[Ibuprofen in the Environment: Chemical Behavior and Ecological Impact in Freshwater Systems]

Gahyun Lim

Abstract

Pharmaceutical contamination of freshwater systems is one of the most pressing environmental challenges of our time, with ibuprofen used to exemplify the risks posed by over-the-counter (OTC) drugs. Even at sub-lethal concentrations, ibuprofen is ubiquitous in surface water, groundwater, and treated effluents, which can contain up to about 1 mg/L and is detected due to high use and frequent improper disposal. Its chemical and biophysical properties support ibuprofen's persistence in aquatic environments and contributes to the failure of traditional wastewater treatment ability to remove all contaminants and byproducts. Environmental research has shown that ibuprofen and its transformation products can negatively affect aquatic life at sub-lethal concentrations such as fish, algae, and invertebrates. Global case studies prepared by Europe, Korea, and the United States confirm its ubiquitous occurrence as well as additional local risks from treatment and infrastructure differences. The ecological consequences of ibuprofen found in freshwater systems can alter food web dynamics, cause biodiversity losses, and continue chronic exposures. Changes to treatment and infrastructure requires technology to formulate new advanced treatment processes and behavior changes, such as take-back programs and public awareness campaigns. Ibuprofen illustrates the broader issue of pharmaceutical pollution in freshwater ecosystems, underscoring the urgent need for integrative management strategies and science-based policies to safeguard environmental and public health.

Introduction

Water pollution by pharmaceuticals is a growing environmental concern resulting from human activities such as the improper disposal of chemicals. Similar to more widely recognized contaminants like heavy metals (e.g., lead, mercury), which are strictly regulated due to their toxicity and persistence, pharmaceutical pollutants can also pose significant risks to both ecosystems and human health. Unlike metals, which are often monitored and controlled through established governmental regulations and water quality standards, pharmaceutical contamination remains less visible to the public, despite evidence of its widespread occurrence and potential long-term ecological impacts.[1,2] Specifically, ibuprofen, a common non-steroidal anti-inflammatory drug (NSAID) is widely consumed and chemically stable, so it is often detected along with other contaminants.

Widespread presence in the environment of ibuprofen is due to its easy accessibility since it is an over-the-counter drug (OTC) and is frequently disposed of through human excretion or flushing unused medications down the toilet. Unlike more strictly regulated prescription drugs, OTC drugs such as ibuprofen are often used without medical supervision, resulting in increased consumption through overdoses and disposal in household waste. This paper aims to explore the behavior of ibuprofen in freshwater ecosystems and to assess its impact on the environment. Ibuprofen has been found in various concentrations across many water systems including surface water, groundwater and even in drinking water. A comprehensive analysis of measured environmental concentrations (MECs) from different countries around the world, pharmaceuticals or their byproducts were detected in over 70 different countries.

Regular detection of ibuprofen in effluents and surface waters have been confirmed in additional studies. In one study, high concentrations of ibuprofen were detected in the influent wastewater, but advanced treatment significantly reduced the ibuprofen content in the final effluent.[3,4] Although this indicates that the removal of ibuprofen is possible it requires sophisticated treatment, however this does not consider the impact the untreated water may be having environmentally before it reaches a treatment facility. Furthermore, in certain parts of the world, treatment plants capable of removing these contaminants may not be common.

While ibuprofen is the main focus, the issue of pharmaceutical contamination extends far beyond a single compound. Other drugs, such as diclofenac, carbamazepine, and antibiotics have also been found in natural waters. Unlike ibuprofen, which is an over-the-counter analgesic with relatively higher degradation potential in some treatment processes, diclofenac and carbamazepine are more chemically stable and persistent in aquatic environments, while antibiotics carry the additional concern of fostering antimicrobial resistance. This suggests that pharmaceutical contamination is a widespread problem worldwide.[5] Furthermore, accidental or illegal releases from pharmaceutical manufacturing facilities can sometimes create localized contamination "hot spots," further amplifying the environmental risk.[6,7,8] The exact route of contamination, chemical properties, and the potential impact on the environment as well as human health are important to consider when examining these different pharmaceutical contaminants found in our water systems. While ibuprofen is the main focus due to it being OTC and its widespread use, many of the topics discussed will apply to other pharmaceutical contaminants.

