hydrobiology

Review

Pharmaceuticals in Water: Risks to Aquatic Life and Remediation Strategies

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Abstract: The presence of pharmaceuticals in the aquatic environment presents a challenge to modern science. The most significant impact this can induce is the emergence of antibiotic resistance, which can lead to a global health emergency. It is important to note that the impact of pharmaceuticals in the aquatic environment is not limited to antibiotic resistance. Pharmaceuticals can also affect the behaviour and reproductive systems of aquatic organisms, with cascading effects on entire ecosystems. Numerous studies have reported the emergence of pharmaceuticals due to the uncontrolled disposal of polluted domestic, agricultural, and industrial wastewater in water bodies. This work discusses the potential of pharmaceuticals that on one hand are highly important for mankind, yet their non-judicious usage and disposal induce equally intriguing and problematic conditions to the health of aquatic systems. Pathways through which pharmaceutics can make their way into water bodies are discussed. Furthermore, the risk imposed by pharmaceuticals on aquatic life is also elaborated. The possible and pragmatic remediation methods through which pharmaceutical products can be treated are also discussed. Emphasis is placed on the potential of phytoremediation and advanced oxidative process, and the factors affecting the efficacy of these remediation methods are discussed.

Keywords: pharmaceuticals; aquatic ecosystems; hydrobiology; phytoremediation; advance oxidative processes

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Citation: Khan, A.H.A.; Barros, R. Pharmaceuticals in Water: Risks to Aquatic Life and Remediation Strategies. *Hydrobiology* **2023**, *2*, 395–409. https://doi.org/10.3390/hydrobiology2020026

Academic Editor: Fernando Cobo

Received: 30 March 2023
Revised: 9 May 2023
Accepted: 31 May 2023
Published: 14 June 2023

1. Introduction

Hydrobiology is a branch of ecology that studies living organisms in aquatic habitats. It focuses on the interactions between aquatic organisms and the physical and chemical environment, as well as their interactions with each other [1]. Emerging pollutants are substances that have recently been identified as environmental contaminants and that have the capacity to induce deleterious impacts on the health of ecosystems and humans [2]. Pharmaceutical products are one example of emerging pollutants as they are found in various aquatic systems around the globe. They are emerging pollutants due to their continuous and widespread usage [3]. When these pharmaceutical products enter water bodies, they can have a significant impact on aquatic organisms, including altering their behaviour and causing reproductive problems and even death. Additionally, these substances are persistent and xenobiotics in the environment, leading to chronic exposure of aquatic organisms and humans who consume contaminated water [2,4].

Recent reports highlight the urgency of understanding the emerging pollutants' impacts on aquatic habitats and their inhabitants, including the field of hydrobiology [3–5]. For instance, research by Li et al. [6] explored the incidence and ecological risk of pharmaceuticals present in a drinking water reservoir source in China (mainland). The examination found that various pharmaceutical compounds and products were present in the water and posed ecological risks to the aquatic organisms in the reservoir. Similarly, a study by Li et al. [3] and Mastrángelo et al. [7] evaluated the impact of emerging pollutants, including pharmaceuticals, on the microbial composition nexus in an urban river. The study found that the microbial community composition was significantly altered in the presence of these pollutants. These studies demonstrate the need for continued research and management strategies to minimize the effects of emerging pollutants on water ecosystems and human health.

Pharmaceutical products have been increasingly detected in water bodies due to various pathways, including direct discharge of treated and untreated wastewater, surface runoff, and agricultural and industrial runoff [8]. The presence of these products in water bodies poses a significant risk to aquatic organisms and human health. The discharge of treated and untreated wastewater containing pharmaceuticals into rivers and streams is one of the major paths and routes for the introduction of these products into aquatic systems [8]. In addition, agricultural activities and livestock farming were identified as potential sources of contamination, as drugs such as antibiotics and hormones are often used in these practices [9]. The existence of pharmaceutical products in environmental matrices, especially water systems, highlights the need for improved waste management practices, increased public awareness, and the development of more effective technologies related to wastewater treatment to reduce the impact of emerging pollutants on the environment and human health [10,11]. The increasing use of pharmaceutical products, combined with inadequate wastewater treatment and disposal systems, highlights the need for better management practices to minimize the environmental and health impacts of these substances present in the aquatic systems, as these items are essential for supporting human health. However, their improper usage and disposal can seriously jeopardize the well-being of aquatic ecosystems. The review also looks at the threat that pharmaceutical products may bring to aquatic life and identifies realistic and scalable strategies for dealing with the treatment of pharmaceutical products to lessen their environmental effect. The main strengths of this review are that it targets both national and international scientific and environmental communities and discusses the problems caused by pharmaceutical products while also presenting solutions for their treatment using scalable and applied methods for pharmaceutical remediation that pose minimal to no risk of development of microbial resistance to these compounds.

