Frontiers in Food, Drug and Natural Sciences (2025), Vol 2: 25-36
An international peer-reviewed online journal
Available online: fd-science.com

Review Article

Aquatic pharmaceuticals and seafood safety: a growing environmental concern

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ARTICLE INFO

Received: 28 January 2025
Received in revised: 12 February 2025
Accepted: 21 February 2025
Published online: 28 February 2025

ABSTRACT

The article delves into the repercussions of pharmaceuticals on the well-being of aquatic ecosystems and the seafood derived from them. The utilization of pharmaceuticals, notably antibiotics and hormones, in both animal agriculture and human healthcare, has resulted in the widespread presence of these substances in aquatic environments. This article explores the adverse effects of these drugs on aquatic organisms, particularly fish, and their potential to accumulate within the food chain, thereby posing a potential threat to human health. Moreover, the paper assesses the complexities associated with the regulation and surveillance of these substances within environmental contexts and offers recommendations for minimizing their environmental footprint. Ultimately, the article underscores the imperative for heightened awareness and proactive measures to confront the challenge of pharmaceutical contamination in aquatic environments and its implications for seafood safety.

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Keywords: Health; Pharmaceutical compounds; Seafood; Veterinary drugs residue.

1. Introduction

As our society grapples with the consequences of drug use, there is a growing concern regarding the impact of pharmaceuticals on our aquatic environment and the seafood we consume. A study conducted by Daughton and Ternes in 1999, revealed that many of the drugs we ingest are not fully metabolized by our bodies and are subsequently excreted into the environment through wastewater (Hosseiniet al., 2008). These pharmaceuticals can find their way into our waterways, where they can exert a wide range of effects on aquatic organisms.

Research has unequivocally demonstrated that even minute traces of pharmaceuticals in our water bodies can exert a significant impact on aquatic life. For instance, a study conducted by Kidd et al. in 2014 discovered that exposure to the antidepressant fluoxetine can diminish the feeding rate and reproductive success of freshwater snails. Other investigations have illuminated how pharmaceutical exposure can trigger alterations in behavior, growth, and development in fish and other aquatic organisms (Brooks *et al.*, 2005; Brooks *et al.*, 2016; Johnson & Jürgens, 2017). A concurrent issue of concern is the accumulation of drug residues within the tissues of fish and other seafood. A study carried out by Grabic *et al.* (2014) disclosed that fish inhabiting the Danube River harbored an array of pharmaceuticals, including antibiotics, antifungals, and antihistamines. Over time, these residues can accumulate, potentially posing a risk to human health for those who partake in seafood consumption.

The demand for healthier ready-to-eat meals has driven innovations in frying technologies. Alikhani Chamgordani *et al.* (2024) developed a dual-stage ultrasound-assisted frying system (UAFS) for potato chips, which effectively reduced oil absorption while maintaining desirable sensory qualities. Ultrasonic pre-treatment and frying processes created controlled pore structures in the chips, resulting in lower oil uptake and improved texture. These advancements align with the food industry's efforts to balance consumer health concerns with product quality (Alikhani Chamgordani *et al.*, 2024).

Moreover, there is apprehension surrounding the potential entry of drug residues into the human food chain. A study led by Huerta-Fontela et al. in 2012 uncovered that the consumption of seafood contaminated with fluoxetine can lead to the accumulation of the drug in human tissues.

Pharmaceutical waste infiltrating the sea emanates from diverse sources, encompassing medical facilities, households, aquaculture, and wastewater treatment plants, as elucidated by Fick and Lindberg in 2015. Medical establishments, including hospitals and clinics, represent significant sources of pharmaceutical waste, generating substantial quantities of unused or expired drugs, along with associated packaging materials and medical supplies, as highlighted by Kümmerer (2010). Household waste, comprising expired or unused drugs and personal care products, also contributes to the influx of pharmaceutical waste into aquatic environments, as indicated by research by Boxall et al. in 2012 (Boxall *et al.*, 2012). Additionally, pharmaceuticals employed in aquaculture, such as antibiotics and antiparasitics, can ultimately find their way into the sea, thus contaminating the water and jeopardizing marine life, as documented by Marques *et al.* (2018). Lastly, if wastewater treatment plants are not adequately equipped to eliminate these substances from the water, they can inadvertently discharge pharmaceutical waste into the sea, as demonstrated by Larsson et al. in 2007 (Larsson *et al.*, 2007; Beigi Keleshteri *et al.*, 2024).