Chemical Properties of Ibuprofen

Ibuprofen($C_{13}H_{18}O_2$) is a commonly used pharmaceutical characterised by several chemical properties which impacts significantly on its environmental behavior. One noticeable chemical property is its relatively low water solubility (approximately 21 mg/L at 25) which limits its ability to dissolve in aquatic systems. Ibuprofen might adhere to sediments or organic particles in the water, potentially reducing its impact on marine organisms but allowing long-term persistence in the environment.[15]

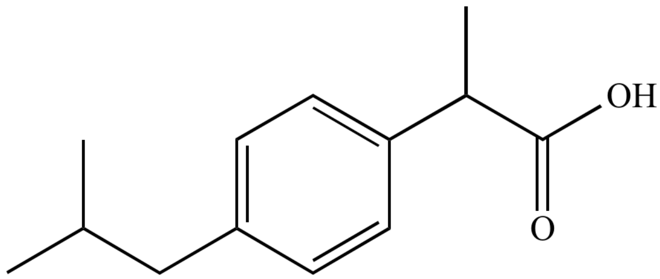

Fig.1. Structure of Ibuprofen

Another chemical property is its low Kow value, also known as the octanol-water partition coefficient, a measure of how a chemical substance distributes between a fatty (octanol) and an aqueous (water) environment. Ibuprofen has a log Kow value of 3.5, indicating moderate hydrophobicity,[3] indicating that ibuprofen has a moderate potential to bioaccumulate in aquatic environments. While this value does not suggest an extreme hydrophobicity, it does not imply a sufficient tendency for the compound to divide into fatty tissues over time, potentially having ecological risks through trophic transfer in aquatic food webs.

Ibuprofen is considered moderately persistent in terms of environmental stability. It shows partial resistance to biodegradation specifically under low oxygen or nutrient deficient conditions that are common in some wastewater systems or natural water bodies.[13] This means that ibuprofen can linger long periods of time before breaking down once it has been introduced into the environment increasing the chance for chronic exposure for aquatic organisms as well as emphasizing the need for wastewater treatment plants capable of removing these persistent contaminants effectively.

These chemical properties have several implications regarding the fate of ibuprofen in environmental systems. Its hydrophobicity and low water solubility directly impacts its mobility in aquatic environments, as it may be capable of moving downstream, albeit less effectively, intermittently binding to sediments. Further, their resistance to biodegradation creates challenges to treating them through wastewater treatment processes including systems reliant on, or highly reliant on, microbial processes. Lastly, their interactions with natural organic matter create complexities for processes such as transport, transformation, and final treatment that either inhibit breakdown or enhance what might be seen as compartmental accumulation within the environment.[10]

In general, these chemical properties explain the repeated detection of ibuprofen in surface waters and wastewater effluents emplaced in the environment and emphasizes the challenges these chemicals pose for environmental management. The European commission proclaimed the need to understand properties like those illustrated in this paragraph thereafter for the purpose of creating and utilizing such treatment approaches, which applies to a variety of water contaminant pathways for other similar chemicals that may share persistence and/or resistance to degradation as ibuprofen.[9]

Pathways into Freshwater Environments

Contamination of Ibuprofen happens through various pathways. One common route is through human excretion, in that unmetabolized ibuprofen, after ingestion, it is excreted, through the sewer system to wastewater treatment plants (WWTPs). These parameters do not prepare WWTPs for pharmaceutical ingestion, because they are not pharmaceutical removal systems, especially when they continue to allow multiple contaminants. Therefore, for treated wastewater, ibuprofen is often identified in rivers or lakes.[11,12]

Environmental pollution is enhanced by inappropriate disposal actions, for example, so many people either ignore pharmaceutical regulations and flush unused medicines down the toilet or discard them with household garbage. This practice increases how much pharmaceutical compounds are delivered to the sewer system, especially in cases where education is lacking or drug recovery programs have no relevance.[11] One can ascertain that ibuprofen is unique compared to prescription drugs, which can be compound-wrapped and stored more easily, leaving reduced amounts for disposal. Ibuprofen is an over-the-counter [OTC] medication, is widely prescribed, is often bought in the bulk quantity, and can remain at home outside of the reach of medical access or purpose, and all of these reasons contribute to improper disposal farther out of reason than prescription drugs and it will also account for the differences between the two products with amounts disposed to to weight apparent being greater through ibuprofen relative to weight and amount.