2. Method

The authors used the Scopus database to conduct a systematic literature review and extract scientific data on environmental sciences related to the keywords "hydrobiology", "River", "pond", "water", and "pharmaceutical". The reason for performing this systematic literature review was to identify the most important publications and keywords related to risks to aquatic life and remediation strategies for pharmaceutical products in water and to visually represent the relationships between them. Of 51,144 studies that were identified through the database search, the authors applied a filter to select only research articles published between 2018 to 2023. This resulted in a total of 1994 articles for analysis. These studies were used for the bibliographic data analysis and mapping was performed using VOS viewer software, with a binary counting of keyword co-occurrence method (Figure 1). The minimum number of occurrences of a term was set to 134 to reduce the number of co-occurring keywords to 110. After manually removing irrelevant keywords, 93 keywords were used for network and overlay visualization analysis. The network formed resulted in four major clusters with 45 elements. The term "water pollutant" was in cluster 1, "Unclassified drug", "wastewater" and "bioremediation" were in cluster 2, "pharmaceuticals" in cluster 3, and "effluent" in cluster 4, were dominating. A total of 988 links were generated, with a link strength of 49,299. Cluster 4 had the highest link strength of 3171, with "effluent" being the most common term.

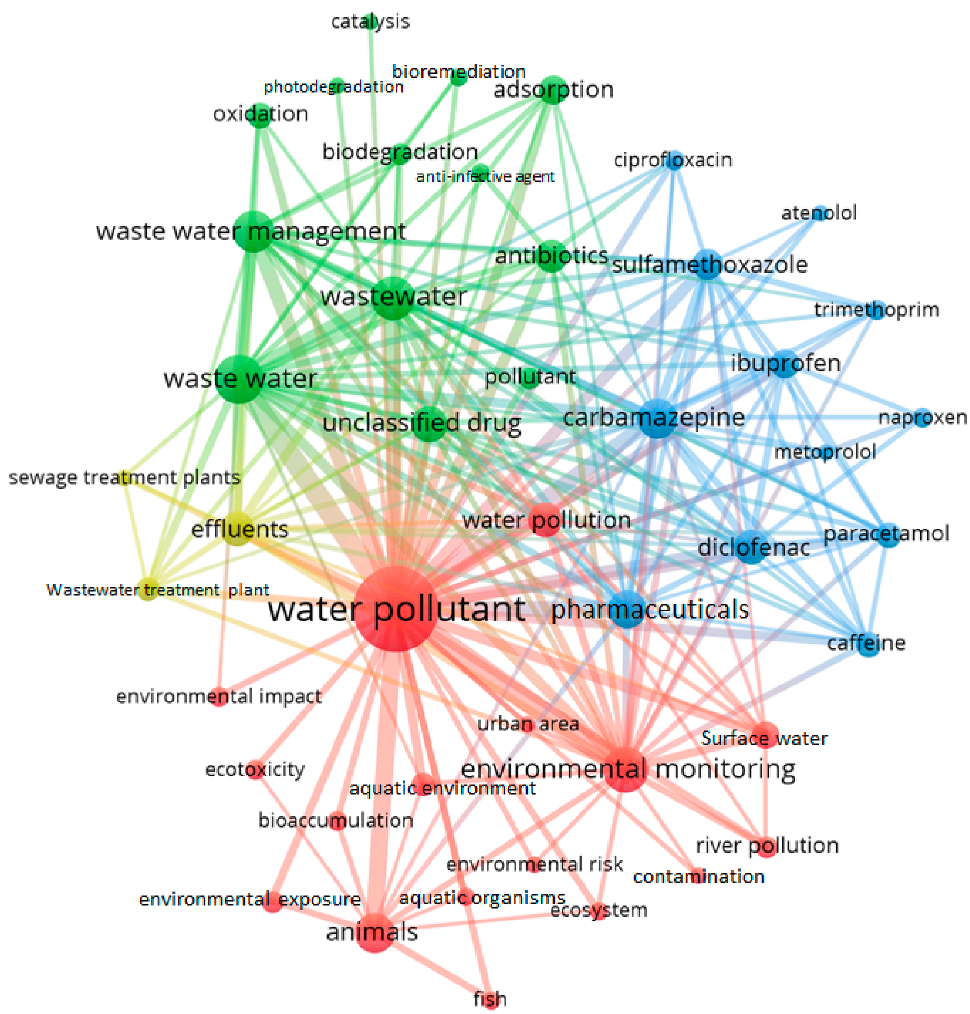

Figure 1. Overlay visualization of keyword co-occurrence in examined papers using VOS viewer software. The thickness of connecting lines indicates the strength of the relationship and coloured clusters indicate frequent co-occurrence of keywords in the same publication.

3. Routes of Pharmaceutical Product Entry into Water Bodies and Their Detection

Pharmaceutical products can enter aquatic systems through various pathways [12]. A general route that presents the channels through which the pharmaceutics can enter aquatic systems is presented in Figure 2. One of the primary sources is direct discharge from wastewater treatment plants [9,11].

