

Chemical Transformation and Environmental Fate of Pharmaceutical Pollutant in Aquatic System

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ABSTRACT

Pharmaceutical pollutants in aquatic systems undergo several abiotic and biotic transformation pathways: Photolysis (Direct & Indirect): Sunlight breaks down light-sensitive pharmaceuticals (such as specific anti-inflammatories and analgesics) either through direct photon absorption or indirectly via reactive oxygen species (ROS like hydroxyl radicals generated by natural organic matter). However, photodegradation can sometimes yield transformation products that are more toxic than the parent compound. ScienceDirect.com +1Biodegradation (Aerobic & Anaerobic): Microorganisms in water columns and sediments metabolize pharmaceutical residues. While compounds like ibuprofen and paracetamol show low persistence (half-life $(DT_{50} \leq 20 \text{ days})$), others resist microbial breakdown completely. Sorption and Sediment Partitioning: Hydrophobic and ionic properties dictate how drugs bind to suspended solids and bed sediments. High sediment sorption is documented for compounds like ivermectin ($K_{oc} = 1172 \text{ L/kg}$), diazepam, oxazepam, and carbamazepine. Incomplete Mineralization: Many active pharmaceutical ingredients (APIs) undergo only partial transformation, retaining their core chemical structures or converting into stable metabolites that may persist longer or revert back to the parent molecule

KEYWORDS- pharmaceutical, pollutant, chemical, transformation, aquatic

INTRODUCTION

In recent years there has been growing interest on the occurrence and the fate of pharmaceuticals in the aquatic environment. Nevertheless, few data are available covering the fate of the pharmaceuticals in the water/sediment compartment. In this study, the environmental fate of 10 selected pharmaceuticals and pharmaceutical metabolites was investigated in water/sediment systems including both the analysis of water and sediment. The experiments covered the application of four ¹⁴C-labeled pharmaceuticals (diazepam, ibuprofen, iopromide, and paracetamol) for which radio-TLC analysis was used as well as six nonlabeled compounds (carbamazepine, clofibric acid, 10,11-dihydro-10,11-dihydroxycarbamazepine, 2-hydroxyibuprofen, ivermectin, and oxazepam), which were analyzed via LC-tandem MS. Ibuprofen, 2-hydroxyibuprofen, and paracetamol displayed a low persistence with DT_{50} values in the water/sediment system $< \text{or} = 20 \text{ d}$. The sediment played a key role in the elimination of paracetamol due to the rapid and extensive formation of bound residues. A moderate persistence was

found for ivermectin and oxazepam with DT50 values of 15 and 54 d, respectively. Lopromide, for which no corresponding DT50 values could be calculated, also exhibited a moderate persistence and was transformed into at least four transformation products. For diazepam, carbamazepine, 10,11-dihydro-10,11-dihydroxycarbamazepine, and clofibric acid, system DT90 values of >365 d were found, which exhibit their high persistence in the water/sediment system. An elevated level of sorption onto the sediment was observed for ivermectin, diazepam, oxazepam, and carbamazepine. Respective Koc values calculated from the experimental data ranged from 1172 L x kg⁻¹ for ivermectin down to 83 L x kg⁻¹ for carbamazepine.[1,2,3]

The discharge of raw, contaminated, and inadequately treated pharmaceutical wastewater into water supplies and river channels contribute to short, medium, and long- term environmental and human health impacts. The deterioration and depletion of natural resources exemplified in recipient surface water systems, entirely account for the poor quality of pharmaceutical wastewater effluent. Consequently, to ensure the safety of communities from polluted environments, this review outlines the different anticipated exposure routes to the environment, situates the impact and fate of some pharmaceutical wastes on the aquatic environment. We highlighted some of the current measures for detecting pharmaceutical effluents and the future trends in the treatment of pharmaceutical effluents.

DISCUSSION

Human therapeutics originated from the utilization of natural products for the treatment of common conditions, the earliest of which came from roots, shrubs, plants, and some fungi [26].