Also, there are studies that show that ibuprofen is not consistently and effectively removed from wastewater even when it reaches treatment facilities. Ibuprofen was found in a survey of EU member states wastewater treatment plants from influent and effluent, and often with incomplete removal due to lousy degradation, such as for example, some studies note that ibuprofen is poorly degraded through conventional activated sludge, and the ibuprofen is still intact for the treated facilities' final discharge.[11,12] In addition, the efficiency of ibuprofen removal from wastewater treatment plants can vary seasonally and with temperature changes.[4]

Patterns of ibuprofen use and environmental contamination trends are clearly linked. For instance, the levels of ibuprofen that are detected in surface and groundwater systems are considerably higher in countries that consume large amounts of ibuprofen, such as the US, Germany, and England.[11] Additionally, a study found that ibuprofen is one of the most commonly detected drugs in global environmental water samples.[3] For ibuprofen concentrations, specific values or averages were not described, but it was noted that similar drugs, such as acetylsalicylic acid (ASA) and paracetamol (PCM), could reach maximum global average concentrations of 0.922 µg/L and 0.161 µg/L globally, and also were noted to have maximum concentrations of 20 µg/L and 230 µg/L respectively.[3] These findings suggest that ibuprofen likely exhibits comparable environmental persistence and frequency of detection, depending on the sampling location and wastewater treatment efficiency.

Table 1. Global average and maximum concentrations of selected analgesics in environmental waters[3]

Pharmaceutical	Global Avg. Concentration (μg/L)	Maximum Reported Concentration (μg/L)
Acetylsalicylic acid	0.922	20.96
Paracetamol	0.161	230.0
Ibuprofen	0.108	303
Naproxen	0.050	32

Environmental Behavior and Degradation

Ibuprofen exhibits moderate environmental persistence when released into aquatic ecosystems due to its physicochemical properties. Ibuprofen is relatively stable in water and has poor biodegradability in typical environmental situations, especially at low temperatures or anaerobic conditions.[12] These factors help explain the detection of ibuprofen in surface waters at measurable concentrations for several days to weeks after release.[11,14]

Ibuprofen can be degraded by photolysis, microbial transformation, and hydrolysis. Photolytic degradation may occur in surface waters when exposed to sunlight. The quality of water (i.e., water depth, turbidity, dissolved organic matter) influences photolytic processes.[13] Most biodegradation of ibuprofen occurs through deterministic pathways dependent on specific microbial communities. Nevertheless, many existing wastewater treatment processes are conducive only to partial degradation. One study showed that some treatment processes, including advanced processing, will ultimately produce transformation products that are bioactive.[13]

These transformation products are important, as they can be as toxic or more toxic than the parent compound. For instance, Buser et al. (1999) showed 2-hydroxyibuprofen, a significant degradation product, was still pharmacologically active in laboratory tests.[14] The detection of ibuprofen and its metabolites could cause chronic exposure to benthic organisms due to the persistence of ibuprofen and its metabolites in sediments. Accordingly, the need is urgent for new and more broadly available elimination approaches to removing ibuprofen and its transformation products from water systems.

This product presents a heightened risk to the environment because it attaches to organic matter and sediment particles, preventing further degradation and distribution. Oh et al., observe how these attachments can reduce the short-term bioavailability of ibuprofen while extending its environmental half-life.[14] As such, though ibuprofen may have been removed from the water column, it may persist in the benthic layer or bioaccumulate in aquatic organisms. This presents a clear need to improve testing protocols and practices to more accurately capture environmental exposure.

The conclusions draw attention to a pressing need for more effective technologies for wastewater treatment, improved public awareness of drug disposal practices, and increased environmental monitoring to determine the long-term effects of ibuprofen, and drugs like it, on the ecosystem.