In this comprehensive review paper, we embark on an exploration of the diverse pathways through which drugs infiltrate aquatic environments, their consequential impact on marine life, and the potential hazards associated with consuming seafood tainted by drug residues. Through this comprehensive examination, our objective is to heighten awareness of this crucial issue and catalyze further discourse and initiatives aimed at safeguarding our oceans and the integrity of the food we consume.

2. Environmental risks of drugs in water

Pharmaceuticals are designed with the noble intention of enhancing the health and well-being of both humans and animals. However, the unintended consequences of their use on the environment have become increasingly evident. When we consume pharmaceuticals, only a fraction of them is metabolized by our bodies, while the rest is excreted in urine and feces. Consequently, pharmaceuticals find their way into the environment through various pathways, including wastewater treatment plants, septic systems, and agricultural runoff. Indeed, pharmaceuticals have been detected in a range of environmental compartments, including water bodies, soil, and even the atmosphere (Boxall *et al.*, 2012). These findings have raised significant concerns regarding the potential risks posed by pharmaceuticals in water and their subsequent impact on both the environment and human health.

The presence of pharmaceuticals in water can manifest a multitude of adverse effects on aquatic organisms. Research has unveiled that exposure to pharmaceuticals in aquatic environments can induce a spectrum of deleterious consequences for fish, amphibians, and other aquatic life forms. For instance, antidepressants have been found to reduce the fear response in fish, rendering them more susceptible to predation (Brodin *et al.*, 2014). Hormonal drugs, such as birth control pills, have been implicated in the occurrence of reproductive abnormalities in fish and other aquatic species (Ortiz de García *et al.*, 2016). Antibiotics present in water bodies can contribute to the emergence of antibiotic-resistant bacteria, posing a potential threat to human health (Fick & Lindberg, 2015; Hosseini *et al.*, 2024).

Although ongoing research continues to elucidate the impact of pharmaceuticals in water on human health, potential risks have been identified. While the concentrations of pharmaceuticals typically found in most drinking water supplies are exceedingly low, there remains a concern regarding the long-term exposure to these substances at such low levels. For instance, exposure to endocrine-disrupting compounds can result in developmental, reproductive, and neurological effects in humans (LaKind *et al.*, 2019). Furthermore, exposure to antibiotics in water may foster the development of antibiotic-resistant bacteria, potentially complicating the treatment of bacterial infections in the future (WHO, 2018).

Efforts to address the issue of pharmaceuticals in water are indeed ongoing, albeit with progress that has been somewhat sluggish. One approach involves heightening public awareness of the issue, with campaigns aimed at promoting the responsible disposal of medications and reducing unnecessary prescription drug usage. Additionally, there have been concerted endeavors to enhance wastewater treatment processes to more effectively remove pharmaceutical residues from water systems (Richardson & Ternes, 2018).

The complexities surrounding the environmental risks posed by pharmaceuticals in water necessitate continual attention and action. While research into the impact of pharmaceuticals on the environment and human health is ongoing, there is compelling evidence that these substances can exert detrimental effects on aquatic organisms and potentially on human beings. Mitigating the negative impact of pharmaceuticals in water involves not only improving wastewater treatment processes but also fostering responsible medication disposal practices. Further research remains imperative to comprehensively grasp the repercussions of pharmaceuticals in water and to formulate effective strategies for mitigating their adverse effects (Hosseini *et al.*, 2023).

3. Permissible amount of drugs in the body of marine organisms and seafood

The presence of pharmaceuticals and personal care products (PPCPs) in the environment is a growing concern worldwide (Boxall *et al.*, 2012). These substances can enter aquatic ecosystems through various pathways, including wastewater discharge, agricultural runoff, and direct discharge from pharmaceutical manufacturing plants. Once in the environment, PPCPs can enter the food chain and accumulate in the tissues of aquatic organisms, including marine animals and seafood (Martínez-López *et al.*, 2018; Alizadeh Pir Alidehi *et al.*, 2023). As a result, there are

increasing concerns about the potential risks to human health from consuming seafood that contains these substances.

