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Silent threat – the ecological dangers of NSAIDs in aquatic ecosystems

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Abstract. Non-steroidal anti-inflammatory drugs (NSAIDs), widely used for their analgesic and anti-inflammatory properties, are increasingly recognized as emerging contaminants in aquatic environments. Despite their therapeutic value for humans, their persistence, bioactivity, and widespread use contribute to continuous input into surface waters through wastewater effluents and agricultural runoff. This review provides a comprehensive synthesis of the current knowledge regarding the occurrence, distribution, and ecological impacts of NSAIDs in aquatic ecosystems. We examine the primary sources of emission, the physicochemical properties influencing their transport and bioaccumulation, and analyze global monitoring data on concentrations of key NSAIDs in freshwater systems. Particular attention is given to their effects on various aquatic organisms, including bacteria, phytoplankton, zooplankton, invertebrates, and vertebrates, with documented outcomes such as developmental abnormalities, physiological disruptions, and oxidative stress. Risk assessment metrics, such as risk quotients (RQ) based on predicted or measured environmental concentrations and predicted no-effect concentrations (PNECs), are evaluated to highlight zones of heightened ecological threat. Finally, we discuss the implications of current trends, forecast future risks, and suggest directions for mitigation through improved wastewater treatment technologies, regulatory measures, and public awareness. NSAIDs, often perceived as benign pharmaceuticals, represent a silent but significant ecological risk requiring urgent interdisciplinary attention.

Introduction

Aquatic ecosystems play a crucial role in sustaining the biosphere, providing essential services such as drinking water, habitats for millions of species, and the regulation of vital ecosystem processes like primary production and biogeochemical cycling. However, these ecosystems are among the most vulnerable to anthropogenic pollution. Global monitoring data reveal a growing prevalence of pharmaceuticals in surface waters, groundwater, and wastewater (Patel et al. 2019). Among these, non-steroidal anti-inflammatory drugs (NSAIDs) are frequently detected in aquatic environments due to their widespread use and the challenges associated with their removal by conventional wastewater treatment methods (Hejna et al. 2022; Ossowicz-Rupniewska et al., 2023; Ma et al., 2023). This contamination not only threatens the health of aquatic organisms but also destabilizes entire food webs, compromising the integrity of these ecosystems (Mustafa et al. 2024). Many NSAIDs exhibit high chemical stability and resistance to biodegradation, allowing them to persist in aquatic environments for extended periods (Divya Lakshmi et al. 2024). As "global chemical pollutants", NSAIDs may exert subtle yet enduring effects on both individual organisms and broader ecological processes (Patel et al. 2019).

Common NSAIDs, such as ibuprofen, diclofenac, naproxen, and ketoprofen, are among the most widely used medications globally. For example, the United States issues more than 100 million prescriptions for NSAIDs annually, with approximately 20% of its citizens using them on a frequent monthly basis at some point during their lives. The market for these drugs is large and continues to grow; the NSAIDs sector is expected to expand from USD 22.06 billion in 2024 to USD 35.93 billion by 2034. These medications are frequently employed for pain management, reducing inflammation, and treating fever, which contributes to their widespread presence in households worldwide (Sohail et al. 2023, Bindu et al. 2020). According to the World Health Organization's Model List of Essential Medicines, NSAIDs account for approximately 5%–10% of annual medication prescriptions, with an estimated 30 million people using these drugs daily. In the USA, more than 111 million NSAID prescriptions are dispensed each year, representing roughly 60% of the country's over-the-counter analgesic market. However, despite prescribed dosage guidelines, studies have shown that 15% of adult NSAID users

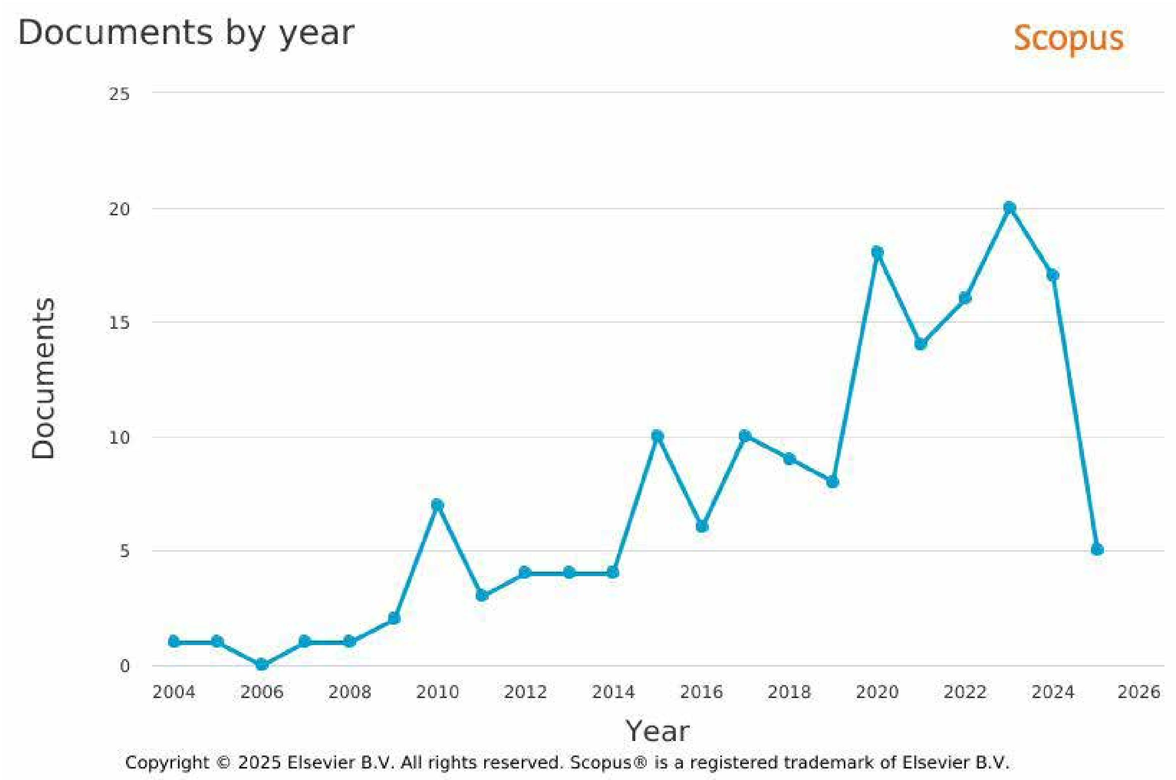


Fig. 1. Number of publications about NSAIDs polllution in waters according to SCOPUS (prepared for the day 13.05.2025, based on words: NSAIDs AND pollution AND water; article number for 2025 is low because of it's still duration during creation of the publication).

in the United States exceed the recommended daily dose. Additionally, a retrospective study of 3,050 individuals with chronic pain revealed that 97% of participants used NSAIDs for more than 21 consecutive days (Montuori et al. 2024).

The growing global population and increasing life expectancy are contributing to the rising demand for pharmaceuticals, including NSAIDs. Projections suggest a continued increase in NSAID consumption, particularly in developing regions where healthcare access is improving rapidly. Research interest in the topic is also expanding, as reflected by the steadily increasing number of related scientific publications (Fig 1 and 2). Despite the widespread presence