Impact on Water Quality and Aquatic Life

The existence of ibuprofen in freshwater systems is a significant threat to both water quality and aquatic life. While ibuprofen is typically present at low concentrations, measured in nanograms to micrograms per liter, it can have demonstrable biological effects on a wide number of aquatic species such as fish, algae, and invertebrates.

In fish, chronic exposure to ibuprofen is associated with oxidative stress, enzyme inhibition, and inflammation. Studies have shown that ibuprofen concentrations as low as 1-10 µg/L, which can be found in the natural environment, will change antioxidant enzyme activity, induce lipid peroxidation, and attenuate endocrine signaling (e.g. Danio rerio (zebrafish) and Oncorhynchus mykiss (rainbow trout)[16,17].

Algae and invertebrates are also very sensitive to ibuprofen contamination. In algae, exposure to ibuprofen could impact chlorophyll biosynthesis, photosynthetic efficiency, and growth.[18] Similarity, in aquatic invertebrates, such as Daphnia magna, exposure to ibuprofen has been shown to result in lowered reproductive success, delayed maturation, and behavioral changes; these changes can occur at ibuprofen concentrations less than 10 µg/L.[19]

Ibuprofen toxicity data is abundant, and its concentration at which is lethal (LC_{50}) is poorly established among different species or duration of exposure. An example of a reported LC_{50} for Daphnia magna indicates approximately 17 mg/L in acute methodology, while lethal effects can be observed at three orders of magnitude earlier. Cumulative physiological stress induced by chronic exposure, even at ng/L concentrations, has previously compromised survival and reproduction in aquatic organisms.[17]

Moreover, ibuprofen has been shown to remain in the environment for a lengthy time, and is frequently detected in effluent and surface water, indicative of sites that are in contact with chronic exposure to ambient concentrations or low doses of ibuprofen. The prolonged, low-dose exposure in many aquatic habitats raises concern over chronic toxicity of ibuprofen in ecosystems and populations. In particular, regions with low water turnover and exposure to many pharmaceutical products increases concern for chronic toxicity of ibuprofen and introduces a "cocktail effect" that can cause additional harmful effects.[18]

These studies support the view that ibuprofen is more than just a chemical persistence problem, but a biologically active pollutant that has the potential to impact aquatic life at the individual and population levels. The large potential ecological impacts from this type of change in an aquatic ecosystem are many, and include loss of biodiversity and altered dynamics in food webs. To account for such an unsustainable change we must use pre-emptive measures to prevent ibuprofen contamination, and monitor pharmaceutical residues in aquatic systems regularly.

Case Studies and Concentration Data

In several studies of environmental monitoring practices, it has been confirmed that ibuprofen is a common contaminant in surface waters found in numerous countries. Studies in Europe, Korea, and the United States situated ibuprofen in both rivers and lakes and confirmed detection in treated wastewater effluent, frequently at concentrations of concern. In Europe, the European Environment Agency (EEA) compiled an extensive range of monitoring studies in many countries and suggests ibuprofen is one of the top 10 most frequently detected pharmaceuticals in the surface waters of member state countries. Monitored concentrations were variable across countries, locations, and sampling times. Ibuprofen was reported at concentrations at the lower ng/L range to ng/L hundreds of ng/L in riverine systems downstream of populations and/or wastewater discharge sites.[20] For example, German and Dutch river systems recorded ibuprofen at concentrations between 100-500 ng/L in proximity to wastewater treatment plant outflows[11].

In the United States, the U.S. Geological Survey (USGS) has reported monitoring pharmaceutical contaminants in over 130 streams. Ibuprofen was detected frequently among analgesic drugs ranging from <10 ng/L in remote areas to over 300 ng/L in urbanized and agricultural zones.[21] The difference in reported concentrations of ibuprofen is likely due to differences in wastewater treatment technology and consumption behaviours, but also reflects the overall population density.

