Aquatic toxicology of pharmaceuticals and their ecological impact on freshwater systems

Hemlata Dewangan[1*]; Tripti Dewangan[2]

Received: 22 July 2025; Revised: 09 September 2025; Accepted: 07 October 2025; Published: 30 October 2025

Abstract

In this paper, the toxicology of pharmaceutical contaminants in the freshwater is discussed and more precisely the impact of different pharmaceutical substances on aquatic organisms and the health of the ecosystem. Pharmaceuticals have become a developing environmental threat commonly released in the freshwater systems through wastewater, agricultural effluents and not properly disposed. Even the low doses of the pharmaceuticals like antibiotics, antidepressants and hormones can affect the stability of the aquatic ecosystems by altering the species composition, reproductive behaviors and ecosystem stability. The paper has been carried out in elaborated way, bioassays, chemical analysis (including HPLC-MS) and ecological modeling have been used to assess the impacts of pharmaceutical contamination. The recent data received research information were integrated with the new findings on the levels of the pharmaceuticals in the rivers, lakes, and wetlands. Survival, behavior and production were measured using individual and mixed species bioassays. There is some early evidence that drugs actually contaminated by pharmaceutical products, in particular, antibiotics and antidepressants, lead to drastic changes regarding breeding rate and behavioral structure of aquatic life. These compounds were reported to have toxicological risks in Zebrafish and Daphnia magna where the levels of ibuprofen concentration led to a decrease in activity and reproductive success. The findings indicate that pharmaceutical contamination has severe effects on aquatic life as a massive threat to biodiversity and the environment. The research article identifies the necessity of the further studies of the long-term effects of pharmaceutical combinations and the development of sustainable and efficient wastewater treatment systems. The regulatory policies will be crucial in reducing the impact of the pharmaceutical pollutants on the environment and protecting the freshwater ecosystems.

Keywords: Aquatic toxicology, Pharmaceuticals, Freshwater systems, Ecological impact, Environmental pollution

1*- Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.
Email: ku.hemlatadewangan@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0004-1414-6649
2- Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.
Email: ku.triptidewangan@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0009-0193-5661
*Corresponding author
DOI: 10.70102/IJARES/V5I2/5-2-46

Introduction

Pharmaceuticals have emerged as a new form of pollution of water. Initially meant to be used to treat humans and animals, the chemicals find their way into fresh water ecosystems as a result of waste disposal, agricultural system run-offs, and poor disposal. Following the existence in environment, pharmaceuticals may exert long-term toxicological effects to the aquatic organisms and, in the vast majority of cases, disrupt ecological systems (Marin-Morales *et al.*, 2016). It has been noted that the use of drugs like antibiotics, hormones, and analgesics in the water system has led to some apprehensions that the long-term effect of these drugs on the aquatic life is possible (Yadav *et al.*, 2025). Studies have shown that the compounds could lead to the disruption of the endocrine system, reproductive behavior changes and the development of strains of bacteria resistant to antibiotics, even in low concentrations.

In freshwater systems (i.e., rivers, lakes, and wetlands), pharmaceutical contamination is very sensitive in nature because they are dynamic and species diverse. Water drugs can impact organisms ranging between the microorganisms and the top predators and cause changes in the ecosystem processes which include the nutrient cycling and food web dynamics. The ecological effects of pharmaceutical pollution are complex, multi-fold, both direct, i.e. due to toxicological effects of the pharmaceutical, and indirect, i.e. due to the effect on the interactions between species and the ecosystem (Patil, 2018).

Recent progress in analytical chemistry has allowed the detection of pharmaceuticals in water over tiny concentrations, although not much is known about their effects on the environment in the long term. Wastewater treatment procedures used currently, in most cases, cannot remove the drugs of pharmaceutical source and this adds to the problem. The toxicity of drugs and their environmental significance in the freshwater systems are critical aspects in the development of successful mitigation strategies.

Key Contributions

- Examination of the toxicology of pharmaceuticals on the aquatic organisms of freshwater ecosystems.
- Determining the ecological effects of pharmaceuticals on biodiversity and ecosystem operations.
- Suggested a new approach to evaluating drug pollution in freshwaters.