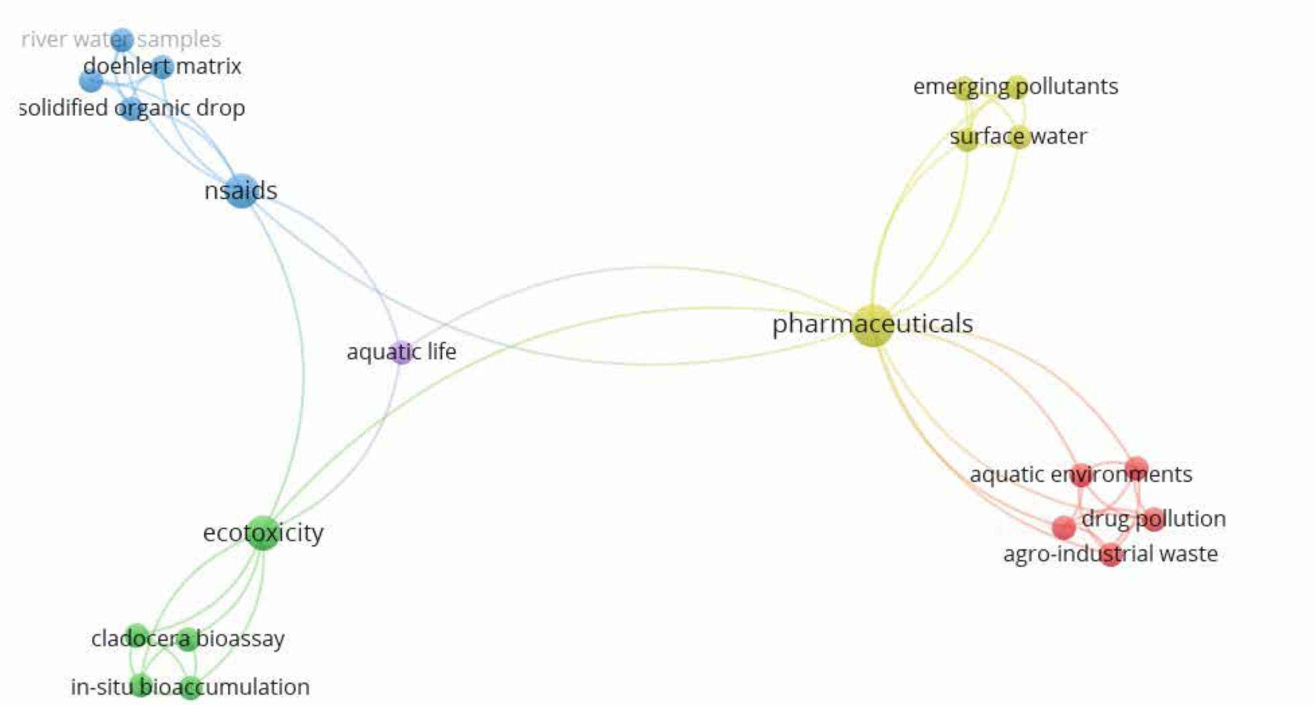


Fig. 2. Network map generated from keywords of articles searched in SCOPUS based on words: NSAIDs AND pollution AND water; map was prepared in VOSviewer software.

of NSAIDs in the environment, these substances remain insufficiently regulated with respect to water protection. Many countries lack comprehensive standards and monitoring protocols for detecting NSAID concentrations in aquatic environments (Leverett et al. 2021).

Given these concerns, a detailed investigation into NSAID contamination in aquatic ecosystems is crucial. This review aims to critically assess the sources and pathways through which NSAIDs enter water systems, their concentrations in aquatic environments, their biological and ecological effects, and the associated environmental risks. Additionally, potential strategies to mitigate NSAID pollution and improve water quality management are discussed.

Sources and dynamics of NSAIDs introduction into the aquatic environment

Sources of NSAIDs emissions

NSAIDs can enter the environment through various pathways, each contributing to their persistence and potential ecological impact on aquatic ecosystems:

- *Sewage and hospital wastewater treatment plants:* NSAIDs are commonly detected in municipal and hospital wastewater due to their extensive use in human medicine. Concentrations in wastewater vary significantly across different countries, with influent levels ranging from 3.99–27.1 μg/L and effluent levels from 1.21–7.94 μg/L (Mussa et al. 2022). Studies have shown that conventional wastewater treatment plants (WWTPs) are not fully effective in removing NSAIDs, with removal efficiencies varying widely depending on the compound and treatment method. For example, diclofenac removal efficiency in traditional treatment systems is approximately 50%, while other NSAIDs, such as ibuprofen and naproxen, may exhibit higher removal rates under specific conditions. However, their transformation products can still pose environmental risks. Advanced oxidation processes and membrane bioreactors show better removal efficiencies but are not universally implemented (Tran et al. 2023).
- *Leachate from solid waste landfills:* NSAIDs disposed of in landfills can leach into surrounding soil and groundwater, exacerbating contamination. Diclofenac, naproxen, and ibuprofen have been detected in landfill leachates at concentrations ranging from 0.2 to 1.5 μg/L (Tao et al. 2021). The mobility of NSAIDs in leachates depends on landfill conditions such as pH, organic matter content, and redox potential, which affect their environmental fate.
- *Direct industrial discharge:* Pharmaceutical manufacturing facilities may release NSAIDs directly into water bodies, further contributing to contamination. Studies have documented NSAID concentrations in pharmaceutical industry effluents reaching several μg/L, with diclofenac being particularly prevalent (Rastogi et al. 2021). In regions with inadequate wastewater treatment infrastructure, direct industrial discharges can serve as major point source of pollution, leading to localized ecological damage and increased bioavailability of these compounds in aquatic systems.
- *Household excretion:* A significant proportion of NSAIDs consumed by humans is excreted unchanged or as metabolites into municipal sewage systems. The extent of metabolism varies: 10–70% of ingested NSAIDs are metabolized, while the remaining portion is excreted unchanged. Wastewater treatment processes often fail to fully degrade these pharmaceuticals, resulting in their continuous release into the environment. A study by Khan et al. (2022) found that household wastewater can contribute up to 80% of NSAID pollution in urban water systems.
- *Agricultural runoff:* NSAIDs used in veterinary medicine and animal husbandry enter the environment through manure and slurry applied to agricultural fields. These compounds subsequently leach into groundwater or are transported via surface runoff into nearby water bodies (Placova et al. 2023). NSAIDs such as flunixin, ketoprofen, and diclofenac have been detected in agricultural runoff at concentrations ranging from 0.05 to 2.5 μg/L, with seasonal variations affecting their dispersion. The accumulation of NSAIDs in agricultural soils poses potential risks to soil microbiota and may affect plant uptake, potentially influencing crop quality and food safety.

NSAIDs – properties, mechanisms of accumulation and transport

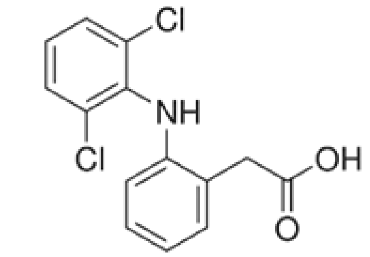
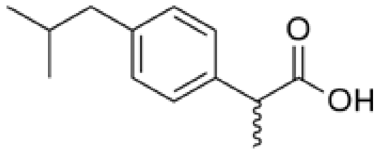
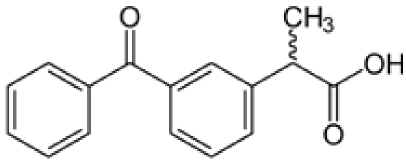
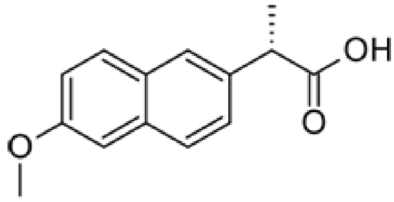
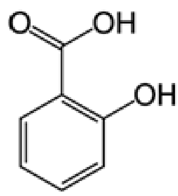
NSAIDs are generally classified into several groups based on their chemical structure and selectivity. These include acetylated salicylates (e.g., aspirin), non-acetylated salicylates (e.g., diflunisal, salsalate), propionic acids (e.g., naproxen, ibuprofen), acetic acids (e.g., diclofenac, indomethacin), enolic acids (e.g., meloxicam, piroxicam), anthranilic acids (e.g., meclofenamate, mefenamic acid), naphthylalanine (e.g., nabumetone), and selective COX-2 inhibitors (e.g., celecoxib, etoricoxib) (Ghlichloo and Gerriets 2025). Table 1 presents the properties of the most commonly used NSAIDs.

The accumulation of NSAIDs in aquatic environments can be understood through phase partitioning. In the water phase, NSAIDs are primarily polar compounds with high solubility, allowing them to remain dissolved and be transported over long distances in rivers and streams. Their physicochemical properties significantly influence their transport and accumulation. Hydrophilic NSAIDs, such as ibuprofen, tend to remain dissolved in the water phase, whereas hydrophobic NSAIDs, like diclofenac, have a greater tendency to adsorb to sediments. Despite their solubility, NSAIDs can still associate with organic matter in sediments and soils, especially in areas with high organic carbon content. The hydrophobicity of certain NSAIDs, such as diclofenac, further promotes their accumulation in sediments, creating localized contamination hotspots (Pires et al. 2024).

The persistence of NSAIDs in aquatic environments is largely due to their chemical structure, which includes aromatic rings and polar functional groups. Furthermore, their continuous introduction into surface waters compensates for their slow degradation, maintaining their presence in the environment (Świacka et al. 2021). As a result, NSAIDs can persist in both surface water and sediments for extended periods. Degradation processes such as photodegradation and biodegradation are often slow, particularly in deep water bodies with limited light penetration (Świacka et al. 2021).

Environmental factors significantly influence the transport and accumulation of NSAIDs . Higher temperatures can

Table 1. The most commonly used NSAIDS by people and their properties. Sources: Petrović et al. 2014, Y.-C. Lin et al. 2015, Wang et al. 2015, Yan et al. 2015, Lv et al. 2014, Aristizabal-Ciro et al. 2017, Paíga et al. 2016, You et al. 2015, Gumbi et al. 2017, Lindim et al. 2016, Subedi et al. 2015, Tran et al. 2014, Vaudreuil et al. 2024, Cerón-Vivas and Peñuela Mesa 2024, Oliveira et al. 2024, Trianda et al. 2024).