Pharmaceutical products are often excreted by humans and animals, and they can pass through wastewater treatment plants without being fully removed [13,14]. There are numerous studies that have reported the presence of pharmaceutical products in wastewater. An extensive review of the presence of pharmaceuticals in domestic wastewater was presented by Petal et al. [15] and Falahi et al. [16]. If the wastewater remains untreated, this can lead to bioaccumulation in aquatic animals. For instance, Carrizo et al. [9] conducted a study in Argentina on pacu fish (*Piaractus mesopotamicus*) and reported the presence of pharmaceuticals and their metabolites (including 1,7-dimethylxanthine, benzoylecgonine, bis(2-ethylhexyl) phthalate, caffeine, carbendazim, cyclamate, dodecanedioic acid, ethylparaben, xanthine, methylparaben, metolachlor, salicylic acid, and saccharin) in all analysed samples. Similarly, in another study conducted by Mastrángelo et al. [7], the presence of acetaminophen, atenolol, carbamazepine, ciprofloxacin, hydrochlorothiazide, sulfamethoxazole, valsartan, and venlafaxine in surface water, ciprofloxacin in the biofilm, and *Lemma gibba*, were reported. It clearly indicates the importance of effective treatment for the removal of pharmaceutical products, as having them in wastewater and water streams can exacerbate the menace of antibiotic resistance in opportunistic pathogens [5,17]. The presence of pharmaceutical products, including antibiotics, in wastewater can lead to the selection and proliferation of antibiotic-resistant bacteria [18]. These resistant bacteria can then be released into the environment, potentially infecting humans and animals. In addition, the discharge of untreated wastewater into water bodies can provide a reservoir for the exchange of resistance genes between different bacterial species [6]. Effective wastewater treatment is therefore essential to prevent the spread of antibiotic resistance and protect public health [14]. Treated wastewater can also contain residual pharmaceuticals that are released into rivers, lakes, and oceans, potentially affecting aquatic organisms [10]. Another source of pharmaceutical products in aquatic systems is leakage from landfills [12].