The structure of this paper is as follows: Section II gives a critical literature review on the ecological impact of pharmaceuticals on water bodies. Section III will have the proposed pharmaceutical toxicity methodology in fresh water. The fourth section contains results and discussion of the recent studies and models, and finally, the conclusion as well as the recommendations appear in the V section.

Literature Survey

In the literature regarding the aquatic toxicology of pharmaceuticals, the number of studies being conducted to study the environmental impact of

pharmaceutical contamination is increasing (Brausch *et al.*, 2012). Pharmaceutical residues have been reported in rivers, lakes and ground water in numerous studies and in many cases the concentration is higher than the limits set by regulations. These investigations highlight the fact that the presence of pharmaceutical pollutants in water should be more carefully supervised and regulated, yet in the developing world, wastewater treatment systems might be inadequate. There are only a few classes of pharmaceuticals, including antibiotics, hormones and anti-inflammatory substances, which are not biodegradable and remain in the environment where they become a major threat to aquatic organisms (Brodin *et al.*, 2014). The cumulative impact of these pollutants on ecosystem has created concern on the long-term effects of the chemicals hence there is the need to know their precise ecological effects (Sibley and Hanson, 2011). In addition, there are new technologies in the field of molecular biology and environmental chemistry that enable scientists to find low concentrations of pharmaceutical pollution in the water system and understand their levels and effects better (Rodrigues *et al.*, 2022).

Pharmaceuticals use and particularly the use of antibiotics has been a major area of concern since the drug is highly used and in case of bioaccumulation in fish. It has been established that prolonged exposure to low doses of antibiotics in water results on the development of antibiotic-resistant bacteria which has a serious consequence on human health and the processes in the ecosystem. Studies have shown that minimal concentration of antibiotics in freshwater system may cause changes in the microbial community structure, decrease biodiversity and even disruption of significant ecological processes (Rosi-Marshall *et al.,* 2015). In addition, the rise of the antibiotic-resistant bacteria can spread the resistance to the human pathogens that complicates the process of treating infections. The implication of these results would be that the environmental impacts of antibiotics would be more comprehended to come up with better policies to regulate the disposal of pharmaceuticals and the prevention of antibiotic resistance in water bodies (Cunningham *et al.*, 2006).

The other categories of pharmaceuticals, such as antidepressants, hormones and pain killers have also been detected within the water systems on top of the antibiotics and each has different effects on the ecology (Guo *et al.*, 2016). Antidepressants, particularly, have been found to disrupt the behavior and reproductive fitness of fish species, some studies have shown that the feeding and mating behaviors are disturbed, and, therefore, it affects population dynamics. Feminization of male fish and other species may also lead to endocrine disturbance of the hormones and particularly the estrogenic compounds. This is called endocrine disruption which is of huge concern in the fact that it might eventually result in distorted sex ratios, low fertility and growth rates. Introduction of analgesics in water bodies like acetaminophen has also been linked to change of behavior of fish and decrease in immune abilities which expose an organism to diseases. Consequently, pharmaceutical pollution

has become the main issue that is of essential concern to the integrity of freshwater ecosystem (Minguez *et al.*, 2016).

The ecological impact of pharmaceutical contamination does not apply to individual species only. Any alteration in reproductive success, behavior and the composition of species can have cascades on the aquatic food web, which, in turn has impacts on the biodiversity and ecosystem services, such as water filtration and nutrient cycling (Costa, 2025). The loss of biodiversity can also cause instability in the ecosystems that render the freshwater systems more vulnerable to other stressors such as climate change and loss of habitats. Extinction of the important species within these ecosystems (e.g. apex predators or significant microorganisms) can cause a change in the trophic interactions and bring about disequilibrium in nutrient cycles. By way of example, if the number of aquatic invertebrates dwelling on exposure to pharmaceuticals decreases, then the fish population will suffer as a result of reduced supplies of food and thus an error involving higher levels of trophic equilibrium (Rosi-Marshall and Royer, 2012). The long-term impacts of those changes in the environment on the functioning of freshwater ecosystems may be extensive and cause the ecological collapse.

