Review Article

International Journal of Chemistry and Aquatic Sciences (IJCA)
Vol.11.Issue.3.2025(July-Sept), Page: 1-15
ISSN: 2355-033X
http://chemistryjournal.kypublications.com/

A review on Prescription to Pollution: Pharmaceutical waste impacts on marine Pollution

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doi: 10.33329/ijca.11.3.1

Article info
Article Received:13/07/2025
Article Accepted:21/08/2025
Published online:26/08/2025

ABSTRACT
Pharmaceutical waste is an emerging and increasingly serious contributor to marine pollution. It refers to unused, expired, or improperly disposed drugs that end up in water bodies, eventually reaching oceans and seas. Pharmaceutical waste represents a growing threat to marine ecosystems. Though often present in trace amounts, their persistence, bioactivity, and cumulative effects make them particularly dangerous. Chemistry plays a key role in identifying, monitoring, and mitigating these pollutants through both scientific innovation and regulatory support. Pharmaceutical waste from aquaculture and livestock runoff is a significant and growing source of marine pollution. The introduction of antibiotics, hormones, and parasiticides into marine environments can cause antibiotic resistance, endocrine disruption, bioaccumulation, and toxicity in marine organisms. Tackling this issue requires a combination of better management practices, advanced treatment technologies, regulations, and public education to mitigate the harmful impact on both marine ecosystems and human health.

Keywords: Pharmaceutical waste, marine pollution, Aquaculture, Livestock Farming, treatment technologies, regulations, and public education.

Introduction

The intersection of pharmaceuticals and ocean life represents a critical environmental issue that has garnered increasing attention in recent years. As marine ecosystems face growing threats from pollution, the presence of pharmaceutical contaminants in oceans has emerged as a significant concern [1]. These chemical pollutants, including active pharmaceutical ingredients (APIs), are altering water quality, disrupting aquatic organisms, and threatening biodiversity. This article provides a comprehensive exploration of how pharmaceuticals enter marine environments, their effects on ocean health, and the broader implications for marine biology and environmental science. Pharmaceuticals pollute oceans, harming marine life and ecosystems. Drug residues, like antibiotics and hormones, enter through wastewater, sewage, and runoff, contaminating water and accumulating in fish and shellfish. These chemicals disrupt hormones, alter fish behavior, and damage coral reefs. Microplastics worsen the issue by carrying drugs, increasing bioaccumulation [2]. To reduce harm, we need better wastewater treatment, responsible drug disposal, and stricter aquaculture regulations. Research in ecotoxicology is vital to understand long-term effects. Protecting ocean health requires global action to limit pharmaceutical pollution and preserve biodiversity.

The issue of pharmaceutical pollution in marine environments extends beyond immediate ecological concerns. It raises fundamental questions about the sustainability of modern healthcare systems and their environmental footprint. Environmental science must grapple with balancing the benefits of pharmaceuticals for human health with their unintended consequences for ocean life. Moreover, the study of pharmaceutical contaminants highlights the interconnectedness of terrestrial and marine systems. Effluent discharge from urban centers thousands of miles inland can ultimately affect coral reefs or deep-sea species, underscoring the need for a holistic approach to water quality management. The presence of pharmaceutical contaminants in marine environments has profound effects on aquatic organisms, ranging from sublethal effects to ecosystem-wide disruptions. These impacts are studied through the lens of ecotoxicology and marine toxicology, which investigate how drug residues affect the physiology, behavior, and reproduction of marine species [3-4].