One of the major concerns associated with the presence of PPCPs in seafood is the potential for these substances to contribute to the development of antimicrobial resistance (AMR) in bacteria (Tello *et al.*, 2012; Cabello *et al.*, 2016). This is because many of the drugs that are used in human medicine and veterinary medicine are also used in aquaculture to treat and prevent bacterial infections in fish and other aquatic animals. As a result, the use of these drugs in aquaculture can lead to the emergence of antibiotic-resistant bacteria in the environment, which can then be transmitted to humans through the consumption of contaminated seafood (Richardson & Ternes, 2018).

To address this issue, regulatory agencies around the world have established guidelines for the permissible levels of drugs in the body of marine organisms and seafood. These guidelines are designed to ensure that the levels of these substances in seafood are safe for human consumption and do not pose a risk of AMR. However, the establishment of these guidelines is a complex process that involves consideration of a range of factors, including the pharmacokinetics of the drug in the organism, the potential for the drug to accumulate in the organism's tissues, and the potential for the drug to contribute to the development of AMR (Cabello *et al.*, 2016).

One example of a drug that is commonly used in aquaculture and has established guidelines for its permissible levels in seafood is oxytetracycline. Oxytetracycline is an antibiotic that is used to treat bacterial infections in fish and other aquatic animals. The European Union has established a maximum residue limit (MRL) of 100 µg kg^{-1} for oxytetracycline in fish and fish products intended for human consumption (EU, 2010). Similarly, the US Food and Drug Administration (FDA) has established a tolerance level of 0.1 ppm for oxytetracycline in the edible tissues of fish (Hosseini *et al.*, 2023; Jairoun *et al.*, 2025).

Another example of a drug that is commonly used in aquaculture and has established guidelines for its permissible levels in seafood is florfenicol. Florfenicol is an antibiotic that is used to treat bacterial infections in fish and shrimp. The EU has established an MRL of 100 µg kg^{-1} for florfenicol in fish and fish products intended for human consumption (Wess, 2021). The FDA has established a tolerance level of 1 ppm for florfenicol in the edible tissues of fish and shrimp (Noormohammadi *et al.*, 2023; Jairoun *et al.*, 2025).

In addition to antibiotics, other drugs are also used in aquaculture and have established guidelines for their permissible levels in seafood. For example, the EU has established an MRL of 100 µg/kg^{-1} for the antiparasitic drug emamectin benzoate in fish and fish products intended for human consumption (EU, 2010). The FDA has established a tolerance level of 0.1 ppm for emamectin benzoate in the edible tissues of fish (Hosseini *et al.*, 2023; Jairoun *et al.*, 2025).

4. Balancing act: Pharmaceuticals and personal care products in seafood and the threat of antimicrobial pesistance

The presence of PPCPs in the environment has emerged as a growing global concern (Boxall *et al.*, 2012). These substances can infiltrate aquatic ecosystems through various routes, including wastewater discharge, agricultural runoff, and direct release from pharmaceutical manufacturing facilities. Once introduced into the environment, PPCPs can permeate the food chain and accumulate in the tissues of aquatic organisms, including marine animals and seafood (Martínez-López *et al.*, 2018). Consequently, there is a mounting apprehension regarding the potential risks to human health associated with the consumption of seafood contaminated by these substances.

One of the primary apprehensions linked to the presence of PPCPs in seafood is their potential contribution to the development of antimicrobial resistance (AMR) in bacteria (Tello *et al.*, 2012; Cabello *et al.*, 2016). This concern arises because many of the drugs employed in human and veterinary medicine are also utilized in aquaculture to treat and prevent bacterial infections in fish and other aquatic creatures. Consequently, the use of these drugs in

aquaculture can foster the emergence of antibiotic-resistant bacteria within the environment. These resistant strains can subsequently be transmitted to humans through the consumption of contaminated seafood.

To tackle this issue, regulatory agencies across the globe have established guidelines governing the allowable levels of drugs in the bodies of marine organisms and seafood. These guidelines are formulated to ensure that the concentrations of these substances in seafood remain safe for human consumption and do not pose a risk of AMR. However, the development of these guidelines is a multifaceted process that necessitates consideration of a range of factors. These factors encompass the pharmacokinetics of the drug within the organism, the potential for the drug to accumulate in the tissues of the organism, and the likelihood of the drug contributing to the development of AMR (Wess, 2021).