Even though the majority of the literature has concentrated on the toxicity of individual pharmaceutical compounds, there is an increasing awareness of the need to investigate the synergistic impacts of the pharmaceutical mixtures in the environment (Gworek *et al.*, 2019). This may cause synergistic or antagonistic interactions between two or more pharmaceuticals; thus, it may be difficult to interpret the results of toxicity. Interactions of different pharmaceutical substances can contribute to the toxicity a phenomenon which cannot be established by examining substances separately. Moreover, these compound mixtures can also react with other environmental pollutants, e.g., heavy metals and pesticides and this way, the impact on aquatic organism can even be more significant (Kidd *et al.*, 2024). This demonstrates the need to study the interactions between different types of contaminants instead of focusing on the individual substances in order to have a better image of pharmaceutical pollution of freshwater environments.

Methodology

The comprehensive approach to researching the toxicity of drugs polluting freshwater ecosystems is used in this study, and it involves chemical analysis, bioassays, and ecological models. The process includes screening/identification of pharmaceutical compounds, toxicology study of the compounds on aquatic organisms and simulation of their effects in the long term on the ecosystem health.

Identification and Quantification of Pharmaceuticals

The first is the identification and quantification of the pharmaceutical pollutants in the fresh water systems. The different classes of pharmaceuticals that are analyzed by high-performance liquid chromatography with a mass spectrometry (MS) are antibiotics, hormones, analgesics, and

antidepressants. The choice of these techniques is due to their vulnerability and the fact that they would be able to detect the pharmaceutical residues in low concentrations (ng/L to ug/L).

Table 1: Pharmaceuticals detected in freshwater systems.

Pharmaceutical Compound	Class	Analytical Method	Concentration Range Detected (ng/L)
Ibuprofen	NSAID	HPLC-MS	50-500
Estrone	Hormonal	HPLC-MS	10-100
Amoxicillin	Antibiotic	HPLC-MS	100-1000
Fluoxetine	Antidepressant	HPLC-MS	50-400

Table 1 summarizes some common pharmaceutical compounds found in freshwater systems and their typical concentration ranges.

Toxicity Assessment Using Bioassays

Bioassays are used to determine toxicity once the pharmaceuticals have been identified. Tests are conducted on Zebrafish (Danio rerio), amphibians (Xenopus laevis), and invertebrates (Daphnia magna). The tests involve Acute Toxicity (LC50) and Chronic Toxicity (NOEC) tests:

- LC50 (Lethal Concentration of 50 percent of organisms): Pharmaceutical concentration that causes 50 percent mortality in the test organism during a specified time period.
- NOEC (No Observations Effect Concentration): This is the maximum concentration at which there are no toxic effects of chronic exposure.

