharmaceutical compounds (Bandana Padhan et al., 2024).
- **Composite Approaches**: Combining chitosan or cellulose with nanomaterials can yield hybrid membranes with enhanced mechanical strength and adsorption performance (Atheena et al., 2024).

8.5 Enzymatic and Microbial Bioremediation

Microbial consortia or specific enzyme systems can break down complex pharmaceutical molecules (Saeed et al., 2024). For instance, white-rot fungi produce laccase and peroxidase enzymes capable of degrading various drug classes. Bacterial strains engineered to metabolize pharmaceuticals offer another frontier, though biosafety and scalability remain concerns (Daba & Elkhateeb, 2024).

- **Aerobic vs. Anaerobic Systems**: Anaerobic digestion is commonly used for biogas production while co-treating pharmaceutical waste, though some drugs resist breakdown in anaerobic conditions (Abubakar et al., 2024).
- **Phytoremediation**: Aquatic plants, such as water hyacinth or duckweed, can uptake low-level pharmaceuticals, though root adsorption and accumulation must be managed to prevent re-release (Kumar, 2024).

Integrating Advanced Technologies

Implementing advanced oxidation, biochar, or nano-adsorbents typically involves tertiary or quaternary treatment stages. For maximum efficiency, hybrid systems combining two or more processes (e.g., an AOP coupled with a biochar column) can achieve higher removal rates (Kumar et al., 2023). Economic feasibility remains a key barrier, as these technologies can be capital-intensive and require technical expertise (Talukder et al., 2023). Nevertheless, pilot-scale and field demonstrations are gradually scaling up globally (Pratap et al., 2022).

9. TOWARDS CIRCULAR ECONOMY AND RESOURCE RECOVERY

9.1 Energy Recovery (e.g., Biogas)

Anaerobic digestion of pharmaceutical-laden wastewater can produce biogas, which offsets treatment costs and energy demands

(Abubakar et al., 2024). However, the presence of high concentrations of API residues may inhibit microbial consortia, necessitating pre-treatment steps or co-digestion strategies (Khan, 2024). The concept of integrated biorefineries, using wastewater as a feedstock, aligns well with global sustainable development goals (Uddin et al., 2024).

9.2 Nutrient and Materials Recovery

Sustainable policy frameworks encourage recovering nitrogen, phosphorus, and other valuable components from wastewater to promote circular economy models (Rehman et al., 2024). Coupling nutrient recovery with advanced pharmaceutical removal processes remains a relatively nascent field, but early results suggest that certain biochars or struvite precipitation could serve dual roles in pollutant removal and nutrient capture (Chauhan et al., 2022).

9.3 Life Cycle Thinking and Green Chemistry Approaches

Pharmaceutical waste management strategies are increasingly adopting **Life Cycle Assessment (LCA)** to evaluate the environmental footprint of drug production, usage, and disposal (Khan, 2024; Sahu, 2024). **Green Chemistry** principles aim to design safer drugs that degrade faster or reduce the use of hazardous reagents in manufacturing (Hussain et al., 2023). By embedding these considerations at the drug design phase, the long-term environmental impacts can be significantly curtailed (Ashraf et al., 2024).

10. POLICY, REGULATION, AND PHARMACIST ROLES

10.1 Regulatory Gaps and Challenges

Many existing laws and guidelines focus on conventional pollutants (e.g., heavy metals, nitrates), leaving a regulatory vacuum for pharmaceutical contaminants (Kataria et al., 2023). Even when threshold limits exist, they often address only a handful of commonly detected drugs. Enforcement varies across jurisdictions, hindered by resource constraints and minimal surveillance infrastructure (Nguyen et al., 2023).

10.2 Pharmaceutical Waste Management Strategies

Safe disposal of unused and expired medications is crucial to prevent these compounds from entering wastewater and landfills (Sapkota & Pariatamby, 2023). Strategies include:

- **Take-Back Programs**: Encouraging consumers to return unused drugs for safe incineration or disposal.
- **Extended Producer Responsibility (EPR)**: Holding pharmaceutical companies accountable for post-consumer waste management (Sahu, 2024).
- **Hospital and Clinical Protocols**: Mandating pre-treatment of hospital effluents before discharge (Nishita Narwal et al., 2023).

10.3 Pharmacist and Stakeholder Engagement

Pharmacists can play a pivotal role in guiding responsible medication usage and disposal. Counseling patients on how to handle leftover medications can significantly reduce pharmaceutical waste (Sahu, 2024). Collaboration among government agencies, healthcare professionals, drug manufacturers, and civil society organizations forms the backbone of a robust pharmaceutical waste management system (Sindhu et al., 2024).