Pharmaceutical	Formula	Molar mass	Density	Solubility in water (20 °C)	Structure
Diclofenac	$C_{14}H_{11}Cl_2NO_2$	296.15 g·mol^{-1}	1.43 g/cm³	33 mg/l	
Ibuprofen	$C_{13}H_{18}O_2$	206.285 g·mol^{-1}	1.03 g/cm³	21 mg/l	
Ketoprofen	$C_{16}H_{14}O_3$	254.285 g·mol^{-1}	1.2 g/cm³	51 mg/l	
Naproxen	$C_{14}H_{14}O_3$	230.263 g·mol^{-1}	1.2 g/cm³	15.9 mg/l	
Salicylic acid	$C_7H_6O_3$	138.122 g·mol^{-1}	1.443 g/cm³	2.48 g/L	

enhance both photolytic and microbial degradation rates, accelerating the NSAID breakdown. For example, the stability of ibuprofen is temperature-dependent: a 10°C increase (from 20°C to 30°C) more than doubles the chemical degradation rate (20°C: $k \approx 3.16 \times 10^{-5}$ min^{-1} ; 30°C: $k \approx 8.36 \times 10^{-5}$ min^{-1}).

Organic matter plays a key role in adsorption processes. Elevated NSAID concentrations are frequently observed near WWTP discharge points, agricultural runoff sites, and pharmaceutical manufacturing facilities (Mussa et al. 2022). High river flow rates can disperse NSAIDs over larger areas, reducing localized accumulation, whereas the presence of organic carbon in sediments or suspended particles facilitates NSAIDs adsorption.

Due to their high solubility and persistence, NSAIDs can be transported over hundreds of kilometers from their original sources. They can also infiltrate groundwater systems when leaching from agricultural soils or landfills, posing risks to drinking water supplies (Mussa et al. 2022).

NSAIDs are readily absorbed by aquatic organisms, including algae, invertebrates, and fish. Even at low environmental concentrations, bioaccumulation can occur over time. In predatory organisms, indirect accumulation may occur through the consumption of contaminated prey, leading to biomagnification within the food web (Placova et al. 2023).

Concentrations of NSAIDs in aquatic ecosystems

Global analysis of main NSAIDs concentrations in the aquatic environment

Studies conducted in various countries have confirmed the presence of a wide range of NSAIDs in aquatic environments, including ibuprofen, naproxen, diclofenac, ketoprofen, and salicylic acid (Rosińska 2022). Reported concentrations of NSAIDs in freshwater systems vary significantly by region, with levels ranging from 0.7 to 420 ng/L in Asia, 9 - 328 ng/L in South America, 1.83 - 23 ng/L in Europe, 4.88 - 5 ng/L in North America, 9.59 - 147 ng/L in Africa, and 11.2 - 80 ng/L in Australia (Placova et al. 2023). A comprehensive overview of NSAID compounds and their recorded concentrations in different freshwater bodies is presented in Table 2.

Highly industrialized countries, such as Germany and the United States, exhibit higher pharmaceutical consumption rates. However, these nations also implement advanced wastewater treatment technologies, which contribute to the reduction of NSAID concentrations in surface waters (Rosińska 2022). In contrast, the absence of stringent environmental regulations in some Asian and African countries is associated with elevated NSAID levels in aquatic ecosystems compared to regions with more rigorous environmental policies (Rosińska 2022). European Union directives, such as the Water Framework Directive, play a crucial role in monitoring and mitigating NSAID pollution in water bodies.

Seasonal variations also influence NSAID concentrations in freshwater systems. Elevated levels are often observed during winter and early spring, a trend attributed to reduced microbial degradation and lower wastewater treatment efficiency at low temperatures. Such seasonal fluctuations have been documented in Nordic countries, where correlations between pollution levels, water temperature, and chlorophyll concentrations have been reported. Additionally, peak NSAID concentrations coincide with periods of heightened pharmaceutical consumption, such as the flu season (Rosińska 2022).

Hydrological conditions further modulate NSAID distribution in aquatic environments. High river flows, such as those occurring during floods, can dilute NSAID concentrations, whereas low-flow conditions, often associated with droughts, may lead to increased accumulation in surface waters. Precipitation events can also resuspend pharmaceuticals from sediments, contributing to their redistribution within water bodies. Moreover, prolonged water residence times during low-flow conditions can enhance NSAID retention in sediments, potentially affecting long-term environmental persistence (Rosińska 2022).

Europe

The presence of pharmaceuticals in European aquatic environments was first documented in the 1980s. Studies conducted in German municipal WWTPs and rivers confirmed the occurrence of various pharmaceutical compounds, including anti-inflammatory, psychotropic, antiepileptic drugs, lipid regulators, β-blockers, and β2-sympathomimetics, in both influent and effluent sewage as well as river water. Concentrations of ibuprofen in sewage entering and exiting German treatment plants were recorded at 3.5 mg/L and 0.3 mg/L, respectively. Additional studies detected diclofenac at concentrations of 2.1 mg/L in sewage and 1.2 mg/L in surface water. Furthermore, diclofenac was identified in the Elbe River at concentrations ranging from 20 to 140 mg/dm^3 (Rosińska 2022).

In the United Kingdom, diclofenac was detected in both sewage and surface waters downstream of sewage discharge sites. Subsequent studies confirmed the presence of NSAIDs, including diclofenac, ibuprofen, and mefenamic acid, in sewage samples. Analysis of water from the lower reaches of the Tyne, Tees, Mersey, Thames, and Belfast Lough identified dextropropoxyphene, diclofenac, ibuprofen, and mefenamic acid. Specifically, ibuprofen concentrations in surface water samples from the River Tyne ranged from 2.37 to 4 ng/L (Thomas and Hilton 2004).

A study conducted in 1998 (Buser et al. 1998) investigated the occurrence and fate of ibuprofen in surface water and sewage samples collected from lakes and rivers in Switzerland and the North Sea, as well as WWTPs in Gossau, Pfäffikon, and Uster. The concentration of ibuprofen in influent sewage was 3 mg/L, while levels in receiving surface waters (rivers and lakes) were found to be 8 ng/L (Rosińska 2022).

In Portugal, analyses of influent and effluent sewage confirmed the presence of pharmaceuticals, predominantly NSAIDs , with concentrations ranging from 0.050 to 100 mg/L in influent and up to 50 mg/L in effluent (Rosińska 2022).

Pharmaceuticals have also been detected in bottom sediments of aquatic ecosystems. Sediment samples from the Wickerbach stream in Frankfurt, Germany, contained diclofenac, fenoprofen, ibuprofen, 2-hydroxy ibuprofen, ketoprofen, and naproxen. Similar findings were reported in sediment samples from four major Iberian river basins (Llobregat, Ebro, Júcar, and Guadalquivir), where ibuprofen was among the most frequently detected compounds, with concentrations reaching 13 ng/g. In Hungary, ibuprofen, naproxen, ketoprofen, and diclofenac were detected in the Danube River, both in water and sediments. Sediment concentrations of naproxen and diclofenac ranged from 2-20 and 5-38 ng/g, respectively (Rosińska 2022).

Between 2016 and 2017, Poland conducted a national monitoring program to assess pharmaceutical contamination in surface waters. Samples were collected from 15 river monitoring stations, and all tested substances were detected above their respective quantification limits (Rosińska 2022). While these findings confirm the presence of pharmaceuticals in Polish surface waters, their concentrations remain below hazardous thresholds (e.g., EQS for the protection of human health calculated by the SCHEER committee for diclofenac is 3.5 μg/L). Diclofenac, widely used in pain relief and anti-inflammatory treatments, exhibited the highest concentrations among the detected substances (median value: 120 ng/L; range: 45 – 310 ng/L). Given the aging population and increased use of such medications, diclofenac concentrations in water may continue to rise. However, current levels remain below hazardous thresholds (Rosińska 2022).

Diclofenac has also been detected in the Baltic Sea, prompting an update to the initial environmental status assessment of Polish marine waters under the Marine Strategy Framework Directive (2008). As a result, diclofenac has been designated as an indicator of pollution in the Baltic Sea. Its presence has been confirmed in three marine basins: the Bornholm Basin, the Gdańsk Basin, and the Gotland Basin. However, the detected concentrations remain below regulatory threshold values, suggesting that diclofenac does not currently compromise the chemical or ecological status of the Baltic Sea (Rosińska 2022).

Asia

In the surface water of the Mankyung River in South Korea, the occurrence of pharmaceuticals was investigated. While some samples showed no detectable contaminants, most exhibited relatively high concentrations. The study identified the following NSAIDs: ibuprofen (n.d.–414 ng/L), mefenamic

Table 2. PNEC, MEC (maximum), and HQs of NSAIDs noted in different types of freshwater and different regions.