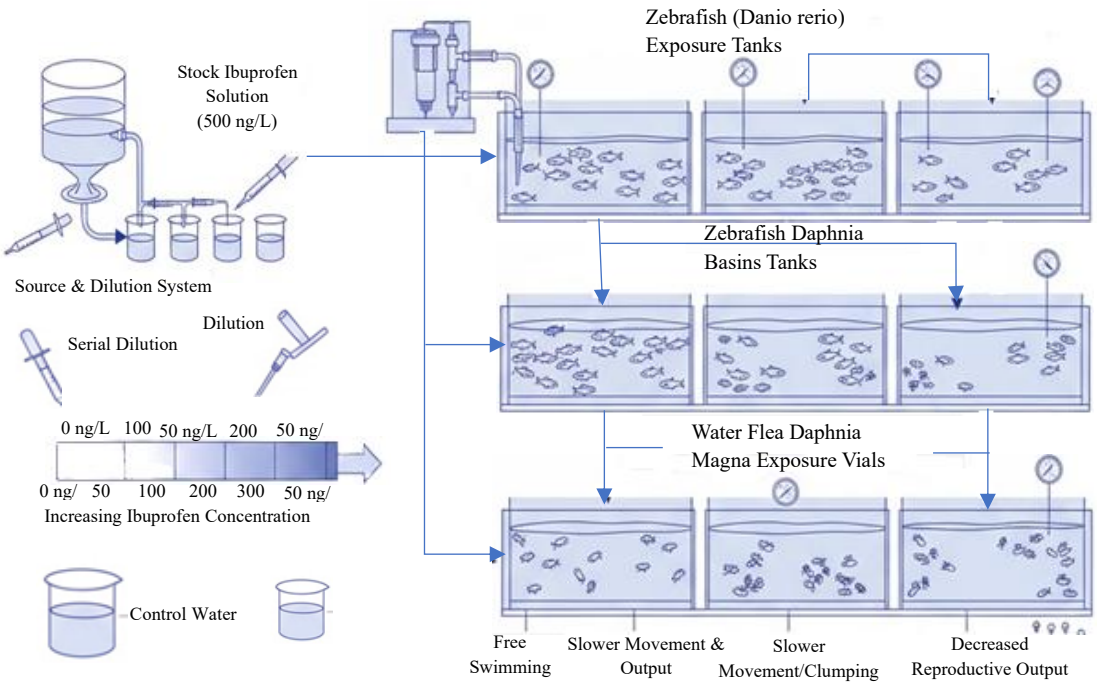

Figure 1: Laboratory bioassay setup: effects of ibuprofen on aquatic species.

As shown in Figure 1, the laboratory bioassay system comprises diluting ibuprofen to different concentrations and exposing Zebrafish and water fleas to

those concentrations. The impact on the two species, including alterations in movement, behavior, and reproductive output, is noted during the toxicity test.

Ecological Modeling

Ecological modeling can be used to simulate the long-term effects of pharmaceutical pollutants in freshwater ecosystems. It involves the EcoTox model, which integrates pharmaceutical stressors and models species correlated with population processes and ecosystems. It uses the Lotka-Volterra equations to estimate predator-prey interactions.

Lotka-Volterra Predator-Prey Model

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) - \frac{aNP}{1 + bP} \qquad (1)$$

Where:

- N= Prey population (e.g., fish or invertebrates)
- P= Predator population (e.g., carnivorous fish)
- r= Intrinsic growth rate of prey
- K= Carrying capacity of the environment
- a= Predation rate coefficient
- b= effect of predator population on prey
- This equation describes how the populations of prey and predators evolve in an ecosystem.

Pharmaceutical Impact on Prey

In order to model the effect of the pollution of prey species by pharmaceuticals, we modify the Lotka-Volterra equation with the effect of the pharmaceutical exposure on the prey population:

Pharmaceutical Impact on Prey Population

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) - \frac{aNP}{1 + bP} - cN \cdot P_{pharma} \qquad (2)$$

Where:

- P_{pharma}= Pharmaceutical concentration in the environment
- c= Constant representing the rate of pharmaceutical toxicity on prey

This change explains the added stress due to pharmaceutical contamination that decreases the rate of growth of prey species.

Risk Assessment

The risk quotient (RQ) is used to measure pharmaceutical contamination of the aquatic systems by comparing the concentration of the pharmaceutical in the environment to the toxicological limit.

Risk Quotient (RQ) Calculation

$$RQ = \frac{C_{env}}{LC50} \qquad (3)$$

Where:

- C_{env}= Concentration of the pharmaceutical in the environment (ng/L)
- $LC50$= Lethal concentration of the pharmaceutical for 50% of the organisms (ng/L)
- An $RQ > 1$ indicates a potential risk, while an $RQ < 1$ suggests minimal risk to the ecosystem.

Mixed-Species Bioassay

The final one is the mixed-species bioassays to determine the effects of pharmaceutical exposures on the species interactions. This is done by placing pharmaceuticals in these bioassays wherein species, such as Danio rerio

(Zebrafish) and Daphnia magna (water flea) are exposed to and parameters, such as those recorded, are as follows:

- Survival Rate: The percentage of organisms that survive during a given time span of exposure.
- Reproductive Output: Reproductive output is the number of offspring produced by the species.
- Adjustments Behavior: eating, mating, and swimming.