11. CASE STUDIES AND GLOBAL PERSPECTIVES

11.1 Real-World Applications of Advanced Treatments

- **Saudi Arabia**: A large-scale study used eco-friendly SPE-UHPLC-MS/MS to identify multi-class pharmaceuticals in wastewater. The approach also assessed the risk of contaminants, revealing moderate to high environmental risk levels for specific antibiotics (Mostafa et al., 2023).
- **Hospital-Scale Constructed Wetlands**: Facilities in parts of Asia and South America have piloted hybrid wetland systems (vertical + horizontal flow) to address antibiotic residues in effluent. Results indicated 60–90% removal efficiencies under optimized conditions (Hameed et al., 2024).

11.2 Regional Challenges (Developed vs. Developing Countries)

- **Developing Countries:** Limited funding for advanced treatment technologies and weak enforcement hamper efforts to mitigate pharmaceutical pollution (Sapkota & Pariatamby, 2023).
- **Developed Countries:** While advanced technologies exist, they can be expensive. Even in regions with robust infrastructure, pharmaceuticals persist at trace levels in drinking water (Letsoalo et al., 2022).

Collectively, these regional case studies underscore the universal nature of pharmaceutical pollution and underscore the need for tailored, context-specific solutions (Kumar et al., 2023).

12. FUTURE DIRECTIONS AND RESEARCH GAPS

12.1 Integration of Multi-Disciplinary Solutions

Ongoing research increasingly suggests that no single technology can address the myriad pharmaceutical pollutants alone (Thakur et al., 2023). Hybrid systems, integrating chemical, biological, and physical methods, are gaining traction. A synergy between advanced oxidation processes and adsorption technologies, for instance, can achieve higher removal efficiencies and degrade transformation products that might otherwise persist (Eissa et al., 2024).

12.2 Climate Change Intersection

Climate change may exacerbate pharmaceutical pollution due to changing precipitation patterns, droughts, and floods. Extreme weather events can mobilize stored contaminants from sediments and landfills (Nassri et al., 2023). Warmer water temperatures may also alter microbial communities, potentially accelerating or decelerating the degradation rates of pharmaceuticals (Rehman et al., 2024). As such, climate resilience should be integrated into future wastewater treatment designs (Chakraborty et al., 2023).

12.3 Sustainable Scale-Up and Technology Transfer

Scaling up solutions like nano-adsorbents or advanced oxidation processes can be cost-intensive. Partnerships between academia, industry, and governments could facilitate technology transfer, especially critical for low- and middle-income countries (Hussain et al., 2023). The challenge is to balance efficacy, cost, and environmental safety to ensure broad adoption (Sahu, 2024).

Further research should address:

- The formation of toxic byproducts in advanced oxidation.
- Long-term operation and maintenance costs of novel treatment systems.
- The synergy of multiple pollutants in real wastewater matrices.

Investments in pilot-scale projects will be crucial to validate lab-scale breakthroughs under real-world conditions (Abdullahi Haruna Birniwa et al., 2023).

13. CONCLUSION

The omnipresence of pharmaceutical contaminants in aquatic environments stands as a pressing global challenge, with wide-ranging implications for ecosystem stability, public health, and industrial accountability (Sindhu et al., 2024). Conventional wastewater treatment methods, though integral, fall short of fully eliminating pharmaceuticals. Rapid advancements in specialized techniques—like advanced oxidation processes, nanotechnology-based adsorption, and biochar application—offer promising avenues, but barriers to large-scale implementation remain significant (Abubakar et al., 2024).

An integrated approach that merges technology, policy, and public engagement appears to be the linchpin for meaningful progress. Regulatory frameworks must evolve to cover more pharmaceutical compounds, align with global best practices, and enforce stringent effluent standards (Sharma & Arora, 2023). Meanwhile, stakeholder involvement—from healthcare professionals to the pharmaceutical industry and end-users—is paramount. Pharmacists, for example, can help shape responsible usage and disposal practices, mitigating pollution at the source (Sahu, 2024).

Efforts to link wastewater treatment to resource recovery and circular economy models can further justify investments in advanced, eco-friendly solutions. Whether through biogas production, nutrient recycling, or transforming waste into biochar and other valuable materials, there is a path toward more sustainable, closed-loop systems (Rehman et al., 2024). Finally, tackling pressing concerns like antibiotic resistance, endocrine disruption, and synergy among multiple drug classes requires coordinated research and policy harmonization (Nishita Narwal et al., 2023).

As the body of scientific knowledge continues to expand, interdisciplinary collaboration will remain crucial. Engineers, microbiologists, chemists, policy-makers, and community organizations must collectively pilot innovative solutions and refine existing frameworks. Only through unified, sustained efforts can the challenges of pharmaceutical pollution be met effectively—paving the way for cleaner waterways, healthier ecosystems, and resilient communities worldwide (Kumar et al., 2023; Thakur et al., 2023).

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