Compounds	Type of PNECs - according to NORMAN Substance Database – NORMAN SusDat	PNECs values - according to NORMAN Substance Database – NORMAN SusDat	Surface Water Source (Water type)	Continent	Country / location	MEC (ng/l)	Source of MEC	HQs - for Lowest PNEC Freshwater [µg/l]	HQs - for Lowest PNEC Sediments
Diclofenac	Lowest PNEC Freshwater [µg/l]	0.04	Ground water	Asia	Taiwan (Taipei and Hsinchu)	33.2	Lin et al. 2015	0.83	0.00
	Lowest PNEC Sediments [µg//kg dw]	11.4	Lake water	Asia	Vietnam (Hanoi)	0.31	Tran et al. 2014	0.01	0.00
			River water	Africa	South Africa (Kwa-Zulu Natal province - Umgeni River)	10200	Gumbi et al. 2017	255	0.89
				Asia	China (Chongqing)	1.5	Yan et al.., 2015	0.04	0.00
				Asia	China (Jiulong River basin and estuary in Southeast China)	58.4	Lv et al.., 2014	1.46	0.01
				Europe	Portugal (Lis river)	38	Paíga et al. 2016	0.95	0.00
				Europe	Sweden (Dal river)	3.6	Lidnim et al. 2016	0.09	0.00
			Surface water	Europe	Serbia (Novi Sad, Zrenjanin, Becej, Vrbas and Obrenovac)	324	Petrović et al. 2014	8.1	0.03
Ibuprofen	Lowest PNEC Freshwater [µg/l]	0.01	Ground water	Asia	Taiwan (Taipei and Hsinchu)	836.7	Lin et al. 2015	76.1	9
	Lowest PNEC Sediments [µg//kg dw]	0.09	Lake water	Asia	Vietnam (Hanoi)	0.58	Tran et al. 2014	0.05	0.01
				North America	United States of America (Skaneateles Lake, New York)	4.98	Subedi et al., 2015	0.45	0.05
			River water	Africa	South Africa (Kwa-Zulu Natal province - Umgeni River)	17600	Gumbi et al. 2017	1600	189
				Asia	China (Chongqing)	115.8	Yan et al.., 2015	10.5	1.25
				Asia	China (Jiulong River basin and estuary in Southeast China)	242	Lv et al. 2014	22	2.60
				Europe	Portugal (Lis river)	1317	Paíga et al. 2016	119.8	14.16

Compounds	Type of PNECs - according to NORMAN Substance Database – NORMAN SusDat	PNECs values - according to NORMAN Substance Database – NORMAN SusDat	Surface Water Source (Water type)	Continent	Country / location	MEC (ng/l)	Source of MEC	HQs - for Lowest PNEC Freshwater [µg/l]	HQs - for Lowest PNEC Sediments
				Europe	Sweden (Dal river)	2.2	Lidnim et al. 2016	0.2	0.02
				North America	Canada (St. Lawrence River)	860	Vaudreuil et al. 2024	78.2	9.25
				South America	Colombia (Oro River Sub-basin)	3260	Cerón-Vivas & Mesa 2024	296.4	35.05
			Reservoir	South America	Colombia - Reservoir (La Fe)	39	Aristizabal-Ciro et al. 2017	3.55	0.42
				South America	Colombia - Reservoir (Rio Grande)	62	Aristizabal-Ciro et al. 2017	5.64	0.67
			Surface water	Europe	Serbia (Novi Sad, Zrenjanin, Becej, Vrbas and Obrenovac)	346	Petrović et al. 2014	31.45	3.72
				Asia	Vietnam	39100	Trianda et al. 2024	3554	420
			Underground water	Europe	Serbia (Novi Sad, Zrenjanin, Becej, Vrbas and Obrenovac)	92	Petrović et al. 2014	8.36	0.99
Ketoprofen	Lowest PNEC Freshwater [µg/l]	2.1	Lake water	Asia	Vietnam (Hanoi)	0.45	Tran et al. 2014	0.00	0.00
	Lowest PNEC Sediments [µg//kg dw]	75.4	River water	Africa	South Africa (Kwa-Zulu Natal province - Umgeni River)	9220	Gumbi et al. 2017	4.39	0.12
				Asia	China (Jiulong River basin and estuary in Southeast China)	54.5	Lv et al. 2014	0.03	0.00
				Europe	Portugal (Lis river)	75.3	Paíga et al.., 2016	0.04	0.00
				Europe	Sweden (Dal river)	1.3	Lidnim et al. 2016	0.00	0.00
			Surface water	Europe	Serbia (Novi Sad, Zrenjanin, Becej, Vrbas and Obrenovac)	45	Petrović et al. 2014	0.02	0.00
Naproxen	Lowest PNEC Freshwater [µg/l]	1.7	Ground water	Asia	Taiwan (Taipei and Hsinchu)	128	Lin et al. 2015	0.08	0.00

Compounds	Type of PNECs - according to NORMAN Substance Database – NORMAN SusDat	PNECs values - according to NORMAN Substance Database – NORMAN SusDat	Surface Water Source (Water type)	Continent	Country / location	MEC (ng/l)	Source of MEC	HQs - for Lowest PNEC Freshwater [µg/l]	HQs - for Lowest PNEC Sediments
	Lowest PNEC Sediments [µg//kg dw]	49.3	Lake water	Asia	Vietnam (Hanoi)	0.45	Tran et al. 2014	0.00	0.00
			River water	Africa	South Africa (Kwa-Zulu Natal province - Umgeni River)	59300	Gumbi et al. 2017	34.9	1.2
				Asia	China (Beijing, Changzhou, Shenzen)	3.5	Wang et al. 2015	0.00	0.00
				Asia	China (Jiulong River basin and estuary in Southeast China)	10.8	Lv et al. 2014	0.01	0.00
				Asia	Singapore (River water)	10.85	You et al. 2015	0.01	0.00
				Europe	Portugal (Lis river)	260	Paíga et al. 2016	0.15	0.01
				Europe	Sweden (Dal river)	0.22	Lidnim et al. 2016	0.00	0.00
				South America	Brazil (Monjolinho River Basin)	224.7	Oliveira et al. 2024	0.13	0.00
			Surface water	Europe	Serbia (Novi Sad, Zrenjanin, Becej, Vrbas and Obrenovac)	74.2	Petrović et al. 2014	0.04	0.00
			Underground water	Europe	Serbia (Novi Sad, Zrenjanin, Becej, Vrbas and Obrenovac)	27.6	Petrović et al. 2014	0.02	0.00
Salicylic acid	Lowest PNEC Freshwater [µg/l]	18	River water	Europe	Portugal (Lis river)	294	Paíga et al. 2016	0.02	0.00
	Lowest PNEC Sediments [µg//kg dw]	62		Asia	Singapore (River water)	112	You et al. 2015	0.01	0.00
				Europe	Sweden (Dal river)	0.00	Lidnim et al. 2016	0.00	0.00
			Surface water	Europe	Serbia (Novi Sad, Zrenjanin, Becej, Vrbas and Obrenovac)	2.7	Petrović et al. 2014	0.00	0.00
			Underground water	Europe	Serbia (Novi Sad, Zrenjanin, Becej, Vrbas and Obrenovac)	2.5	Petrović et al. 2014	0.00	0.00

acid (n.d.–326 ng/L), and indomethacin (n.d.–33.5 ng/L). Similarly, Kim et al. (2007) analyzed the presence of 22 pharmaceuticals in three major rivers receiving treated sewage in South Korea. Pharmaceutical contaminants were detected at all sampling locations, both in the upper and lower reaches of the rivers.

Sim et al. (2011) examined the occurrence of pharmaceuticals in sewage discharged near major river basins in Korea. NSAIDs, caffeine, and carbamazepine were the predominant compounds, with their distribution varying depending on sampling locations and periods.

Lin et al. (2005) investigated the presence of ibuprofen, naproxen, ketoprofen, and diclofenac in groundwater, tap water, and river water from the Fu-Hsing River, as well as in sewage from WWTPs in China. None of the tested compounds were detected in tap water or groundwater. However, naproxen was found in river water at a concentration of 30 ng/L. Ibuprofen and naproxen were identified in sewage samples, with concentrations of 30 ng/L and 170 ng/L, respectively.

Water quality studies conducted in the Pearl River Delta in Guangzhou, southern China, detected salicylic acid and ibuprofen, with maximum concentrations of 2.1 ng/L and 1.42 ng/L, respectively. Further research on pharmaceutical contamination in Lake Taihu, China, revealed the presence of ibuprofen and diclofenac in both water and sediment samples, with concentrations ranging from 0.78 to 118 ng/L (Xie et al. 2015).

In northern Taiwan, Fang et al. (2012) detected four pharmaceuticals in sewage and seawater samples collected near sewage discharge areas. The concentrations of ibuprofen ranged from 2.2 to 724 ng/L.

In Pakistan, studies documented a catastrophic decline in the vulture population, partly attributed to dietary exposure to diclofenac-treated domestic animals. The concentration of diclofenac in the kidneys of affected vultures ranged from 0.05 to 0.64 mg/g (Oaks et al. 2004).

North America

In a comparative study conducted by the Minnesota Pollution Control Agency on the occurrence of pharmaceuticals in US lakes, a broad spectrum of drugs was detected, with concentrations ranging from 5 to 510 ng/L. Furthermore, literature data confirmed the presence of NSAIDs in the bottom sediments of the US aquatic ecosystems, such as Mississippi, Sauk, South Fork of the Crow, and Grindstone Rivers, as well as in Okabena Stream, and Lakes Pepin, Superior, and Shagawa in Minnesota.