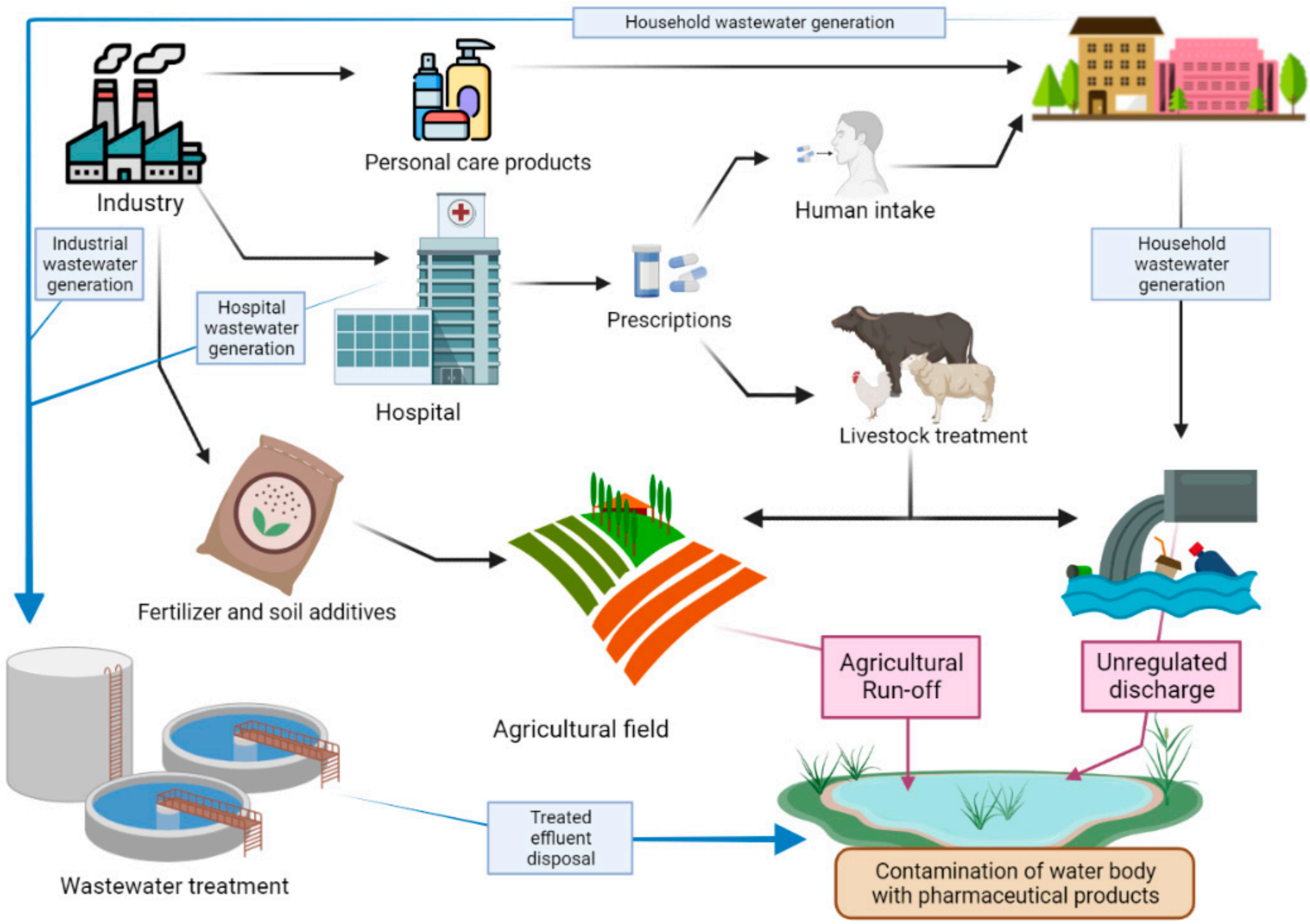

Figure 2. Pathways through which pharmaceutical contaminants can enter aquatic systems [12].

When pharmaceuticals are disposed of in landfills, they can leach into the surrounding groundwater and surface water. This can happen when rainwater percolates through the landfill and carries dissolved pharmaceuticals with it [19]. Over time, the leached pharmaceuticals can find their way into streams, rivers, and other aquatic systems. Agricultural runoff is another potential pathway for pharmaceutical products to enter aquatic systems. Livestock farms and agricultural fields often use pharmaceuticals such as antibiotics and hormones to prevent disease and promote growth in animals [9]. These chemicals can be excreted in animal waste and washed off fields by rainwater or irrigation. The runoff can then enter streams and rivers, carrying with it residual pharmaceuticals that can potentially harm aquatic organisms [20]. Overall, the presence of pharmaceutical products in aquatic systems can have significant ecological impacts. It is important to understand the sources and pathways of pharmaceuticals to minimize their impact on the environment and ensure the safety of aquatic ecosystems.