Results and Discussion

Results show that ibuprofen affects Zebrafish (Danio rerio) and Water Fleas (Daphnia magna) negatively. Survival, reproduction, and behavior in bioassay experiments were compared at different concentrations of ibuprofen. Even at concentrations typical of polluted aquatic ecosystems, the results show the severe impact of pharmaceutical pollutants on aquatic life.

Impact on Zebrafish (Danio rerio)

Zebrafish were subjected to 100 ng/L, 50 ng/L, 0 ng/L and 500 ng/L of ibuprofen. As the concentration of ibuprofen increased, mosquito survival, reproduction, and behavior were adversely affected at all recorded levels. The control group had nearly 100 percent survival, but at 50 ng/L concentration survival was reduced to 85 percent, and at 500 ng/L to 60 percent. This gives evidence to the low-level acute toxicity of ibuprofen and corresponds with findings on the impact of pharmaceutical contaminants in freshwater bodies.

Higher concentrations also affected the behavior of the zebrafish. At 500 ng/L zebrafish were less active and spent long periods at the bottom of the tank, while control group zebrafish swam regularly and actively. This behavioral depression is suggestive of stress or perhaps an endocrine disorder. At high concentrations there was also an impairment to the zebrafish reproduction. The control group had normal reproductive output and offspring, but there was a 10 percent reduction at 50 ng/L and a 50 percent reduction at 500 ng/L. This suggests that ibuprofen, in at least some part, hinders zebrafish reproduction and possibly causes other physiological/psychological stress.

Table 2: Effect of ibuprofen on zebrafish survival and reproductive output.

Ibuprofen Concentration (ng/L)	Survival Rate (%)	Reproductive Output (Number of Offspring)	Behavioral Change
0 ng/L (Control)	98	100	Normal Swimming
50 ng/L	85	90	Reduced Activity
100 ng/L	75	60	Slower Movement
500 ng/L	60	45	Abnormal Spawning

The effects of ibuprofen on Zebrafish survival, reproductive outputs, as well as behavioral changes in various concentrations look at in Table 2. The lower survival and reproductive success at the higher concentrations show the toxic effects of ibuprofen on aquatic life.

Impact on Daphnia magna (Water Fleas)

Daphnia magna was also exposed to the same amounts of ibuprofen and similar results were observed. The control group survived at a rate of 95%. At 500 ng/L however, that rate dropped to 45 percent demonstrating that the water fleas are very sensitive to ibuprofen. At higher concentrations, subjective behavioral observations showed the water fleas were lethargic, and the ones treated with 500 ng/L barely moved at all and spent most of their time at the water's surface. This also had a very significant impact on reproductive output in Daphnia magna. When the level of offspring production dropped to 50 ng/L, it decreased by 20 percent, and when it dropped to 500 ng/L, it decreased by 75 percent. This implies that ibuprofen has direct effects on the reproductive biology of Daphnia magna, which may involve hormonal regulation or other biological functions required for reproduction.