A comparative summary of typical ibuprofen concentrations in surface waters across selected countries is outlined below:

Table 2.Reported Concentrations of Ibuprofen in Surface Waters across Selected Countries[20,21,22]

Country	Range of Ibuprofen Concentration in Surface Water	Source
Germany	100–500 ng/L	EEA (2018)[20]
United States	<10–300+ ng/L	Kolpin et al. (2002)[21]
Netherlands	~200–800 ng/L	EEA (2018)[20]
UK	100–400 ng/L	Hughes et al. (2013)[22]

These case studies demonstrate that ibuprofen pollution is a widespread and persistent issue, particularly near areas with limited advanced wastewater treatment systems or high consumption rates. The presence of ibuprofen in surface water, even after conventional treatment, suggests the need for a multi-faceted approach to mitigation.

Conclusion

This study has established that ibuprofen is a pharmaceutical that is biologically active and can have consequences for the environment. It has environmental persistence, it is not able to be effectively removed by standard wastewater treatment, and it exhibits bioactivity at low concentrations. Ibuprofen is most often detected at levels from nanograms to micrograms per litre, but many research studies have demonstrated that these concentrations are more than enough to elicit oxidative stress, inhibition of enzymes, inhibition of growth, or reproductive toxicity in many types of aquatic organisms.

Fish, algae, and invertebrates can all exhibit measurable biological responses to exposure to ibuprofen that can include changes to the activity of antioxidant enzymes, fertility reductions, inhibition of photosynthesis, and individually these examples can affect all three levels of biological species, and their umbrella functions and ancillary roles within the categorical functional structures of aquatic ecosystems. As the consequences of exposure to ibuprofen are cumulative and chronic, this pollution is not simply a chemical persistence problem, but an ecological problem with very concerning future implications.

In conclusion, to help mitigate risk, we need both behavioral and technological interventions. At the level of governance and policy there may be the potential for improvements and reductions on pharmaceutical inputs in wastewater. First of all, expanding the scope of pharmaceutical take-back programs, and implementing green pharmacy principles by design will reduce pharmaceutical inputs into wastewater disposal systems. Upgrades to old wastewater treatment plants, such as for ozonation, activated carbon treatment, or new membrane bioreactor technologies can help improve better management of removal efficiency as well. Public awareness also plays an important role. Public education campaigns about how to dispose of medications have the potential to significantly impact the amount of ibuprofen going to sewage systems. Simple behavior changes, such as returning unused drugs to their pharmacy, are likely to show some measurable differences.

With respect to risk, communities reliant on untreated well water or where the wastewater collection or treatment infrastructure is failing can be particularly vulnerable to even non-lethal levels of contamination from pharmaceuticals. In these contexts, pharmaceutical contamination has the potential to impact drinking water quality and potentially public health, which is a compelling argument for equitable environmental protections across both geographic and socioeconomic divides.

In conclusion, ibuprofen is a model compound in the context of broader pharmaceutical pollution. Its extensive prevalence, environmental impacts and incomplete removal classifies pharmaceutical pollution as a systemic issue that needs to be urgently considered with evidence-based policy, international collaboration and community awareness.