A comprehensive review of the literature focusing on methods for monitoring and assessing the levels of pharmaceutical products in water is presented by Rathi et al. [21]. These methods can be classified based on underlying working principles (Analytical Chemistry Techniques or biological methods) and monitoring methodology statutes (active and passive techniques). Table 1 summarizes those methods used for the detection of pharmaceutical products in aquatic environments. Passive sampling involves the use of devices or materials to absorb or adsorb chemicals from water over time, while active sampling requires physically collecting water samples. Laboratory techniques such as high-performance liquid chromatography (HPLC), mass spectrometry (MS), enzyme-linked immunosorbent assay (ELISA), and polymerase chain reaction (PCR) can be used to detect and quantify specific pharmaceutical products in water samples [22,23]. Similarly, biological methods can be used to assess the potential effects of pharmaceutical products on living organisms in the aquatic system [23–28]. Using a combination of these methods, researchers and regulatory agencies can better understand the presence and potential impacts of pharmaceutical products in water and take appropriate actions to protect public health and the environment.

Table 1. Methods used for the detection of pharmaceutical products in aquatic systems.

Methods		Description	Monitoring Status	Usage	References
Analytical Chemistry Techniques: Pharmaceutical products can be detected and quantified using various analytical chemistry techniques	High-Performance Liquid Chromatography (HPLC)	Separates and identifies individual components in a sample based on their chemical properties.	Active	Commonly used methods (individually and in combination) for the detection of pharmaceutical contaminants	[29]
	Gas Chromatography (GC)	Separates and analyzes volatile compounds in a sample.	Active		
	Mass Spectrometry (MS)	Measures the mass-to-charge ratio of ions to identify and quantify compounds in a sample.	Active		
	Diffusive Gradients in Thin Films (DGT)	Uses a resin gel that binds to the pharmaceuticals, allowing for their detection after being collected on the resin.	Passive	Antiviral agent, hypoglycemic, blood lipid regulator, anticonvulsant drug, anti-inflammatory drug, antidepressant, antiplatyhelmintic drug, antirheumatic drug, β-lactams, macrolides, fluoroquinolones, sulfonamide, tetracyclines, and other antibiotics	[30]
	Polar Organic Chemical Integrative Samplers (POCIS)	Uses a sorbent material to collect pharmaceuticals over time.	Passive	Carbamazepine, Ibuprofen, Gemfibrozil, Triclosan, Octocrylene, Caffeine, Ketoprofen, Naproxen, Diclofenac, Mefenamic acid	[22]
	Solid Phase Microextraction (SPME)	Uses a small fiber coated with a sorbent material to extract pharmaceuticals from the water over time.	Passive	Nifedipine, furosemide, hydrochlorothiazide, valsartan, pravastatin sodium, rosuvastatin calcium salt, and gemfibrozil	[23]

Table 1. *Cont.*

Methods		Description	Monitoring Status	Usage	References
Biological Methods. Living organisms or biological origin products that can be used to monitor the effects of pharmaceutical products on aquatic ecosystems	Bioassays	Measures the biological response of an organism or cell to a pharmaceutical product. (Growth, reproduction, and survival—*Caenorhabditis elegan*, germination assay—*Lactuca sativa*, and bio-luminance assay-*Vibrio fischeri*)	Active	Ibuprofen	[27]
	Biomarkers	Measures the presence or levels of specific molecules or genes in an organism that indicate exposure to a pharmaceutical product. (Enzymatic profiling for Fish—invasive, Hemolymph for carb—Noninvasive)	Passive	Triclosan and 17α-Ethynylestradiol	[26,28]
	Ecotoxicology	Examines the effects of pharmaceutical products on the behavior, reproduction, growth, and survival of aquatic organisms. (Mortality (LC50) and reproduction inhibition (NOEC) in *Daphnia magna*	Passive	Diclofenac, ibuprofen, clofibric acid, carbamazepine, salicylic acid, gemfibrozil, acetaminophen, bezafibrate, tolfenamic acid	[25]
	Enzyme-Linked Immunosorbent Assay (ELISA)	A type of immunoassay that detects and measures specific molecules, including pharmaceuticals, in a sample.	Active	Amoxicillin, caffeine, chloramphenicol, ciprofloxacin, dexamethasone, diclofenac, nitrofurazone, sulfamethoxazole, and triclosan	[24]