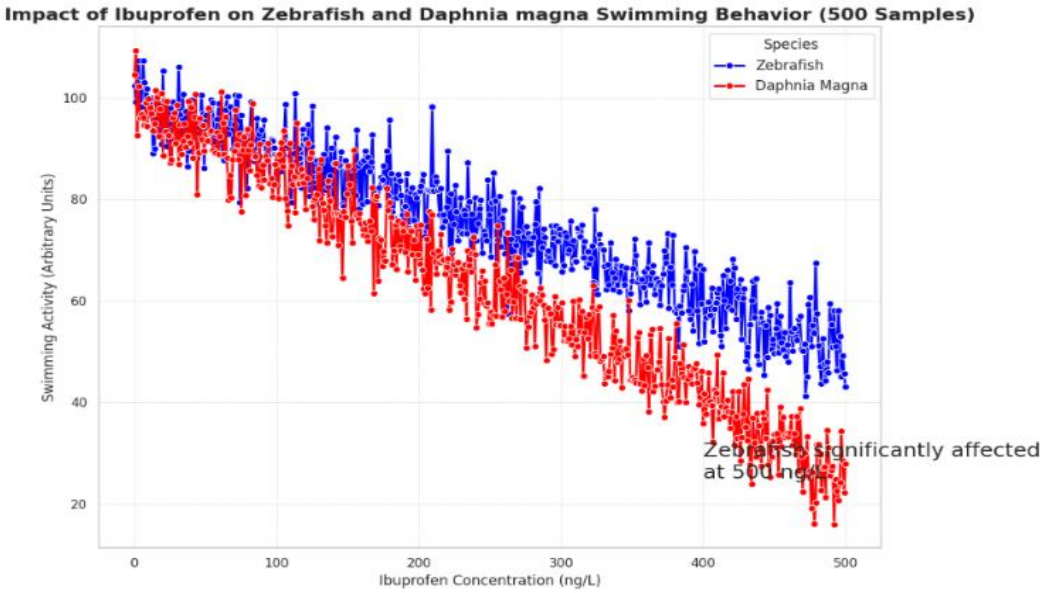

Figure 2: Impact of ibuprofen on zebrafish and daphnia magna swimming behavior.

Figure 2 shows that the concentration of ibuprofen affected the swimming behaviour of two aquatic organisms: Zebrafish (Danio rerio) and Water Fleas (Daphnia magna). The x-axis is the concentration of IbuIbuprofeng/L) with the values varying between 0 ng/L and 500 ng/L, and the y-axis gives the swimming activity of the two species in arbitrary units.

Each data point is represented by a plot with confidence limits to show the variation in swimming activity across the 500 samples. Since the concentration of ibuprofen has increased, the activity in both species has decreased, with the most impact in Zebrafish at the highest concentration.

The blue lines represent zebrafish while the red lines show Daphnia magna. Most severely impacted zebrafish activity in the lines is annotated at the 500 ng/L point. This graph illustrates the possible extent to which the health of aquatic organisms may be compromised due to pharmaceutical contamination and the possible consequences to the ecology of freshwater ecosystems.

Combined Effects on Species Interactions (Mixed-Species Bioassay)

Investigating species interactions in the context of bioassays with Zebrafish and Daphnia magna was implemented with the same concentration of ibuprofen. Daphnia magna feeding Zebrafish exhibited reduced Daphnia predation as ibuprofen concentration in the water increased. At concentration of 100 ng/L and above Zebrafish reduced their feeding behavior and predation of Daphnia magna. This was not enough to cause predation mitigation as the Daphnia magna population was negatively affected due to reduced reproductive success.

When Daphnia magna was 500 ng/L ibuprofen and suffered with 75 percent reproductive crippling it demonstrated the loss of reproductive performance was a direct effect of ibuprofen even when not under predatory pressure. This indicates pharmaceutical contamination may soften trophic interactions and filtration pressure in freshwater ecosystems. For example, reduced predation pressure on Daphnia magna will enable population growth, but sustained predation and exposure to ibuprofen will cause population decline and prevent reproduction.

The mixed-species bioassay highlights the complexities of ecosystems responding to pharmaceutical pollution. The reproductive impact on Daphnia magna will always be harmful, even when alleviating predation on Zebrafish.

Conclusion

This research demonstrates the impact of different use levels of ibuprofen on swimming performance and female fecundity of Zebrafish (Danio rerio) and Daphnia magna, and on both species' reduction of the compound's activity. These findings suggest even low levels of pharmaceuticals can impact aquatic life and disrupt species relationships and ecosystems. Findings, particularly those associated with the 500 ng/L concentration, suggest the scope of research on the long-term ecological consequences of pharmaceutical pollution on species diversity, food webs, and the interrelationship of ecosystems and biodiversity, is invaluable. Future research should investigate the ecological impacts of pharmaceutical mixtures, prioritize the development of effective wastewater treatment design, and impose tougher policy limits on the pharmaceutical pollution of freshwater ecosystems.