Bibliography

1. Biel-Maeso, M., Corada-Fernández, C., & Lara-Martín, P. A. (2018). Monitoring the occurrence of pharmaceuticals in soils irrigated with reclaimed wastewater. Environmental Pollution, 235, 312–321. https://doi.org/10.1016/j.envpol.2017.12.085
2. Bastos, M. C., Marilyne Soubrand, Thibaut Le Guet, Floch, É. L., Joussein, E., Baudu, M., & Casellas, M. (2020). Occurrence, fate and environmental risk assessment of pharmaceutical compounds in soils amended with organic wastes. Geoderma, 375, 114498–114498.
3. aus der Beek, Tim, *et al.* "Pharmaceuticals in the Environment—Global Occurrences and Perspectives." *Environmental Toxicology and Chemistry*, vol. 35, no. 4, 2016 (published online 14 Dec. 2015), pp. 823–835.
4. Gracia-Lor, Eva, *et al.* "Occurrence and Removal of Pharmaceuticals in Wastewater." *Science of the Total Environment*, 2012.
5. Wilkinson, John L., et al. "Pharmaceutical pollution of the world's rivers." *Proceedings of the National Academy of Sciences*, vol. 119, no. 7, 2022, e2113947119.
6. ERM. "Water quality in the pharmaceutical value chain: Addressing API contamination at the source." *ERM Insights*, 18 July 2025.
7. Eapen, J. V. "A review of the effects of pharmaceutical pollutants on …" *Exploration Pharma & Env. Studies*, 2024.
8. Munzhelele, Epaineta P., et al. "A Review of Sources, Pathways, Occurrence, Effects, and …" *Water (MDPI)*, vol. 16, no. 6, 2024, 796.
9. Scientific Committee on Health and Environmental Risks (SCHER). *Opinion on Draft Environmental Quality Standards under the Water Framework Directive – Ibuprofen*, 30 Mar. 2011, European Commission. PDF.
10. National Center for Biotechnology Information. "Ibuprofen." *PubChem*, Compound ID 3672, U.S. National Library of Medicine, https://pubchem.ncbi.nlm.nih.gov/compound/Ibuprofen. Accessed 24 Jun. 2025.
11. Ternes, T. A. "Occurrence of Drugs in German Sewage Treatment Plants and Rivers." Water Research, vol. 32, no. 11, 1998, pp. 3245–3260.
12. Vieno, Niina M., Tuula Tuhkanen, and Leif Kronberg. "Seasonal Variation in the Occurrence of Pharmaceuticals in Effluents from a Sewage Treatment Plant and in the Recipient Water." *Environmental Science & Technology*, vol. 39, no. 21, Nov. 2005, pp. 8220–8226.
13. Tixier, Céline, Heinz P. Singer, Sjef Oellers, and Stephan R. Müller. "Occurrence and Fate of Carbamazepine, Clofibric Acid, Diclofenac, Ibuprofen, Ketoprofen, and Naproxen in Surface Waters." *Environmental Science & Technology*, vol. 37, no. 6, 15 Mar. 2003, pp. 1061–1068.
14. Buser, H.-Rudolf, Thomas Poiger, and M. D. Müller. "Occurrence and Environmental Behavior of the Chiral Pharmaceutical Drug Ibuprofen in Surface Waters and in Waste Water." *Environmental Science & Technology*, vol. 33, no. 15, Aug. 1999, pp. 2529–2535.
15. Oh, Sanghwa, Won Sik Shin, and Hong Tae Kim. "Effects of pH, Dissolved Organic Matter, and Salinity on Ibuprofen Sorption on Sediment." *Environmental Science and Pollution Research*, 2016.
16. Bartoskova, M., et al. "Evaluation of ibuprofen toxicity for zebrafish (Danio rerio): targeting on selected biomarkers of oxidative stress." *PubMed*, 2013.

17. Jeffries, Ken M., Susanne M. Brander, Monica T. Britton, Nann A. Fangue, and Richard E. Connon. “Chronic Exposures to Low and High Concentrations of Ibuprofen Elicit Different Gene Response Patterns in a Euryhaline Fish.” *Environmental Science and Pollution Research International*, vol. 22, no. 22, Nov. 2015, pp. 17397–17413, doi:10.1007/s11356-015-4227-y.
18. Gonzalez-Rey, Maria, and Maria João Bebianno. “Does non-steroidal anti-inflammatory (NSAID) ibuprofen induce antioxidant stress and endocrine disruption in mussel *Mytilus galloprovincialis*?” *Environmental Toxicology and Pharmacology*, vol. 33, no. 2, Mar. 2012, pp. 361–371.
19. Das, Sushree Akankshya, et al. “Ibuprofen: Its toxic effect on aquatic organisms.” *ResearchGate*, 2019.
20. European Environment Agency. European Waters: Assessment of Status and Pressures 2018. Publications Office of the European Union, 2018.
21. Kolpin, Dana W., et al. "Pharmaceuticals, Hormones, and Other Organic Wastewater Contaminants in U.S. Streams, 1999–2000: A National Reconnaissance." Environmental Science & Technology, vol. 36, no. 6, 2002, pp. 1202–1211. American Chemical Society
22. Hughes, Spencer R., et al. “Global Synthesis and Critical Evaluation of Pharmaceutical Occurrence, Concentration, and Removal in Surface Waters and Wastewaters.” *Environmental Science & Technology*, vol. 47, no. 21, 2013, pp. 11,253-11,282, doi:10.1021/es3030148.