In surface and coastal water samples from Costa Rica, 34 pharmaceuticals were analyzed. Salicylic acid (maximum concentration = 274 μg/L; median concentration <11 μg/L) was one of the most frequently detected compounds, found in 41% of the samples. Higher concentrations were also observed for ibuprofen (37 μg/L) and ketoprofen (10 μg/L) (Rosińska 2022).

Other regions

In the regions of Australia and Oceania, Africa, and South America, there is a clear need for more detailed studies on the presence and concentrations of NSAIDs in surface waters to better understand the extent of contamination and potential ecological risks. The scarcity of comprehensive research in these areas hinders accurate assessment of the contamination levels. However, global studies indicate the widespread presence of pharmaceuticals in aquatic environments, underscoring the need for further investigations in these regions. In Australia, ibuprofen concentrations in rivers and canals range from 28 to 360 ng/L. In treated wastewater in South Africa, ibuprofen was detected at a concentration of 58.7 ng/L, highlighting the inefficiency of current wastewater treatment processes in fully removing this compound (Pashaei et al. 2022).

Impact of NSAIDs on aquatic organisms

Bacteria and microorganisms

NSAIDs significantly impact microbial communities (see Table 3), leading to alterations in biofilm structure, metabolic functions, composition, and formation. These changes can disrupt nutrient balances in surface waters, soils, and marine environments (Pinto et al. 2022). Additionally, NSAIDs may interfere with biogeochemical processes such as denitrification, potentially affecting nitrogen cycling (Cycoń et al. 2016). Their presence can also modify soil biochemical and microbial activities, potentially disturbing soil functionality (Cycoń et al. 2016). Farkas et al. (2023) demonstrated that microcosms treated with NSAIDs exhibited higher cell counts than controls, though microbial diversity decreased, indicating that NSAIDs in aquatic environments can alter microbial community composition.

Increasing NSAID concentrations may also influence bacterial resistance mechanisms by imposing selective pressure, thereby contributing to the spread of antimicrobial resistance (AMR). Notably, non-antibiotic emerging compounds, including NSAIDs, at environmentally relevant concentrations, have been linked to the acquisition and dissemination of antimicrobial resistance (Pinto et al. 2022). These findings underscore the need for comprehensive research on the environmental impacts of NSAIDs and other pharmaceuticals to better understand their role in microbial community dynamics and the spread of antimicrobial resistance.

Phytoplankton and zooplankton

A wide range of NSAIDs can affect the growth and physiology of both phytoplankton and zooplankton. Research has shown that unicellular cyanobacteria are generally less sensitive to NSAIDs compared to eukaryotic algae, with NSAIDs exerting weaker effects in natural assemblages dominated by cyanobacteria. However, NSAIDs can induce compositional changes in communities dominated by eukaryotic algae. Many NSAIDs also exhibit toxic effects on algae (Placova et al. 2023).

NSAIDs can also affect the physiology, growth, and fitness of phytoplankton consumers, such as zooplankton. As these pharmaceuticals accumulate in primary consumers, they can alter trophic interactions and potentially propagate effects up the food chain. Even at low concentrations (ng/L), NSAIDs can significantly impact aquatic organisms. Several compounds have been detected in various zooplankton species including arctic marine zooplankton (Sørensen et al. 2023). Similar to their impact on phytoplankton, the accumulation of NSAIDs in primary consumers such as zooplankton can induce oxidative stress, which propagates up the food chain and affects higher trophic levels such as fish and birds, thereby amplifying ecological disruption (Divya Lakshmi et al. 2024).

Table 3. The impact of NSAIDs on different groups of organisms.

Organism		Influence of NSAIDs	Reference
Bacteria and microorganisms		changes in the composition of microbial communities (higher cell count values, decreased diversity of microbial communities).	Farkas et al. 2023
		alterations in biofilm structure, metabolic function, composition and formation in consequence: alterations in the balance of nutrients in surface waters, soil and even in marine environments	Pinto et al. 2022
		possibility of disruption of biogeochemical processes (e.g. denitrification)	Cycoń et al. 2016
		alternation the biochemical and microbial activity of soil what may cause the disturbance in soil functioning	Cycoń et al. 2016
		acquisition and dissemination of antimicrobial resistance	Pinto et al. 2022
Phytoplankton		negative effect on growth and physiology	Bácsi et al. 2016
		compositional changes in eukaryotic algal dominated assemblages	Bácsi et al. 2017
Zooplankton		oxidative stress	Divya Lakshmi et al. 2024
	Daphnia magna	changes in activity of alkaline and acid phosphatases, lipase, peptidase, β-galactosidase, and glutathione-S-transferase	Michalaki and Grintzalis 2023
Aquatic invertebrates	*Gammarus pulex and Hyalella azteca*	formation of highly toxic diclofenac metabolites	Wojcieszyńska et al. 2022
	Bivalves	changes in redox balance, antioxidant mechanisms, metabolism, increase in oxidative stress	Pires et al. 2024
Fish	*Cirrhinus mrigala*	decrease in blood parameters: red blood cells (RBC), haemoglobin (Hb), mean corpuscular volume (MCV), and mean corpuscular haemoglobin (MCH)	Binukumari et al. 2016
	Cyprinus carpio	delayed hatching, developmental retardation, and deformations in gill lamellae	Sehonova et al. 2017
	Oncorhynchus mykiss	cytological damage to the liver, kidney, and gills	Chen et al. 2014
	Salmo trutta	tissue damage	Lonappan et al., 2016
	Danio rerio	severe developmental abnormalities, including shorter body length, reduced eye size, pericardial and body edema, liver and intestinal malformations, muscle degeneration, and altered gene expression linked to cardiovascular and nervous system defects	Chen et al. 2014
	Oryzias latipes	growth during the egg phase, decreased hatchability, and delayed hatching	Lonappan et al. 2016
	Tinca tinca	reduced glutathione peroxidase and catalase activities, potentially increasing oxidative stress	Stancova et al. 2017
Bird	*Phoenicopterus sp., Grus sp.*	kidney damage	Cuthbert et al. 2016
	Gyps bengalensis, Gyps indicus, and Gyps tenuirostris	visceral gout and death	Lonappan et al. 2016

Transgenerational studies on *Daphnia magna*, a key member of freshwater zooplankton, demonstrated that exposure to NSAIDs led to significant changes in various enzymes, including alkaline and acid phosphatases, lipase, peptidase, β-galactosidase, and glutathione-S-transferase, in the first generation, with these changes being further enhanced in the second generation. The third recovery generation did not exhibit these alterations (Michalaki and Grintzalis 2023).

Aquatic invertebrates

Information on the impacts of pharmaceuticals such as NSAIDs on aquatic invertebrates remains limited, in contrast to fish, which are among the most frequently contaminated organisms in aquatic environments. This knowledge gap is primarily due to structural differences that hinder the extrapolation of results (Pires et al. 2024).

Extensive research over many years has demonstrated the toxic effects of acetylsalicylic acid, diclofenac, ibuprofen, and naproxen on freshwater invertebrates. Studies have shown that in *Gammarus pulex* and *Hyalella azteca*, diclofenac undergoes transformation into various oxidation products and conjugates, including two rare forms: the diclofenac taurine conjugate and diclofenac methyl ester. In *H. azteca*, the conversion to the methyl ester derivative is catalyzed by an S-adenosylmethionine-dependent carboxylic acid methyltransferase. The estimated LC50 for diclofenac in *H. azteca* is 216 mg/L, while the LC50 for diclofenac methyl ester decreases significantly to 0.53 mg/L, indicating a 430-fold increase in acute toxicity for the methylated derivative compared to the parent compound. Given that O-methyltransferases are present in plants, bacteria, yeast, and humans, it is possible that this highly toxic diclofenac metabolite may also form in these organisms (Wojcieszyńska et al. 2022).

Several studies have also evaluated the impact of NSAIDs on bivalves, particularly mussels (Freitas et al. 2020)one of the most widely prescribed non-steroidal anti-inflammatory drug, is globally detected in environmental compartments. Due to its occurrence in freshwater and potential impact on aquatic organisms, it has been added to the watch list of chemicals in the EU Water Directive; consequently, research on the impact of DCF in model aquatic organisms has great regulatory implications towards ecosystem health. DCF is also detected in coastal waters at concentrations from ng/L to 1 µg/L, as well as in marine organisms, such as the mussel Mytilus. Increasing evidence indicates that environmental concentrations of DCF have multiple impacts in adult mussels. Moreover, in M. galloprovincialis, DCF has been shown to affect early embryo development. The developmental effects of DCF in mussels were further investigated. DFC (1 and 10 µg/L. These studies reported changes in redox balance, antioxidant mechanisms, and metabolism, as well as increased oxidative stress in mussels exposed to these contaminants. Such changes can impair the growth and reproduction of these species (Pires et al. 2024).