A prominent example of a drug frequently employed in aquaculture, with established guidelines for permissible levels in seafood, is oxytetracycline. Oxytetracycline is an antibiotic used to combat bacterial infections in fish and other aquatic animals. The European Union has set a maximum residue limit (MRL) of 100 µg kg^{-1} for oxytetracycline in fish and fish products intended for human consumption (Wess, 2021).

Likewise, the U.S. Food and Drug Administration (FDA) has established a tolerance level of 0.1 ppm for oxytetracycline in the edible tissues of fish (Jairoun *et al.*, 2025).

Another illustration of a commonly used drug in aquaculture, accompanied by established guidelines for permissible levels in seafood, is florfenicol. Florfenicol is an antibiotic employed in the treatment of bacterial infections in fish and shrimp. The EU has defined an MRL of 100 µg/kg^{-1} for florfenicol in fish and fish products intended for human consumption (European, 2010). The FDA has stipulated a tolerance level of 1 ppm for florfenicol in the edible tissues of fish and shrimp (Jairoun *et al.*, 2025).

Apart from antibiotics, other drugs are also utilized in aquaculture and have established guidelines dictating their allowable levels in seafood. For instance, the EU has set an MRL of 100 µg/kg^{-1} for the antiparasitic drug emamectin benzoate in fish and fish products intended for human consumption (Wess, 2021). The FDA has established a tolerance level of 0.1 ppm for emamectin benzoate in the edible tissues of fish (Jairoun *et al.*, 2025).

5. Effects of drugs on marine organisms

Organisms commonly affected by the drugs used by humans encompass a spectrum of aquatic life, including fish, crustaceans, mollusks, and various other aquatic invertebrates. These organisms are susceptible to drug exposure through diverse pathways, including the discharge of wastewater from sewage treatment plants, runoff from agricultural activities, and accidental spills. Pharmaceutical waste has the potential to contaminate water bodies, including the vast expanses of the sea, thereby posing a significant threat to marine ecosystems. Many drugs and their metabolic byproducts elude removal by conventional wastewater treatment methods, persisting in aquatic environments, including the sea, for extended durations (Daughton, 2020). These substances can exert toxic effects on marine organisms, spanning from fish and shellfish to plankton, thereby disturbing the delicate equilibrium of the marine ecosystem (Fent *et al.*, 2006).

One illustrative instance of a drug capable of inflicting harm upon marine organisms is the anti-inflammatory drug diclofenac. A study unveiled that exposure to diclofenac induced developmental abnormalities in zebrafish, manifesting as behavioral alterations and diminished survival rates (Wang *et al.*, 2016). Similarly, another investigation reported that exposure to the antidepressant fluoxetine resulted in reduced feeding rates and modified behavior in marine snails (Basili, 2018).

The repercussions of drugs on marine organisms are intricate and can exhibit variability contingent upon several factors. These factors encompass the specific drug in question, the dosage and duration of exposure, as well as the unique characteristics of the organisms and their surrounding environment. Moreover, drugs can have broader ecological consequences, including the alteration of the behavior of aquatic

organisms, further complicating their ecological impacts. Numerous other drugs have also been identified as having detrimental effects on marine organisms, including:

5.1. Antibiotic resistance

Antibiotics that are found in extensive use in both human and veterinary medicine can infiltrate the marine environment via wastewater discharge, thereby potentially exerting detrimental effects on marine bacteria and other organisms. One study documented that exposure to the antibiotic tetracycline elicited alterations in the composition and diversity of marine bacterial communities (Zhang *et al.*, 2021).

Moreover, the improper disposal of unused or expired drugs can exacerbate the emergence of antibiotic-resistant bacteria in marine ecosystems. These antibiotic-resistant bacteria pose a considerable concern as they may then spread to other marine organisms and more critically, to humans who partake in seafood consumption. This scenario heightens the risk of antibiotic-resistant infections emerging, a concern previously emphasized by the European Commission in 2015 (Wess, 2021). This phenomenon underscores the urgency of addressing the issue of antibiotic contamination in marine environments and its potential ramifications for public health.

5.2 Hormonal contraceptives

Hormonal contraceptives, when discharged into the environment through wastewater, can induce endocrine-disrupting effects (EDCs) in aquatic organisms. A study demonstrated that exposure to the contraceptive hormone ethinylestradiol resulted in alterations in the reproductive behavior of male fish (Schwindt & Harrington, 2020). This highlights the potential ecological consequences of hormonal contraceptive contamination in aquatic ecosystems.