Reference

Brausch, J.M., Connors, K.A., Brooks, B.W. and Rand, G.M., 2012. Human pharmaceuticals in the aquatic environment: a review of recent toxicological studies and considerations for toxicity testing. *Reviews of Environmental Contamination and Toxicology Volume 218*, pp.1-99.

Brodin, T., Piovano, S., Fick, J., Klaminder, J., Heynen, M. and Jonsson, M., 2014. Ecological effects of pharmaceuticals in aquatic systems—impacts through behavioural alterations. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1656), p.20130580. https://doi.org/10.1098/rstb.2013.0580

Costa, E., 2025. Aquaponics to Promote Long-Term Food Safety and Water Quality Improvement. *Aquatic Ecosystems and Environmental Frontiers*, *3*(4), pp.13-16.

Cunningham, V.L., Buzby, M., Hutchinson, T., Mastrocco, F., Parke, N. and Roden, N., 2006. Effects of human pharmaceuticals on aquatic life: next steps.

Guo, J., Sinclair, C.J., Selby, K. and Boxall, A.B., 2016. Toxicological and ecotoxicological risk-based prioritization of pharmaceuticals in the natural environment. *Environmental Toxicology and Chemistry*, *35*(6), pp.1550-1559. https://doi.org/10.1002/etc.3319

Gworek, B., Kijeńska, M., Zaborowska, M., Wrzosek, J., Tokarz, L. and Chmielewski, J., 2019. Pharmaceuticals in aquatic environment. Fate and behaviour, ecotoxicology and risk assessment–a review. *Acta Poloniae Pharmaceutica-Drug Research*, *76*(3), pp.397-407.

Kidd, K.A., Backhaus, T., Brodin, T., Inostroza, P.A. and McCallum, E.S., 2024. Environmental risks of pharmaceutical mixtures in aquatic ecosystems: Reflections on a decade of research. *Environmental Toxicology and Chemistry*, *43*(3), pp.549-558. https://doi.org/10.1002/etc.5726

Marin-Morales, M.A., Campos-Pereira, F.D., Navarro, F.F. and de Oliveira, J.A., 2016. Eco-toxicological impact of pharmaceuticals for human use in aquatic systems. *Aquatic Toxicology*, pp.1-20.

Minguez, L., Pedelucq, J., Farcy, E., Ballandonne, C., Budzinski, H. and Halm-Lemeille, M.P., 2016. Toxicities of 48 pharmaceuticals and their freshwater and marine environmental assessment in northwestern France. *Environmental Science and Pollution Research*, *23*(6), pp.4992-5001.

Patil, P.J., 2018. An ecological analysis of forest accounting. *International Academic Journal of Innovative Research,* *5*(1), pp.109–127. https://doi.org/10.9756/IAJIR/V5I1/1810010

Rodrigues, P., Oliva-Teles, L., Guimarães, L. and Carvalho, A.P., 2022. Occurrence of pharmaceutical and pesticide transformation products in freshwater: Update on environmental levels, toxicological information and future challenges. *Reviews of Environmental Contamination and Toxicology*, *260*(1), p.14.

Rosi-Marshall, E.J. and Royer, T.V., 2012. Pharmaceutical compounds and ecosystem function: an emerging research challenge for aquatic ecologists. *Ecosystems*, *15*(6), pp.867-880.

Rosi-Marshall, E.J., Snow, D., Bartelt-Hunt, S.L., Paspalof, A. and Tank, J.L., 2015. A review of ecological effects and environmental fate of illicit drugs in aquatic ecosystems. *Journal of hazardous materials*, *282*, pp.18-25. https://doi.org/10.1016/j.jhazmat.2014.06.062

Sibley, P.K. and Hanson, M.L., 2011. Ecological impacts of organic chemicals on freshwater

ecosystems. *Ecological Impacts of Toxic Chemicals. Bentham e Books*, pp.138-164.

Yadav, V., Bhumika, B., Deepak, S. and Thulasiram, R., 2025. Examining the Liver Metabolic Alterations Induced by Olive Leaf Compounds in Aquatic Species. *Natural and Engineering Sciences*, *10*(1), pp.352-362. https://doi.org/10.28978/nesciences.1648743