There has been an unprecedented increase of pharmaceutical consumption since its advent in early the 1900's. The rate at which pharmaceuticals are used is considerably dependent on the pharmaceutical class [27]. Some pharmaceuticals are purchased over the counter, such as painkillers and antibiotics and as a result their usage is likely to be higher compared to prescription drugs.

Novel drugs are perpetually being developed to reduce side effects, improve effectiveness, and enhance specificity [28]. For example, progestins which are used in treating embryogenesis and controlling menstrual cycles were observed to cause masculinization effects which included growth of facial hair in women. This made it necessary for the generation of more effective medications with little or no adverse effects [4,5,6].

Pharmaceuticals and active pharmaceutical ingredients

Pharmaceuticals are substances or combination of substances that are administered to animals or human for the purposes of modifying metabolic and physiological functions by applications of immunological and pharmacological actions.

Active pharmaceutical ingredients on the other hand are defined as the active components in a drug and they can also be composed of other ingredients that are biologically active. There are mostly referred to as excipients and are incorporated into many medications to help in absorption and augment solubility [30].

Essentially, pharmaceuticals and APIs are substances that produce biological effects when administered [31]. They are designed to instigate changes in biological functions in humans and animals. Pharmaceuticals are mainly composed of organic molecules that contain hydrocarbon groups, and their molecular structures are made up of hydrophobic and hydrophilic molecules [32].

Pharmaceutical effluent

These are residual by-products generated by pharmaceutical industries during drug production processes. Pharmaceutical effluents are difficult to treat because they are mostly composed of recalcitrant substances such as organic matter (pharmaceutical actives), and inorganic nutrients (phosphates, nitrates, sulphates). Thus, there is no definite treatment technique for the efficient removal of pharmaceuticals, and this contributes to why a cocktail of treatment techniques are recommended [7,8,9]

Ecopharmacology

Ecopharmacology is a novel study and an evolving field that deals with environmental pharmaceuticals, and the deleterious environmental impacts posed by lipophilic pharmaceutical actives and their metabolites [34]. Pharmaceuticals may have various impacts on certain organisms in the environment. Up until now, there has been limited information based on the potential of pharmaceutical residues to bioaccumulate in ecosystems and food webs [35]. It has been observed that if certain compounds and actives are distributed within the food web in the ecosystem, it may result in various deleterious effects. For instance, Diclofenac is the most extensively investigated pharmaceutical globally and have been found to accumulate in the prey of vultures [36]. The presence of other studied pharmaceuticals such as phenelzine, venlafaxine and the norfluoxetine and naltrexone metabolites have been detected in fish [37]. Residues of diclofenac and hepatic disease were experimentally replicated by exposing gray-backed vultures to direct-oral feeding of diclofenac-treated livestock

Pharmaceuticals are increasingly recognised as emerging contaminants in aquatic environments due to their continuous input, persistence and biological activity. Despite typically occurring at trace concentrations (ng/L to µg/L), these substances

can exert potential effects on ecological and human health through diverse biological mechanisms, even at low exposure levels. This review synthesises recent evidence on the occurrence, fate, transport and removal efficiency of major therapeutic classes, including antibiotics, non-steroidal anti-inflammatory drugs, antidepressants, hormones and steroids, and beta-blockers across the aquatic environment. A cradle-to-grave perspective is applied to characterise the full lifecycle of pharmaceutical residues from production and consumption to environmental persistence. Current and emerging treatment technologies are critically examined alongside regulatory and governance frameworks. To address these challenges, this paper proposes an integrated management framework that interconnects lifecycle thinking, advanced treatment technologies and adaptive regulatory governance to support sustainable protection of drinking-water resources. Collectively, this work advances a holistic understanding of pharmaceutical pollution in water and provides strategic direction for future research, policy development and environmental management.[10,11,12]