5.3. Antifungal drugs

Antifungal drugs, when introduced into the marine environment through wastewater discharge, can exert toxic effects on marine organisms. A study revealed that exposure to the antifungal drug fluconazole resulted in decreased survival and growth rates in marine mussels (Schultz *et al.*, 2020). This underscores the importance of understanding the impact of antifungal drug contamination on marine life.

5.4. Anti-cancer drugs

Anti-cancer drugs, when introduced into the environment through wastewater discharge, can have detrimental effects on marine organisms. A study demonstrated that exposure to the anti-cancer drug tamoxifen resulted in decreased survival and growth rates in marine mussels (Chen *et al.*, 2020). This highlights the need for greater awareness of the potential ecological impacts of such pharmaceutical contaminants in aquatic ecosystems (Kidd *et al.*, 2014).

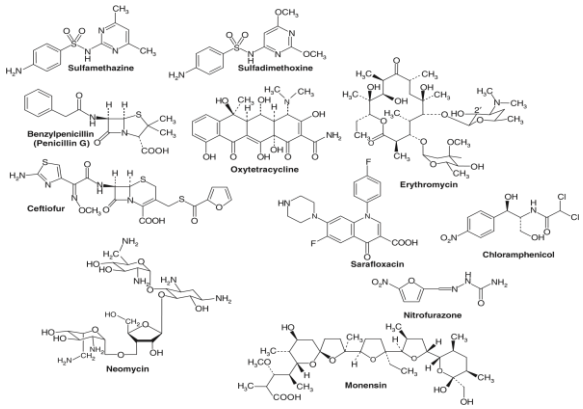

Figure 1.
Structures of antibiotics.

5.5 Bioaccumulation

Pharmaceuticals and their metabolites can accumulate within the tissues of marine organisms, a phenomenon known as bioaccumulation. This can lead to elevated concentrations of drugs and their breakdown products in specific species, and subsequently, these substances can progress through the food chain to higher trophic levels, ultimately affecting humans (Fick & Lindberg, 2015).

The effects of pharmaceuticals on marine organisms represent a complex and critical realm of research, especially given the escalating use of pharmaceuticals and their ever-expanding presence in the environment. It is imperative to gain a comprehensive understanding of the potential repercussions of these drugs on marine

Table 1.
Classification and monitoring of veterinary drugs in animal-based matrices.

Drug class	*Function*	*Examples of compounds*	*Typical matrices*	*Detection*	*Comments*
Benzimidazoles	Anthelmintics, growth efficiency	Albendazole, fenbendazole, oxfendazole, thiabendazole	Bovine and swine tissue, milk	LC-UV (290nm), LC-MS	May form sulfone metabolites
Avermectins and Milbemycins	Anthelmintics	Ivermectin, eprinomectin, doramectin, moxidectin	Milk, bovine, swine, and fish tissue	LC-fluorescence, LC-MS	Forms sodium adducts that are detected by LC-MS
Triphenylmethane dyes	Fungus and parasite infections	Malachite green, crystal violet, brilliant green	Fish, shrimp	LC-visible, LC-MS	Convert leuco metabolites to chromic form for detection, no tolerance
Tranquilizers	Reduce stress and aggression, pre-anesthetic transport aid	Acepromazine, azaperone, chlorpromazine, propionyl promazine, xylazine, carazolol	Tissue	LC-UV, LC-FLD, LC-MS	Multi-residue methods available
Anti-inflammatory	Reduce inflammation	Flunixin, phenylbutazone, ketoprofen	Milk, bovine tissue (kidney)	LC-UV, LC-MS	5-Hydroxyflunixin is a flunixin metabolite

organisms and ecosystems. This knowledge is crucial for the development of effective management strategies aimed at safeguarding aquatic environments and the myriads of organisms' dependent upon them.

6. The methodology used for analysis is influenced by the physical and chemical characteristics

To detect trace amounts of an analyte in complex matrices, residue methods must possess the capability to isolate and identify extremely small concentrations, often in parts per billion or even less. When determining the best techniques for extraction, isolation, and detection at these residue levels, careful consideration must be given to the physical and chemical properties of both the drug(s) under investigation and the accompanying matrix. Various molecular properties, such as polarity, charge state, size, volatility, thermal stability, and the presence or absence of a chromophore, can significantly influence the analytical approach for a given compound (Table 1).