Pharmaceuticals enter marine ecosystems through multiple pathways, primarily as a result of human activity. Effluent discharge from wastewater treatment plants is one of the most significant sources. These facilities often lack the advanced filtration needed to remove drug residues, including antibiotics, antidepressants, hormones, and estrogenic compounds. As a result, pharmaceutical runoff from urban and agricultural areas flows into rivers, estuaries, and ultimately the oceans. Another key contributor is sewage outfalls, where untreated or partially treated wastewater is released directly into coastal waters [5]. Veterinary pharmaceuticals, used in aquaculture and livestock farming, also play a role, as these compounds are often excreted unchanged and enter waterways. Additionally, improper disposal of unused medications—flushed down toilets or discarded in landfills further exacerbates water contamination. Once in the ocean, these chemical pollutants interact with marine ecosystems in complex ways. Unlike traditional pollutants, pharmaceuticals are designed to be biologically active; meaning even trace amounts can have significant effects. The persistence of persistent organic pollutants (POPs) and the interaction of pharmaceuticals with microplastics amplify their environmental impact, creating a web of challenges for ocean health [6-7].

The impact of pharmaceuticals on ocean life is a pressing environmental challenge that demands urgent attention. From bioaccumulation and endocrine disruption to coral reef degradation and fish behavior alteration, the effects of chemical pollutants are far-reaching and complex [7]. By addressing the root causes such as effluent discharge, sewage outfalls, and pharmaceutical runoff—and investing in innovative solutions, we can mitigate the harm to marine ecosystems and safeguard biodiversity. This issue serves as a reminder of our responsibility to protect ocean health for future generations. Through advances in wastewater treatment, responsible pharmaceutical use, and global cooperation, we can reduce the footprint of pharmaceutical contaminants and ensure that marine biology thrives in a cleaner, healthier environment. As research in ecotoxicology and environmental science continues to evolve, it will provide the insights needed to navigate this complex challenge and preserve the delicate balance of life beneath the waves [8].

1 .Sources of Pharmaceutical Waste in Marine Environments

1.1 Human Excretion

After consumption, drugs are partially metabolized and excreted via urine or feces. Wastewater treatment plants do not completely remove many pharmaceuticals.After consumption, many pharmaceutical compounds are not fully metabolized by the human body.Active drug residues and their metabolites are excreted through urine and feces**.** These residues enter the sewage system and are transported to wastewater treatment plants (WWTPs)**.**Most conventional WWTPs are not equipped to completely remove pharmaceutical compounds, allowing them to pass into rivers, lakes, and eventually the ocean [9]**.** Expired or unused drugs are often flushed down toilets or thrown in household trash. When disposed of in landfills, rainwater can leach pharmaceutical compounds into groundwater or nearby water bodies. Flushing medicines lead to direct contamination of wastewater systems. Pharmaceutical manufacturing plants can discharge highly concentrated drug residues in their wastewater. If not properly treated, these effluents become point sources of marine pharmaceutical pollution. Hospitals and clinics use a wide range of pharmaceuticals .Improper waste management can result in direct discharge of drugs into municipal sewage systems or natural water bodies. Some substances may be disposed of as liquid waste, bypassing standard solid waste controls. Drugs used in veterinary medicine (especially antibiotics and hormones) are excreted by animals. Runoff from farms during rain carries these residues into streams and rivers. Aquaculture (fish farming) uses antibiotics and other chemicals that may be released directly into the surrounding marine environment .Fish farms often use pharmaceuticals like antibiotics and antiparasitic agents to prevent or treat disease. These drugs can leach directly into the sea**,** affecting nearby ecosystems. Flushing unused medicines down toilets or sinks. Throwing pharmaceuticals in landfills, where they leach into groundwater and rivers. Pharmaceutical manufacturing facilities and hospitals may discharge waste containing high concentrations of drugs [10-11].

Pharmaceuticals pollute oceans, harming marine life and ecosystems. Drug residues, like antibiotics and hormones, enter through wastewater, sewage, and runoff, contaminating water and accumulating in fish and shellfish. These chemicals disrupt hormones, alter fish behavior, and damage coral reefs as shown in Fig1.