Fish

Several studies have demonstrated the toxic effects of NSAIDs at low concentrations in fish species, including *Cyprinus carpio, Salmo trutta fario, Oncorhynchus mykiss, Gasterosteus aculeatus*, and *Tinca tinca* (Wojcieszyńska et al. 2022). For instance, reductions in blood parameters such as red blood cells (RBC), hemoglobin (Hb), mean corpuscular volume (MCV), and mean corpuscular hemoglobin (MCH) were observed in *Cirrhinus mrigala* following both short- and long-term exposure to diclofenac (Wojcieszyńska et al. 2022).

Sehonova et al. (2017) reported significant impacts of subchronic naproxen exposure on the early developmental stages of common carp, including delayed hatching, developmental retardation, and gill lamellae deformities. Similar effects were observed with diclofenac, although at much lower concentrations, indicating a substantially higher risk. For example, a 21-day exposure to 1232 µg/L of naproxen resulted in a 25% mortality rate and notable histopathological changes in the kidneys of fish, whereas similar effects from diclofenac occurred at only 4.6 µg/L (Näslund et al. 2020).

Further studies demonstrated that exposure to 3.38 nM diclofenac over 28 days caused cytological damage to the liver, kidneys, and gills of *Oncorhynchus mykiss*. Even at environmentally relevant concentrations, diclofenac caused tissue damage in *Salmo trutta*. In zebrafish embryos (*Danio rerio*), a four-day exposure to diclofenac resulted in severe developmental abnormalities, including shorter body length, reduced eye size, pericardial and body edema, liver and intestinal malformations, muscle degeneration, and altered gene expression associated with cardiovascular and nervous system defects. Additionally, in *Oryzias latipes*, diclofenac exposure impaired growth during the egg phase, decreased hatchability, and delayed hatching.

Stancova et al. (2017) found that exposure to ibuprofen and diclofenac reduced glutathione peroxidase and catalase activities in *Tinca tinca*, potentially increasing oxidative stress. The combination of these pharmaceuticals induced oxidative stress even at environmentally relevant concentrations, triggering antioxidant enzyme production and alterations in gene transcription associated with detoxification pathways. These energy-intensive cellular processes can disrupt physiological functions, including reproduction, and lead to DNA damage and cellular changes. NSAIDs have also been linked to teratogenic effects in fish (Świacka et al. 2021).

Other vertebrates - indirect influence on non-aquatic organisms

A notable example of NSAID toxicity in non-target species is the nephrotoxic effects observed in birds. Flunixin has been documented to cause kidney damage in cranes and flamingos, while similar effects were observed in broiler chickens following diclofenac administration. Between 1990 and 2007, populations of three vulture species in South Asia (*Gyps bengalensis, Gyps indicus*, and *Gyps tenuirostris*) declined by up to 97% due to the veterinary use of diclofenac for cattle treatment. Carcasses of treated cattle became a food source for vultures, leading to widespread fatalities (Wojcieszyńska et al. 2022).

Diclofenac exposure causes renal damage in birds by interfering with normal uric acid excretion, resulting in crystallization on organ surface and within visceral organs. This leads to visceral gout and death, making diclofenac particularly hazardous not only to Asian vultures but also to other scavenging bird species worldwide. The severe ecological consequences highlight the urgent need for global regulatory measures to mitigate the risks posed by diclofenac and other NSAIDs to wildlife populations (Wojcieszyńska et al. 2022).

Ecological risk associated with NSAIDs in waters

Determination of ecological risk indicators

It is particularly striking that most studies on NSAID toxicity focus primarily on acute effects in non-target organisms, which are not always representative of real environmental scenarios. Although NSAIDs are generally perceived as safe by the public, research clearly demonstrates their adverse impact on biocenoses, even at environmentally relevant concentrations (Wojcieszyńska et al. 2022). This highlights the growing need for systematic monitoring and the determination of ecological risk indicators.

Environmental risk assessments typically follow the guidelines proposed in the EU draft framework for medicinal products intended for human use. These assessments involve calculating a risk quotient (RQ) by comparing the predicted environmental concentration (PEC) or measured environmental concentration (MEC) with the predicted no-effect concentration (PNEC) under worst-case scenario assumptions (Stuer-Lauridsen et al. 2000).

In a study conducted in 2000, the PEC/PNEC ratios exceeded one for ibuprofen and acetylsalicylic acid (Stuer-Lauridsen et al. 2000). For ibuprofen, both the PEC/PNEC ratio of 600 and the MEC/PNEC ratio of 1.9 indicated environmental risks, as both exceeded the threshold value of one. Diclofenac also presented a significant concern, with a PEC/PNEC-based RQ of 15; however, the MEC/PNEC ratio for diclofenac remained below one. These findings demonstrate that ibuprofen poses a particularly significant environmental hazard, being the only NSAID for which both PEC/PNEC and MEC/PNEC ratios exceed the critical threshold, indicating a probable environmental risk (Divya Lakshmi et al. 2024). The calculated RQ values of substances and recorded concentrations in various types of freshwater are presented in Table 2.

Zones of high ecological risk

Regions with high ecological risk include both developed and developing countries. In developed countries, elevated concentrations of NSAIDs have been detected in Europe (e.g., in the Rhine River in Germany and the Thames in the UK) and in North America. This is primarily due to intensive pharmaceutical use and high population density, which increase the likelihood of pharmaceutical residues entering water systems (Belov et al. 2022).In contrast, in developing countries, such as those in Africa, South Asia, and South America, the lack of effective sewage treatment systems often leads to significant exceedances of the predicted no-effect concentration (PNEC) for NSAIDs (Belov et al. 2022).

Various factors influence the levels of NSAID pollution in different regions. High concentrations are often found in urban areas, where pharmaceuticals are most widely used. However, these compounds can also be present in rural areas as a result of agricultural practices, particularly through the use of organic fertilizers (e.g., slurry), which can contain drug metabolites and contribute to water contamination (Belov et al. 2022).

Practical challenges facing mitigation

While numerous technological advances have been proposed to minimize NSAID residues in aquatic environments, their large-scale implementation faces several practical limitations. Conventional WWTPs are not specifically designed to remove pharmaceuticals, and advanced methods such as ozonation, activated carbon adsorption, or advanced oxidation processes require substantial financial investment and increased energy consumption (Marjanović et al., 2023). Moreover, treatment efficiency can vary depending on water chemistry, seasonal fluctuations in contaminant loads, and the presence of competing organic matter. From a regulatory perspective, the implementation of environmental quality standards for pharmaceuticals remains inconsistent across countries, and enforcement is often limited by gaps in monitoring capacity and analytical infrastructure.

Notably, some success stories demonstrate the feasibility of mitigation. For example, Switzerland introduced a nationwide program to upgrade WWTPs with advanced treatment technologies, leading to measurable reductions in pharmaceutical loads entering surface waters (Eggen et al., 2014). Similar pilot projects in Sweden and Germany also showed that targeted regulations, combined with technological upgrades, can effectively mitigate ecological risks, although scalability and cost remain significant barriers.

Future Risk Forecasts

The increase in global consumption of NSAIDs, particularly in developing countries, is expected to result in higher concentrations of these substances in surface waters. Concurrently, the aging population in developed countries leads to an increased use of anti-inflammatory drugs, placing additional strain on water systems.

Rising temperatures may accelerate the biodegradation of NSAIDs, but they could also contribute to reduced river water levels, which would concentrate pharmaceuticals in aquatic systems. Extreme weather events, such as floods, have the potential to mobilize NSAIDs from sediments back into surface waters, further exacerbating contamination.

The metabolites of NSAIDs and their degradation products are of increasing concern, as they may pose greater toxicity risk than the parent compounds. The lack of regulatory oversight for these substances further heightens their potential environmental impact (Ebele et al. 2017).

Conclusions

NSAIDs, although widely used in medicine for their therapeutic efficacy, pose a significant threat to aquatic ecosystems. Their presence in the environment is primarily due to incomplete removal during conventional sewage treatment processes and direct entry into surface waters from uncontrolled sources, such as sewage runoff or improper drug disposal (Mustafa et al. 2024, Patel et al. 2019).

The primary concern with NSAIDs is their toxicity to aquatic organisms, even at low concentrations. Studies indicate that substances such as diclofenac, ibuprofen, and naproxen cause a range of detrimental effects, including tissue deformation, impaired organ function, delayed development, and reduced survival rates in fish, invertebrates, and phytoplankton. Diclofenac, in particular, is noted for its high toxicity and its ability to induce kidney damage in fish at concentrations as low as a few micrograms per liter (Pires et al. 2024, Wojcieszyńska et al. 2022).

Furthermore, NSAIDs have the potential to bioaccumulate, intensifying their effects on higher trophic levels. In organisms such as fish and birds, histopathological changes and disturbances in oxidative metabolism have been observed, suggesting that these compounds trigger oxidative stress mechanisms. In South Asia, for instance, the veterinary use of diclofenac in has caused a dramatic decline in vulture populations, primarily due to acute renal failure (Wojcieszyńska et al. 2022).