For instance, the polarity and charge state of the analyte are crucial factors in designing an efficient extraction and isolation scheme. Techniques like liquid-liquid extraction with pH adjustment and the use of solid-phase extraction (SPE) cartridges, including reversed-phase, ion-exchange, or mixed-mode varieties, can facilitate the transfer of the analyte between polar and non-polar solvents and remove impurities such as salts and lipids. Gel permeation chromatography can also be employed for sample clean-up based on analyte size. The work of Fedeniuk & Shand (1998) offers an extensive exploration of the relationship between the chemical properties of veterinary drugs and the required strategies for their extraction and isolation.

To achieve further isolation of an analyte, chromatographic separation is often employed.

Gas chromatography (GC) is notably effective for The choice of the optimal LC stationary phase (e.g., C18, C8, phenyl) and mobile phase components (buffer, organic modifier) depends on various factors, including the pKa of any ionizable groups and the presence of other functional moieties like a phenyl ring. When detecting any compound, the physical and chemical properties of the molecule must be considered. Different detectors, such as nitrogen- and sulfur-specific detectors for GC or electron capture detectors (ECD) for volatile analytes containing electrophilic functional groups, can be used to selectively detect certain compounds. Traditional LC systems typically employ UV, visible, or fluorescence detectors that leverage unique chromophores present in the analyte or introduced through derivatization.

The aquaculture industry, which involves the farming of fish, has witnessed rapid growth. In the United States, nearly 80% of seafood, encompassing fish and shellfish, is imported from other countries. In 2004, over 2 billion euros of harvested seafood were imported into the country, with approximately 40% of it being produced through aquaculture (Knapp & Rubino, 2016). As the industry has expanded, the utilization of antibiotics and antifungal drugs has risen in aquaculture facilities. Due to the high-density environment in which fish are raised, they may experience heightened stress and possess weakened immune systems, rendering them more susceptible to disease outbreaks. Consequently, the use of veterinary drugs becomes necessary. The quality and efficiency of freezing processes for agricultural products remain critical in preserving their functional attributes. Recent advancements in ultrasound-assisted freezing methods have demonstrated significant improvements. Farshbaf Aghajani *et al.* (2023) explored the application of probe-type ultrasonication combined with immersion freezing for button mushrooms, achieving reduced freezing times and enhanced quality by optimizing parameters such as power intensity and ultrasonication mode. These findings underscore the potential of ultrasound technologies in the food preservation industry to enhance product quality and reduce energy consumption (Farshbaf Aghajani *et al.*, 2023).

7. Regulation of pharmaceutical waste in the sea

The regulation of pharmaceutical waste in the sea varies from country to country and region to region. For instance, in the European Union, the European Medicines Agency (EMA) has issued guidelines for the disposal of pharmaceuticals. Simultaneously, the Water Framework Directive regulates the quality of water bodies, including the sea, and sets limits for the concentration of certain substances, including pharmaceuticals (European Medicines, 2017; Carvalho *et al.*, 2019). In the United States, the Environmental Protection Agency (EPA) is responsible for regulating the disposal of pharmaceutical waste under the Resource Conservation and Recovery Act (RCRA), and the Clean Water Act oversees the quality of water bodies (Mueller & Gasteyer, 2021).

Mitigating the impact of pharmaceutical waste on the sea necessitates a comprehensive approach that encompasses reducing waste generation, improving waste management practices, and promoting sustainable production and consumption of pharmaceuticals. Several strategies can be implemented to achieve this:

1. Source Reduction: One of the most effective ways to mitigate the impact of pharmaceutical waste on the sea is to reduce its generation at the source. This can be achieved through initiatives like reducing the over-prescription of drugs, advocating for the use of non-pharmaceutical alternatives, and implementing drug take-back programs to encourage the safe disposal of unused or expired drugs (Fatta-Kassinos *et al.*, 2011).

2. Improved Waste Management Practices: Enhancing waste management practices, including proper storage, collection, and disposal of pharmaceutical waste, is another crucial strategy. This entails implementing best practices for medical facilities, households, and wastewater treatment plants. It also involves promoting the adoption of technologies that can remove pharmaceuticals from wastewater, such as advanced oxidation processes and membrane filtration (Kümmerer, 2010).