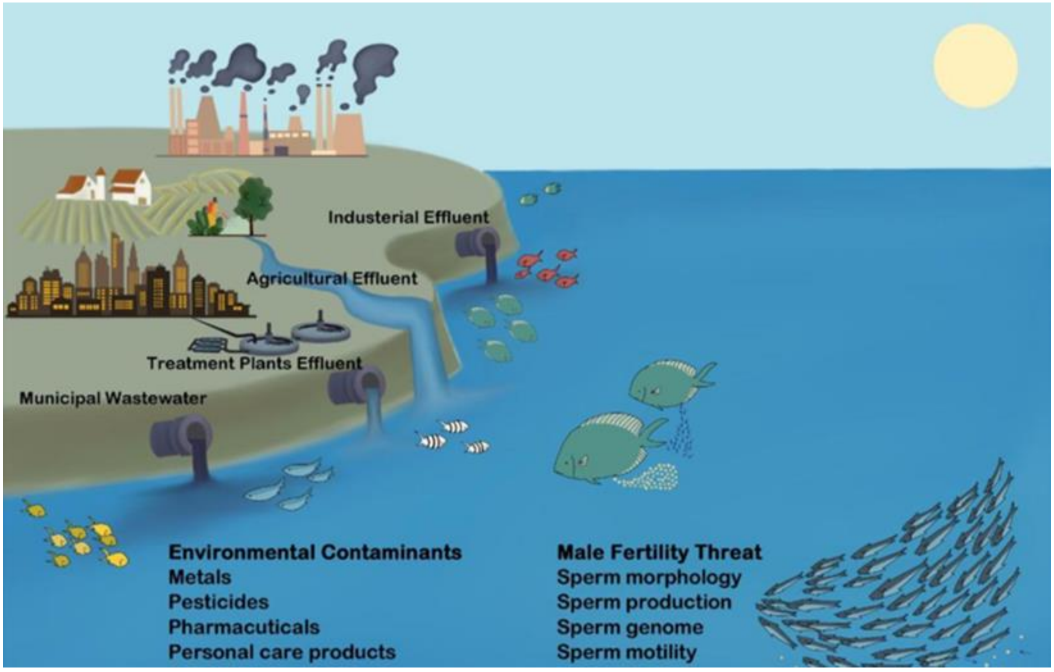

Figure1: Pharmaceuticals pollute oceans

2. Aquaculture and Livestock Runoff

Antibiotics and hormones used in aquaculture or livestock can run off into rivers and coastal waters. Aquaculture (the farming of aquatic organisms such as fish, shellfish, and algae) and livestock farming (particularly in the case of antibiotics**,** hormones and Parasiticides) are significant contributors to pharmaceutical waste in marine environments. Both sectors use a wide range of pharmaceutical products to promote growth, prevent disease, and treat illnesses. However, the discharge of these pharmaceuticals into the surrounding aquatic environment can have serious ecological consequences [12-15].

- Antibiotics: Commonly used to treat bacterial infections and promote growth in both fish farming (e.g., tilapia, salmon) and livestock farming (e.g., cattle, poultry).
- Hormones: Used to control growth, reproduction, and sex determination in aquaculture and livestock.
- Parasiticides: Applied to control external and internal parasites (e.g., lice in fish, worms in livestock).
- Vitamins and Minerals: Used as growth promoters and to improve animal health.

2.1 . Pharmaceutical Use in Aquaculture and Livestock Farming

Pharmaceutical waste from aquaculture and livestock farming is increasingly recognized as a significant contributor to marine pollution [16].

2.2 Pharmaceuticals Enter Marine Ecosystems

Primary Pathways:

- Wastewater Discharge: Many treatment plants lack the technology to fully remove pharmaceutical residues, allowing antibiotics, hormones, and other drugs to flow into rivers and oceans.
- Agricultural Runoff: Veterinary drugs used in livestock and aquaculture are often excreted unchanged and washed into waterways during rainfall.
- Improper Disposal: Flushing unused medications or discarding them in landfills leads to leaching into groundwater and eventually into marine environments.
- Aquaculture Effluents: In fish farming, medicated feed and water treatments release active pharmaceutical ingredients directly into aquatic systems [17-19].