This threat is further compounded by the lack of adequate regulations governing pharmaceutical emissions into the environment. Many countries still lack effective monitoring systems or technologies capable of efficiently removing these substances from water. Additionally, public awareness regarding the ecological consequences of improper drug disposal and overuse remain insufficient. Consequently, given the persistence and widespread occurrence of NSAIDs in various environmental compartments, effective monitoring and regulatory measures are essential to mitigate their ecological impact. Enhanced wastewater treatment technologies, stricter disposal regulations, and improved pharmaceutical stewardship are critical steps in reducing NSAID pollution and protecting aquatic ecosystems (Mustafa et al. 2024, Tran et al. 2023).

A critical but often underestimated issue is the mixture toxicity of NSAIDs co-occurring with other pharmaceuticals and pollutants in aquatic ecosystems. In natural waters, organisms are rarely exposed to a single compound; rather they encounter complex chemical cocktails that may include antibiotics, hormones, pesticides, and heavy metals (Backhaus and Faust, 2012). These mixtures can produce additive, synergistic, or antagonistic effects, significantly complicating risk assessment. For instance, studies have demonstrated that combinations of diclofenac and ibuprofen with antibiotics or endocrine-disrupting compounds amplify oxidative stress responses in fish and invertebrates, even at concentrations where individual compounds alone showed limited effects (Kidd et al., 2024).

This highlights the urgent need to adopt cumulative risk assessment approaches rather than compound-by-compound evaluations, as recommended by recent ecotoxicological frameworks. Without considering mixture effects, environmental risks posed by NSAIDs are likely underestimated, particularly in highly urbanized or industrialized catchments where multiple classes of contaminants co-occur.

In summary, the presence of NSAIDs in aquatic environments represents a critical ecological challenge that requires a comprehensive approach. This includes the implementation of advanced wastewater treatment technologies, regulatory reforms, and educational initiatives to raise public awareness. Only through the adoption of multifaceted measures can the negative impacts of these substances on aquatic ecosystems be mitigated, ensuring their protection for future generations.

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References

Backhaus, T., Faust, M. (2012). Predictive environmental risk assessment of chemical mixtures: a conceptual framework. *Environmental science & technology* 46, 5, 2564-2573. DOI:10.1021/es2034125.

Belov, V.S., N. V. Ivanova, A. I. Samarkin. (2022). On the Mechanisms of Pharmaceutical Pollution of the Environment Risk Reduction, in: *Industry 4.0: Fighting Climate Change in the Economy of the Future*, Zavyalova, E.B., Popkova, E.G. (Eds.). Cham: Springer International Publishing, pp. 119–28. DOI:10.1007/978-3-030-79496-5_10.

Bindu, S., Mazumder, S. ,Bandyopadhyay, U. (2020). Non-steroidal anti-inflammatory drugs (NSAIDs) and organ damage: A current perspective. *Biochemical Pharmacology* 180, 114147. DOI:10.1016/j.bcp.2020.114147.

Buser, H.-R., Müller, M.D., Theobald, N. (1998) Occurrence of the pharmaceutical drug clofibric acid and the herbicide mecoprop in various Swiss lakes and in the North sea. Environmental Science & Technology 32, 188-192. DOI:10.1021/es9705811.

Cycoń, M., Borymski, S. , Żołnierczyk, B., Piotrowska-Seget, Z. (2016). Variable Effects of Non-steroidal Anti-inflammatory Drugs (NSAIDs) on Selected Biochemical Processes Mediated by Soil Microorganisms. *Frontiers in Microbiology* 7, 1969. DOI:10.3389/fmicb.2016.01969.

Divya Lakshmi, S., Geetha, B.V., Vibha, M. (2024). From prescription to pollution: The ecological consequences of NSAIDs in aquatic ecosystems. *Toxicology Reports* 13, 101775. DOI:10.1016/j.toxrep.2024.101775.

Ebele, A.J., Abou-Elwafa Abdallah, M., Harrad, S. (2017). Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. *Emerging Contaminants* 3, 1, 1–16. DOI:10.1016/j.emcon.2016.12.004.

Eggen, R. I., Hollender, J., Joss, A., Schärer, M., & Stamm, C. (2014). Reducing the discharge of micropollutants in the aquatic environment: the benefits of upgrading wastewater treatment plants. Environmental Science & Technology 48, 14, 7683–7689. DOI:10.1021/es500907n

Fang, T.-H., Nan, F.-H., Chin, T.-S., Feng, H.-M. (2012). The occurrence and distribution of pharmaceutical compounds in the effluents of a major sewage treatment plant in Northern Taiwan and the receiving coastal waters. *Marine Pollution Bulletin* 64, 7, 1435–44. DOI:10.1016/j.marpolbul.2012.04.008.

Farkas, R., Mireisz, T., Toumi, M., Abbaszade, G., Sztráda, N., Tóth, E. (2023). The Impact of Anti-Inflammatory Drugs on the Prokaryotic Community Composition and Selected Bacterial Strains Based on Microcosm Experiments. *Microorganisms* 11, 6, 1447. DOI: 10.3390/microorganisms11061447.

Freitas, R., Silvestro, S., Coppola, F., Meucci, V., Battaglia, F., Intorre, L., Soares, A.M.V.M., Pretti, C., Faggio, C. (2020). Combined Effects of Salinity Changes and Salicylic Acid Exposure in Mytilus Galloprovincialis. *The Science of the Total Environment* 715,136804. DOI:10.1016/j.scitotenv.2020.136804.

Ghlichloo, I., Gerriets, I.V. (2025). Nonsteroidal Anti-Inflammatory Drugs (NSAIDs), in: *StatPearls*. Treasure Island (FL): StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK547742/.

Hejna, M., Kapuścińska, D. , Aksmann, A. (2022). Pharmaceuticals in the Aquatic Environment: A Review on Eco-Toxicology and the Remediation Potential of Algae. *International Journal of Environmental Research and Public Health* 19, 13, 7717. DOI:10.3390/ijerph19137717.

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

Kim, S.D., Cho, J., Kim, I.S. , Vanderford, B.J., Snyder, S.A. (2007). Occurrence and removal of pharmaceuticals and endocrine disruptors in South Korean surface, drinking, and waste waters. *Water Research* 41, 5, 1013–21. DOI:10.1016/j.watres.2006.06.034.

Leverett, D., Merrington, G., Crane, M., Ryan, J., Wilson, I. (2021). Environmental quality standards for diclofenac derived under the European Water Framework Directive: 1. Aquatic organisms. *Environmental Sciences Europe* 33, 1, 133. DOI:10.1186/s12302-021-00574-z.

Lin, W.-C., Chen, H.-C.,. Ding, W.-H. (2005). Determination of pharmaceutical residues in waters by solid-phase extraction and large-volume on-line derivatization with gas chromatography–mass spectrometry. *Journal of Chromatography A* 1065,2 , 279–85. DOI:10.1016/j.chroma.2004.12.081.

Ma, J., Cui, Y., Kuang, P., Ma, C., Zhang, M., Chen, Z., & Zhao, K. (2023). Study on the removal efficiency of antibiotics in coastal wetlands by Suaeda and Nelumbo nucifera. *Archives of Environmental Protection* 49(2), 59-65. DOI:10.24425/aep.2023.145897.

Marjanović, T., Bogunović, M., Tenodi, S., Vasić, V., Kerkez, D., Prodanović, J., & Ivančev-Tumbas, I. (2023). Advanced treatment of the municipal wastewater by lab-scale hybrid ultrafiltration. *Sustainability* 15, 12, 9519. DOI: 10.3390/su15129519

Michalaki, A., Grintzalis, K. (2023). Acute and Transgenerational Effects of Non-Steroidal Anti-Inflammatory Drugs on Daphnia Magna. *Toxics* 11, 4, 320. DOI:10.3390/toxics11040320.

Montuori, P., Zahra Shojaeian, S., Pennino, F., D'Angelo, D., Sorrentino, M., Di Sarno, S., Nubi, R., Nardo, A., Triassi, M. (2024). Consumer Awareness and Knowledge Regarding Use of Non-Steroidal Anti-Inflammatory Drugs (NSAIDs) in a Metropolitan Area. *Frontiers in Pharmacology* 15. DOI:10.3389/fphar.2024.1362632.

Mussa, Z.H., Fadhil Al-Qaim, F., Jawad, A.H., Scholz, M., Mundher Yaseen. Z. (2022). A Comprehensive Review for Removal of Non-Steroidal Anti-Inflammatory Drugs Attained from Wastewater Observations Using Carbon-Based Anodic Oxidation Process. *Toxics* 10, 10, 598. DOI: 10.3390/toxics10100598.

Mustafa, S.A., Jasim Al-Rudainy, A., Mohammad Salman, N. (2024). Effect of environmental pollutants on fish health: An overview. *Egyptian Journal of Aquatic Research* 50, 2, 225–33. DOI:10.1016/j.ejar.2024.02.006.

Näslund, J., Asker, N., Fick, J., Joakim Larsson, D.G., Norrgren, L. (2020). Naproxen Affects Multiple Organs in Fish but Is Still an Environmentally Better Alternative to Diclofenac. *Aquatic Toxicology (Amsterdam, Netherlands)* 227, 105583. DOI:10.1016/j.aquatox.2020.105583.