3. Sustainable Production and Consumption: Promoting the sustainable production and consumption of pharmaceuticals is a key strategy for mitigating the impact of pharmaceutical waste on the sea. This can involve initiatives such as reducing the use of antibiotics in aquaculture, encouraging the development of eco-friendly pharmaceuticals, and educating consumers about choosing eco-friendly products (Kosoff *et al.*, 2009). By adopting these strategies and implementing robust regulations and guidelines, countries and regions can work toward reducing the environmental impact of pharmaceutical waste in the sea and safeguarding marine ecosystems.

Spirulina (*Arthrospira platensis*) cultivation relies heavily on cost-intensive culture media. Masoumi Varaki *et al.* (2023) proposed innovative modifications to the Zarrouk medium, significantly reducing costs while maintaining or enhancing biomass yield. Their study demonstrated the feasibility of using animal husbandry-based components and modified lighting methods to achieve comparable results to traditional media at a fraction of the cost. These findings hold promise for sustainable and economically viable large-scale Spirulina production.

8. The impact of climate change on pharmaceutical pollution

Climate change is poised to exert a substantial impact on the aquatic environment, heralding alterations in water temperature and precipitation patterns. These transformations could significantly influence the transport and fate of pharmaceuticals in the environment, potentially exacerbating their repercussions on marine organisms. This section will delve into the potential ramifications of climate change on pharmaceutical pollution and proffer strategies for alleviating these effects.

The effects of climate change on pharmaceutical pollution in the aquatic environment have garnered attention from researchers. Studies have indicated that shifts in water temperature and precipitation patterns may modify the behavior of pharmaceuticals in the environment, potentially amplifying their influence on marine organisms and human health (Boxall *et al.*, 2012; Noyes *et al.*, 2009). For instance, elevated water temperatures can expedite the biotransformation of specific pharmaceuticals, resulting in heightened toxicity (Fent *et al.*, 2006). Concurrently, alterations in precipitation patterns can perturb water flow, conceivably augmenting the concentration of pharmaceuticals in specific regions (Kümmerer, 2010). Moreover, there is evidence to suggest that climate change might perturb the rate at which pharmaceuticals are metabolized within the human body, possibly increasing the volume of pharmaceuticals excreted into the environment (Noyes *et al.*, 2009). These dynamics underscore the imperative for intensified efforts to regulate pharmaceutical waste disposal and curtail pharmaceutical usage in the context of a changing climate (Hill & Whitehouse, 2016).

Various strategies have been postulated to mitigate the repercussions of pharmaceutical pollution in the face of climate change. These encompass advancements in wastewater treatment technologies, curbing pharmaceutical utilization, and formulating alternative approaches for treating human and animal ailments that do not hinge on traditional pharmaceuticals (Lahti & Martikainen, 2011). Sustained monitoring and appraisal of the perils linked to pharmaceutical pollution remain pivotal. A comprehensive grasp of the potential hazards linked to pharmaceutical pollution amid a changing climate is indispensable for devising efficacious strategies to temper these threats and safeguard the well-being of marine organisms and humanity alike.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

9. Conclusions and perspectives

In conclusion, pharmaceutical pollution in the sea represents a multifaceted and intricate challenge that necessitates a comprehensive approach to temper its repercussions on the environment and human health. The utilization

of pharmaceuticals is on an upward trajectory, and their pervasive presence in the environment constitutes a looming menace to both marine organisms and human well-being. The impacts of pharmaceuticals on marine organisms manifest as intricate and multifarious, often culminating in enduring consequences for ecosystems.

To mitigate the influence of pharmaceutical pollution on the sea, a medley of strategies can be implemented. These encompass curtailing the generation of waste, enhancing waste management practices, and advocating for the sustainable production and consumption of pharmaceuticals. Furthermore, the potential ramifications of climate change on pharmaceutical pollution underscore the imperativeness of sustained monitoring and risk assessment pertaining to this issue.

Comprehending the latent hazards entwined with pharmaceutical pollution in an ever-changing climate stands as a cornerstone for crafting efficacious strategies that safeguard the health of marine organisms and humanity at large.

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>>>> **This project was undertaken as a partial requirement for a class assignment. The manuscript is submitted to encourage and acknowledge the contributors for their commendable efforts.**