2.3 Impacts on Marine Life

Biological Disruption:

- Hormonal Effects: Drugs like birth control pills and antidepressants can cause feminization in fish, reduced sperm production, and disrupted reproductive cycles.
- Behavioral Changes: Exposure to psychoactive drugs alters feeding rates, risk-taking behavior, and predator avoidance.
- Toxicity & Tissue Damage: Antibiotics and painkillers can damage organs and inhibit photosynthesis in algae.
- Antibiotic Resistance: Marine bacteria exposed to antibiotic residues may develop resistance, posing risks to both marine and human health.
- Bioaccumulation:Pharmaceuticals can accumulate in fish and shellfish, entering the human food chain and raising concerns about long-term health effects [20].

2.4. Pathways of Pharmaceutical Waste into Marine Environments

Pharmaceuticals can enter the environment through several key pathways

A. Runoff from Land-Based Farms

- Rainwater and irrigation carry antibiotics, hormones, and other drugs from animal waste (manure, urine) into nearby rivers, lakes, and coastal waters.
- Intensive livestock farming, especially in industrial-scale operations, leads to concentrated pharmaceutical residues in animal waste, which is often stored in lagoons and can leach into the environment as shown in fig-2

B. Direct Discharge from Aquaculture Farms

- Water used in fish tanks **or** floating cages in coastal areas often contains pharmaceuticals that are directly discharged into the surrounding environment.
- Antibiotics and hormones are released when the fish shed waste into the water or when chemicals are used in feed or as treatment agents for parasites and disease [21-24].

C. Sediment Contamination

- Pharmaceuticals can bind to suspended particles and sediments in the water, which then settle on the ocean floor, continuing to release chemicals over time as they degrade slowly.