Oaks, J.L., Gilbert, M., Virani, M.Z., Watson, R.T., Meteyer, C.U., Rideout, B.A, Shivaprasad, H.L. et al. (2004). Diclofenac Residues as the Cause of Vulture Population Decline in Pakistan. *Nature* 427 (6975), 630–33. DOI:10.1038/nature02317.

Ossowicz-Rupniewska, P. E., Kucharska, E., Klebeko, J., Kopciuch, E., Bilska, K., & Janus, E. (2023). Effect of the type of amino acid on the biodegradation of ibuprofen derivatives. *Archives of Environmental Protection* 49(4). DOI:10.24425/aep.2023.148685.

Pashaei, R., Dzingelevičienė, R., Bradauskaitė, A., Lajevardipour, A., Mlynska-Szultka, M., Dzingelevičius, N., Raugelė, S. et al. (2022). Pharmaceutical and Microplastic Pollution before and during the COVID-19 Pandemic in Surface Water, Wastewater, and Groundwater. *Water* 14 (19), 3082. DOI:10.3390/w14193082.

Patel, M., Kumar, R., Kishor, K., Mlsna, T., Pittman, C.U., Mohan, D. (2019). Pharmaceuticals of Emerging Concern in Aquatic Systems: Chemistry, Occurrence, Effects, and Removal Methods. *Chemical Reviews* 119 (6), 3510–3673. DOI:10.1021/acs.chemrev.8b00299.

Pinto, I., Simões, M, Gomes, I.B. (2022). An Overview of the Impact of Pharmaceuticals on Aquatic Microbial Communities. *Antibiotics* 11 (12), 1700. DOI:10.3390/antibiotics11121700.

Pires, P., Pereira, A.M.P.T., Pena, A., Silva, L.J.G. (2024). Non-Steroidal Anti-Inflammatory Drugs in the Aquatic Environment and Bivalves: The State of the Art. *Toxics* 12 (6), 415. DOI:10.3390/toxics12060415.

Placova, K., Halfar, J., Brozova, K., Heviankova, S. (2023). Issues of Non-Steroidal Anti-Inflammatory Drugs in Aquatic Environments: A Review Study. *Engineering Proceedings* 57 (1), 13. DOI:10.3390/engproc2023057013.

Rastogi, A., Tiwari, M.K., Ghangrekar, M.M. (2021). A review on environmental occurrence, toxicity and microbial degradation of Non-Steroidal Anti-Inflammatory Drugs (NSAIDs). *Journal of Environmental Management* 300, 113694. DOI:10.1016/j.jenvman.2021.113694.

Rosińska, A. (2022). *Emerging pollutants wyzwaniem dla gospodarki wodno-ściekowej: monografia*. Częstochowa: Wydawnictwo Politechniki Częstochowskiej.

Sehonova, P., Plhalova, L., Blahova, J., Doubkova, V., Prokes, M., Tichy, F., Fiorino, E., Faggio, C., Svobodova, Z. (2017). Toxicity of Naproxen Sodium and Its Mixture with Tramadol Hydrochloride on Fish Early Life Stages. *Chemosphere* 188, 414–23. DOI:10.1016/j.chemosphere.2017.08.151.

Sim, W.-J., Lee, J.-W., Lee, E.-S., Shin, S.-K., Hwang, S.-R., Oh, J.-E. (2011). Occurrence and distribution of pharmaceuticals in wastewater from households, livestock farms, hospitals and pharmaceutical manufactures. *Chemosphere* 82 (2), 179–86. DOI:10.1016/j.chemosphere.2010.10.026.

Sohail, R., Mathew, M., Patel, K.K., Reddy, S.A., Haider, Z., Naria, M., Habib, A., Abdin, Z.U., Razzaq Chaudhry, W., Akbar, A. (2023). Effects of Non-steroidal Anti-inflammatory Drugs (NSAIDs) and Gastroprotective NSAIDs on the Gastrointestinal Tract: A Narrative Review. *Cureus* 15 (4), e37080. DOI:10.7759/cureus.37080.

Sørensen, L., Schaufelberger, S., Igartua, A., Størseth, T.R., Beathe Øverjordet, I. (2023). Non-target and suspect screening reveal complex pattern of contamination in Arctic marine zooplankton. *Science of The Total Environment* 864, 161056. DOI:10.1016/j.scitotenv.2022.161056.

Stancova, V., Plhalova, L., Blahova, J., Zivna, D., Bartoskova, M., Siroka, Z., Marsalek, P., Svobodova, Z. (2017). Effects of the pharmaceutical contaminants ibuprofen, diclofenac, and carbamazepine alone, and in combination, on oxidative stress parameters in early life stages of tench (Tinca tinca). *Veterinární medicína* 62 (2), 90–97. DOI:10.17221/125/2016-VETMED.

Stuer-Lauridsen, F., Birkved, M., Hansen, L.P., Lützhøft, H.C.,Halling-Sørensen, B. (2000). Environmental Risk Assessment of Human Pharmaceuticals in Denmark after Normal Therapeutic Use. *Chemosphere* 40 (7), 783–93. DOI:10.1016/s0045-6535(99)00453-1.

Subedi, B., Codru, N., Dziewulski, D.M., Wilson, L.R., Xue, J., Yun, S., Braun-Howland, E., Minihane, C., Kannan, K. (2015). A Pilot Study on the Assessment of Trace Organic Contaminants Including Pharmaceuticals and Personal Care Products from On-Site Wastewater Treatment Systems along Skaneateles Lake in New York State, USA. *Water Research* 72, 28–39. DOI:10.1016/j.watres.2014.10.049.

Świacka, K., Michnowska, A., Maculewicz, J., Caban, M., Smolarz, K. (2021). Toxic effects of NSAIDs in non-target species: A review from the perspective of the aquatic environment. *Environmental Pollution* 273, 115891. DOI:10.1016/j.envpol.2020.115891.

Thomas, K.V., Hilton, M.J. (2004). The occurrence of selected human pharmaceutical compounds in UK estuaries. *Marine Pollution Bulletin* 49 (5), 436–44. DOI:10.1016/j.marpolbul.2004.02.028.

Tran, N.H., Taro, U., Ta, T.T. (2014). A Preliminary Study on the Occurrence of Pharmaceutically Active Compounds in Hospital Wastewater and Surface Water in Hanoi, Vietnam. *CLEAN – Soil, Air, Water* 42 (3), 267–75. DOI:10.1002/clen.201300021.

Wojcieszyńska, D., Guzik, H., Guzik, U. (2022). Non-steroidal anti-inflammatory drugs in the era of the Covid-19 pandemic in the context of the human and the environment. *Science of The Total Environment* 834, 155317. DOI:10.1016/j.scitotenv.2022.155317.

Xie, Z., Lu, G., Liu, J., Yan, Z., Ma, B., Zhang, Z., Chen, W. (2015). Occurrence, bioaccumulation, and trophic magnification of pharmaceutically active compounds in Taihu Lake, China. *Chemosphere* 138, 140–47. DOI:10.1016/j.chemosphere.2015.05.086.

Ciche zagrożenie – ekologiczne zagrożenia NLPZ w ekosystemach wodnych

Streszczenie. Niesteroidowe leki przeciwzapalne (NLPZ), powszechnie stosowane ze względu na swoje właściwości przeciwbólowe i przeciwzapalne, są coraz częściej uznawane za nowe, coraz bardziej niebezpieczne zanieczyszczenia w środowiskach wodnych. Pomimo ich wartości terapeutycznej dla ludzi, ich trwałość, bioaktywność i powszechne stosowanie przyczyniają się do ciągłego przedostawania się do wód powierzchniowych poprzez ścieki i spływy rolnicze. Niniejsza praca przeglądowa zawiera kompleksową syntezę aktualnej wiedzy na temat występowania, dystrybucji i wpływu ekologicznego NLPZ na ekosystemy wodne. W pracy omawiane są główne źródła emisji, właściwości fizykochemiczne wpływające na transport i bioakumulację NLPZ oraz analizowane są globalne dane dotyczące stężeń kluczowych NLPZ w wodach słodkich. Szczególną uwagę zwrócono na ich wpływ na organizmy wodne, w tym bakterie, fitoplankton, zooplankton, bezkręgowce i kręgowce, z udokumentowanymi skutkami, takimi jak nieprawidłowości rozwojowe, zaburzenia fizjologiczne i stres oksydacyjny. W pracy zebrano również globalne dane na temat wartości PNEC, MEC i HQs w różnych typach wód słodkich. Na koniec omówiono implikacje obecnych trendów, prognozy przyszłych możliwych zagrożeń i sugerowane środki zaradcze: ulepszone technologie oczyszczania ścieków, środki regulacyjne i zwiększanie świadomości społecznej. NLPZ, często postrzegane jako łagodne leki, stanowią ciche, ale znaczące ryzyko ekologiczne wymagające pilnej interdyscyplinarnej uwagi.