RESULTS

Pharmaceutical compounds enter rivers, lakes and coastal waters through domestic sewage, hospital effluents, agricultural run-off and pharmaceutical manufacturing discharges. Many active pharmaceutical ingredients (APIs) and their transformation products resist conventional treatment processes, leading to widespread detection in surface water, sediments and biota. Even at low concentrations, these compounds can disrupt endocrine systems, alter microbial communities and select for antimicrobial resistance. The risk is both local and global: hotspots often coincide with densely populated or industrial regions, yet long-range transport can expose remote ecosystems. Analytical advances now enable trace-level monitoring and non-target screening, revealing mixtures of analgesics, antibiotics, antidepressants and anti-inflammatories in water bodies worldwide. Despite growing scientific understanding, gaps remain in linking environmental concentrations to ecological effects, in standardising risk assessment thresholds and in developing cost-effective remediation strategies. Integrated approaches that combine improved wastewater treatment, source control and targeted monitoring are essential to safeguard aquatic health and mitigate public health risks associated with long-term exposure and resistance proliferation.

Research shows that pharmaceuticals entering the environment through flushing or other means negatively affect aquatic ecosystems, including and fish and animal populations. Read some brief excerpts on the subject:[13,14,15]

According to the U.S. Geological Survey, “the primary concern, has got to be for aquatic wildlife like fish. Because many of these compounds are obviously produced for function in human beings, the presence of these compounds in rivers,

in streams or even worse in drinking water supplies is obviously a matter of deep concern for a lot of people. But it's important to remember people don't actually live in rivers or streams...On the other hand, fish and other aquatic wildlife do live in rivers, and they're much more vulnerable to certain types of emerging contaminants.”

According to the European Commission, pharmaceuticals “have been shown to pose a risk to fish or other wildlife, for example, by affecting their ability to reproduce, altering their behaviour in ways jeopardising their survival, or through direct toxic effects.” They may also “contribute to the serious problem of antimicrobial resistance.”

According to the Organisation for Economic Co-operation and Development, “the vast majority of pharmaceuticals have not yet been evaluated for their long-term toxicity, occurrence or fate in the environment. Nevertheless, certain pharmaceuticals have been proven to cause undesired adverse effects on ecosystems, including mortality and changes to physiology, behaviour or reproduction.”[16,17,18]

Aquatic ecosystems and organisms are particularly vulnerable. Continuous input of APIs into rivers and streams through wastewater treatment systems adversely affects the aquatic ecosystems of water bodies due to the intrinsic bioactivity (having an effect on a living organism) of these compounds.

Aquatic pollution is particularly troublesome because aquatic organisms live in the contaminated water and are exposed continuously throughout their lifecycle.

Some contaminants are problematic because they are persistent (meaning they stay in place for a long time), or they are so common that they are ever-present even though their residence times are low (Daughton, 1999).

Common drugs like non-steroidal anti-inflammatory drugs (e.g., ibuprofen, aspirin, naproxen) negatively impact the organ functions of aquatic organisms and cause cytotoxic and genotoxic damage, high oxidative cell stress, and detrimental effects on growth, reproduction, and behavior (Oaks, 2004).

Endocrine disrupting chemicals damage reproductive physiology resulting in low reproductive rates (Jobling 2004), and in some cases, cause male fish to develop female characteristics (Kidd, 2007).

Antibiotics are another frequently-prescribed class of API that negatively impact ecosystems. Antibiotics are designed to kill living organisms, and they are likewise poisonous to aquatic plants

CONCLUSION

Researchers continue to examine human health effects of pharmaceuticals in the environment. The important features and risks of the problem are evident:

Pharmaceuticals are intrinsically bioactive compounds, meaning they are designed to act on living systems (Ginebreda, 2009).

Pharmaceutical use and its subsequent input into the environment continue to increase worldwide. (Ginebreda, 2009).

Exposure is not to a single pharmaceutical, but to many pharmaceuticals, with unintended, interactive, and often unknown effects (Ginebreda, 2009).

Some pharmaceuticals bioaccumulate in humans, which could decrease fertility and cause breast and testosterone cancers (Tijani, 2013).

Some pharmaceuticals in the environment increase the presence of antibiotic-resistant bacteria.

The Centers for Disease Control and Prevention estimates that, annually, at least two million illnesses and 23,000 deaths in the U.S. are caused by antibiotic-resistant bacteria.[19,20]

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