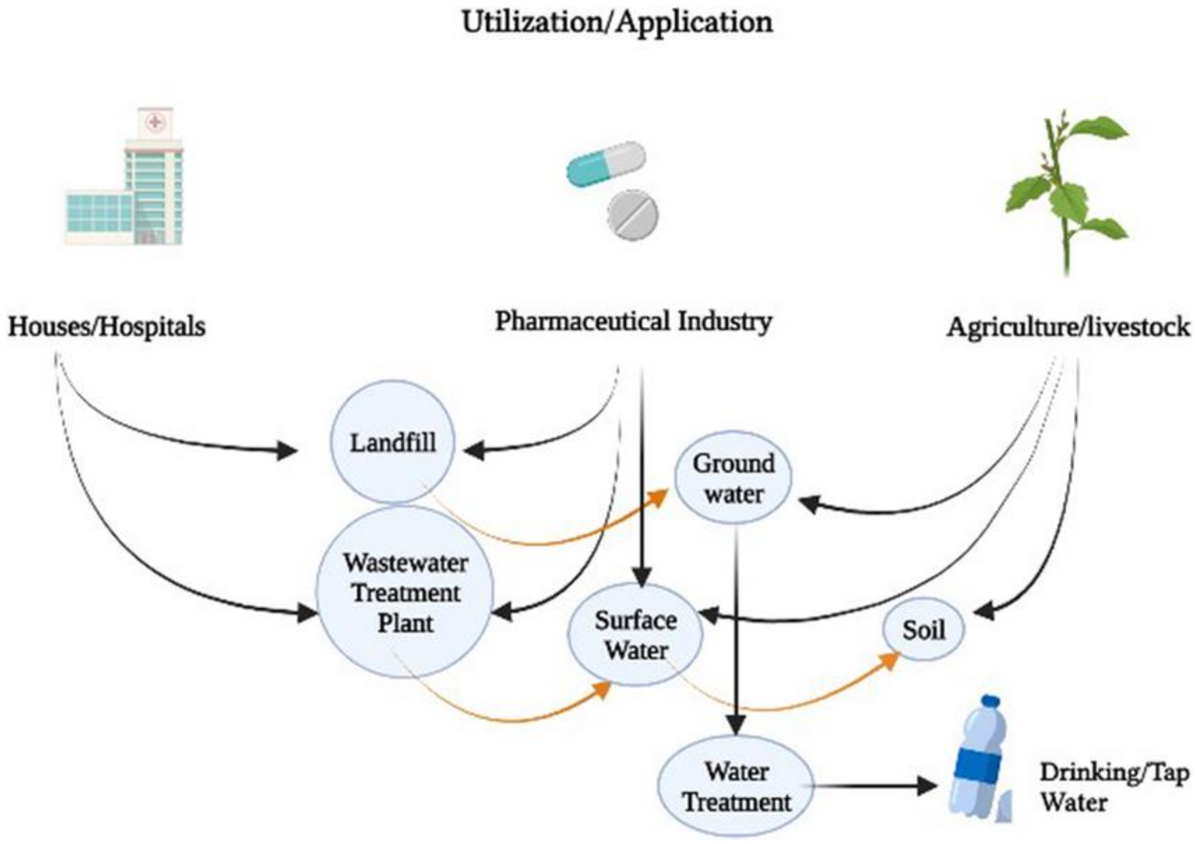

Figure.2. Pharmaceuticals can enter the environment through several key pathways

2.5. Environmental and Ecological Impacts of Pharmaceutical Waste from Aquaculture and Livestock

Antibiotic Resistance

- Continuous exposure to sub-lethal concentrations of antibiotics in the environment encourages the development of antibiotic-resistant bacteria.
- Antimicrobial resistance **(AMR)** is a growing concern, as resistant bacteria can transfer to humans through seafood consumption or the food chain (via livestock).

- In marine environments, these resistant bacteria may spread rapidly due to the interconnected nature of ecosystems [25-26].

Hormonal Disruption (Endocrine Disruption)

- Pharmaceuticals like estrogens **or** growth hormones can mimic natural hormones and interfere with the endocrine system of marine organisms.
- Fish and other aquatic species exposed to hormonal residues may exhibit abnormal reproductive behavior **and** developmental changes (e.g., feminization of male fish).
- Altered reproductive success can threaten biodiversity and disrupt the balance of aquatic ecosystems [27]**.**

Bioaccumulation

- Many pharmaceutical compounds, such as antibiotics and hormones**,** bioaccumulate in marine organisms.
- As the drugs accumulate in the tissues of fish, mollusks, or other marine species, they move up the food chain.
- Higher predators, including humans, may consume contaminated seafood, leading to chronic exposure to harmful substances [28].

Toxicity to Marine Organisms

- Some pharmaceuticals, such as parasiticides **and** anti-inflammatory drugs, are toxic even in low concentrations.
- These substances can affect fish growth, survival rates**,** and behavioral patterns (e.g., impaired navigation or predator avoidance).
- Long-term exposure can result in declining fish populations, harming commercial fisheries and the health of marine ecosystems [29].

2.6. Case Studies and Evidence of Impact

A. Case Study 1: Antibiotic Resistance in Fish Farms (Norway)

- In Norwegian salmon farming, resistance to antibiotics has been identified in both fish and bacteria in the surrounding environment.
- Antibiotics like oxytetracycline were found in the sediments around fish farms.
- Studies revealed that resistant strains of bacteria were thriving in areas where antibiotic use was high, creating a "resistance reservoir" in marine ecosystems.

B. Case Study 2: Endocrine Disruption in Fish (United Kingdom)

- Research has shown that estrogenic compounds from fish farms, specifically 17β-estradiol**,** have caused feminization in male fish species near salmon farms.
- Male fish exhibited altered reproductive organs, significantly impacting their ability to reproduce [30].

2.7. Strategies for Mitigating Pharmaceutical Waste in Aquaculture and Livestock

Improved Wastewater Treatment

- Enhancing wastewater treatment technologies at aquaculture farms to reduce pharmaceutical discharges into nearby water bodies. Technologies like membrane filtration, ozonation, and activated carbon filtration can significantly remove pharmaceutical residues [31].

Integrated Pest Management (IPM)

- Reducing the need for pharmaceuticals in aquaculture through sustainable, alternative management techniques like biological controls, vaccination, and genetically resistant species[32].

Reduced Use of Antibiotics and Hormones

- Implementing regulations that limit the use of antibiotics in aquaculture and livestock farming.
- Encouraging healthier farming practices such as better sanitation and improved animal husbandry to reduce the need for pharmaceutical interventions [33].

Buffer Zones and Containment

- Establishing buffer zones around aquaculture farms and implementing better containment practices to prevent pharmaceutical-laden runoff from entering the marine environment [34].

Public Awareness and Education

- Educating farmers, industries, and the public on the proper disposal of pharmaceutical **waste** and the environmental risks of improper disposal.

3. Types of Pharmaceutical Pollutants

Common classes of pharmaceuticals found in marine environments. Many pharmaceuticals are highly stable, water-soluble, and bioactive at low concentrations [35-38]. These properties make them persistent and difficult to degrade in aquatic environments include as shown in Fig3:

1) Antibiotics (e.g., ciprofloxacin, tetracycline)
2) Hormones (e.g., estrogen, testosterone)
3) Analgesics (e.g., ibuprofen, diclofenac)
4) Antidepressants (e.g., fluoxetine)
5) Antiepileptics (e.g., carbamazepine)

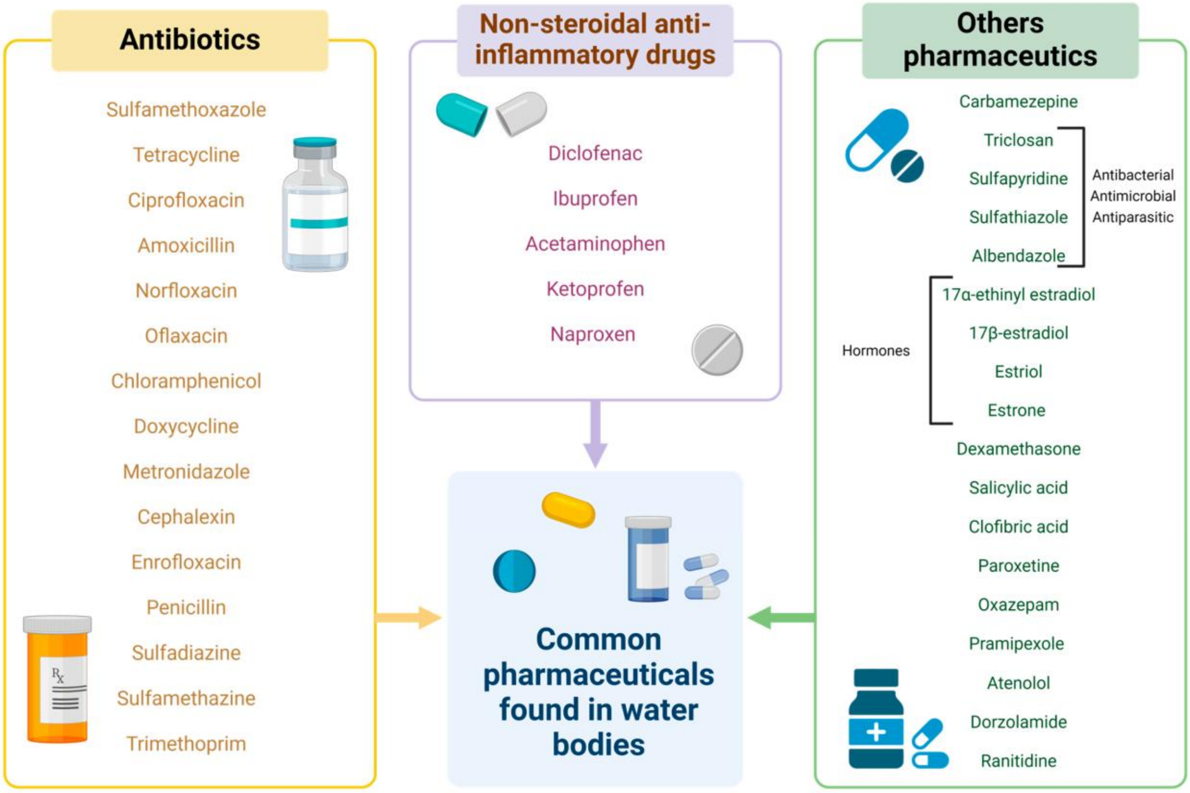

Figure.3. Types of Pharmaceutical Pollutants

4. Impacts on Marine Life

1. **Endocrine Disruption**
    a. Hormonal drugs interfere with the reproductive systems of fish and marine invertebrates.
    b. Example: Male fish developing female traits (feminization) due to exposure to estrogenic compounds [39].
2. **Antibiotic Resistance**
    a. Constant exposure to antibiotics promotes the development of antibiotic-resistant bacteria in the marine environment.
    b. This poses a global public health threat.
3. **Behavioral Changes**
    a. Antidepressants and sedatives can alter fish behavior, such as feeding, reproduction, and predator avoidance.
4. **Bioaccumulation**
    a. Pharmaceuticals can accumulate in the tissues of marine organisms, entering the food chain and potentially impacting humans.
5. **Toxicity to Non-target Species**
    a. Drugs designed for humans and animals can be **toxic** to plankton, mollusks, and crustaceans[40-44].

5. Environmental and Human Health Concerns

Pharmaceutical waste from aquaculture and livestock farming poses serious environmental and human health risks, particularly through its impact on marine pollution. Low-dose, long-term exposure to pharmaceutical mixtures can have chronic effects. Human exposure occurs via seafood consumption or contaminated drinking water sources. Potential risks include endocrine disorders, antibiotic resistance, and other health impacts [45-48].

5.1 Environmental Concerns

1. Ecosystem Disruption:

- Pharmaceuticals like antibiotics, hormones, and antidepressants can alter aquatic ecosystems even at low concentrations.
- These substances disrupt endocrine systems in fish and amphibians, impairing reproduction and growth [49-51].

2. Bioaccumulation & Biomagnification:

- Drugs persist in water and sediments, accumulating in aquatic organisms and magnifying through the food chain[52].

3. Antimicrobial Resistance (AMR):

- Continuous exposure to antibiotics in water bodies fosters resistant bacteria, which can spread to humans and animals.
- This is a major global health threat, reducing the effectiveness of life-saving drugs [53].

4. Altered Microbial Communities:

- Pharmaceuticals affect microbial diversity and nutrient cycling, destabilizing aquatic food webs.

5.2 Human Health Concerns

1. Contaminated Water Sources:

- Pharmaceutical residues have been detected in surface water, groundwater, and even drinking water.
- Long-term exposure may lead to hormonal imbalances, neurological effects, and increased cancer risk [54].

2. Food Safety Risks:

- Consumption of contaminated seafood can expose humans to drug residues and resistant bacteria.
- This is especially concerning in regions with high seafood consumption and limited regulation[55].

3. Inequitable Impact:

- Marginalized communities often face greater exposure due to inadequate wastewater treatment and poor access to clean water

6. Chemical and Environmental Solutions

Pharmaceutical waste from aquaculture and livestock farming is a growing contributor to marine pollution, with serious consequences for both environmental and human health. Fortunately, chemical and environmental solutions are being developed to mitigate these impacts[56-58].

6.1 Chemical Solutions

Advanced Oxidation Processes (AOPs):

- Techniques like ozonation, photocatalysis, and Fenton reactions break down pharmaceutical compounds into less harmful substances.
- Effective for removing persistent drugs like antibiotics and NSAIDs from wastewater.

Adsorption Technologies:

- Activated carbon and biochar (often derived from agro-industrial waste) are used to adsorb pharmaceutical residues from water.
- Materials like rice husk, wheat straw, and bamboo have shown promising results in removing drugs like sulfamethoxazole and diclofenac.

Membrane Filtration:

- Nanofiltration and reverse osmosis can physically separate pharmaceutical molecules from water.
- Often used in combination with other treatments for higher efficiency [59].

6.2 Environmental & Biological Solutions

Bioremediation:

- Microorganisms, especially fungi (mycoremediation), are used to degrade pharmaceutical pollutants.
- Fungal technologies are gaining traction for their ability to break down complex drug molecules in aquatic environments.

Constructed Wetlands:

- Engineered ecosystems that use plants and microbes to filter and degrade contaminants.
- Cost-effective and sustainable for rural or decentralized wastewater treatment.

Green Chemistry Approaches:

- Designing pharmaceuticals that degrade more easily in the environment.
- Encouraging the development of "benign by design" drugs with reduced ecological persistence.
- Designing drugs that biodegrade easily after use.

Advanced Wastewater Treatment: Use of ozonation, activated carbon, and membrane filtration to remove pharmaceutical residues.

Take-Back Programs: Promoting safe disposal through pharmaceutical return schemes.

Regulation and Monitoring: Enforcing stricter laws on pharmaceutical disposal and wastewater discharge limits.

Bioremediation: Using fungi and other biological agents to break down drug residues.

Legislation & Guidelines: Enforcing proper disposal protocols and regulating pharmaceutical use in farming.

Public Awareness: Educating communities about safe medication disposal and environmental risks [60-61].

Conclusions:

1) Pharmaceutical waste represents a growing threat to marine ecosystems. Though often present in trace amounts, their persistence, bioactivity, and cumulative effects make them particularly dangerous. Chemistry plays a key role in identifying, monitoring, and mitigating these pollutants through both scientific innovation and regulatory support.
2) Pharmaceutical waste poses a growing and insidious threat to marine ecosystems. Unlike many pollutants, pharmaceuticals are designed to be biologically active even in trace amounts which makes their presence in aquatic environments particularly concerning.
3) Marine pollution from pharmaceutical waste is not just a chemical issue, it's a biological and ecological crisis. Tackling it requires coordinated global action to protect ocean health and biodiversity.
4) Pharmaceuticals often resist degradation, remaining in the environment for extended periods. They undergo biotic and abiotic transformations, bind to particulate matter, and persist in sediments
5) To mitigate these impacts: Upgrade wastewater treatment technologies to effectively remove pharmaceutical residues. Promote responsible drug disposal practices. Regulate pharmaceutical use in aquaculture and agriculture. Expand ecotoxicological research to understand long-term effe cts.

Acknowledgements

The author is thankful to Almighty God for the wisdom, grace, and strength he gave me to complete this manuscript. The special thanks are presented to Dr. M. Sasidhar – Principal, Dr. K. Sai Manoj -CEO, Sri K. Rama Mohana Rao Secretary and Correspondent, Sri K. Lakshmi Karthik President and Sri K. Ramesh babu- Industrialist, Chairman of Amrita Sai Institute of Science and Technology whose candor, patience, understanding, and demonstration of empathy inspired me throughout this challenging journey of writing this manuscript. The author also gratefully acknowledges all the members of the S&H, & CRT departments.

Disclosure Statement

No potential conflict of interest was reported by the authors.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors' Contributions

The author has contributed to data analysis, drafting, and revising of the article and agreed to be responsible for all the aspects of this work.

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