4. Assessment of Risk Related to Pharmaceutical Products in Water Bodies

The risk of pharmaceutical products to hydrobiology can be assessed using a range of different techniques. The first step is to measure the concentrations of pharmaceutical contaminants in the aquatic system [31]. This is typically done using chemical analyses such as gas chromatography or high-performance liquid chromatography. It is also important to assess the bioavailability and toxicity of the pharmaceuticals, as this can help inform risk assessments. This can be done by measuring the aquatic concentration of the compound, as well as its rate of degradation in the environment [32]. The next step is to study the direct and indirect effects of pharmaceuticals on aquatic organisms [5,33]. This includes assessing the accumulation and metabolism of the compounds by organisms, as well as their effects on population sizes, feeding, and reproductive behaviour. For example, studies can look at the risk posed by pharmaceuticals to specific species or species of conservation importance [34]. It is also important to track the overall health of the aquatic ecosystem, for example by assessing water quality parameters such as the levels of nitrates and phosphates, pH levels, dissolved oxygen, and temperature [35]. The risks associated with pharmaceutical products in aquatic systems can include toxicity to aquatic organisms, antibiotic resistance development, and endocrine disruption [36]. These products can also affect the food chain, with the potential to harm the health of fish and other aquatic life that humans consume [17]. Additionally, pharmaceutical products can lead to the growth of harmful algae and bacteria in the water, which can harm aquatic life and make the water unsuitable for human use. The accumulation of pharmaceutical products in the environment can also have unknown long-term effects on the ecosystem, making it crucial to monitor and regulate the use and disposal of these products. These risks posed by pharmaceutical products to hydrobiology have been highlighted in several studies. For instance, Tambosi et al. [37] and Patel et al. [15] pointed out that pharmaceutical products can introduce new or higher concentrations of various chemicals into the environment, disrupting the balance of aquatic ecosystems.

These pollutants include antibiotics, hormones, and antifouling agents, among others. Similarly, a study by Kayode-Afolayan et al. [33] highlighted the impact of pharmaceuticals on nitrogen and phosphorus levels in water bodies, as well as their effects on the health and behaviour of aquatic species. This work also proposed that some pharmaceuticals can act as endocrine-disrupting compounds, causing serious biological effects on aquatic organisms.

These findings demonstrate the importance of continued research and management efforts to minimize the impact of pharmaceutical products on aquatic ecosystems. Pharmaceuticals in water bodies can accumulate in sediments, potentially leading to long-term exposure to aquatic organisms [33,38]. Another study by Foster et al. [39] highlighted the potential of fluoxetine to cause changes in the metabolism and gene expression of *Rana pipiens*, potentially leading to negative impacts on their growth, development, and survival. Additionally, a recent study by Leonardo et al. [40] showed that the presence of pharmaceuticals in water bodies can lead to the development of antibiotic-resistant bacteria, posing potential risks to human health. In another study, Bereketoglu et al. [41] observed various effects in zebrafish embryos and larvae caused by nonsteroidal anti-inflammatory drugs (NSAIDs). These effects included malformations and mortality in the embryos, apoptosis in the larvae, downregulation of genes that are biased towards females, and an increase in the proportion of males. The effects were particularly significant in areas with high concentrations of the drug. It demonstrates the harmful impact that pharmaceutical products can have on aquatic ecosystems and the need for effective management practices to mitigate these effects. A few other risks presented by the presence of pharmaceutical products in the aquatic environment are summarized in Figure 3. By understanding the potential risks posed by pharmaceuticals, and developing methods to mitigate their negative impacts, we can ensure that aquatic ecosystems remain healthy and thrive.

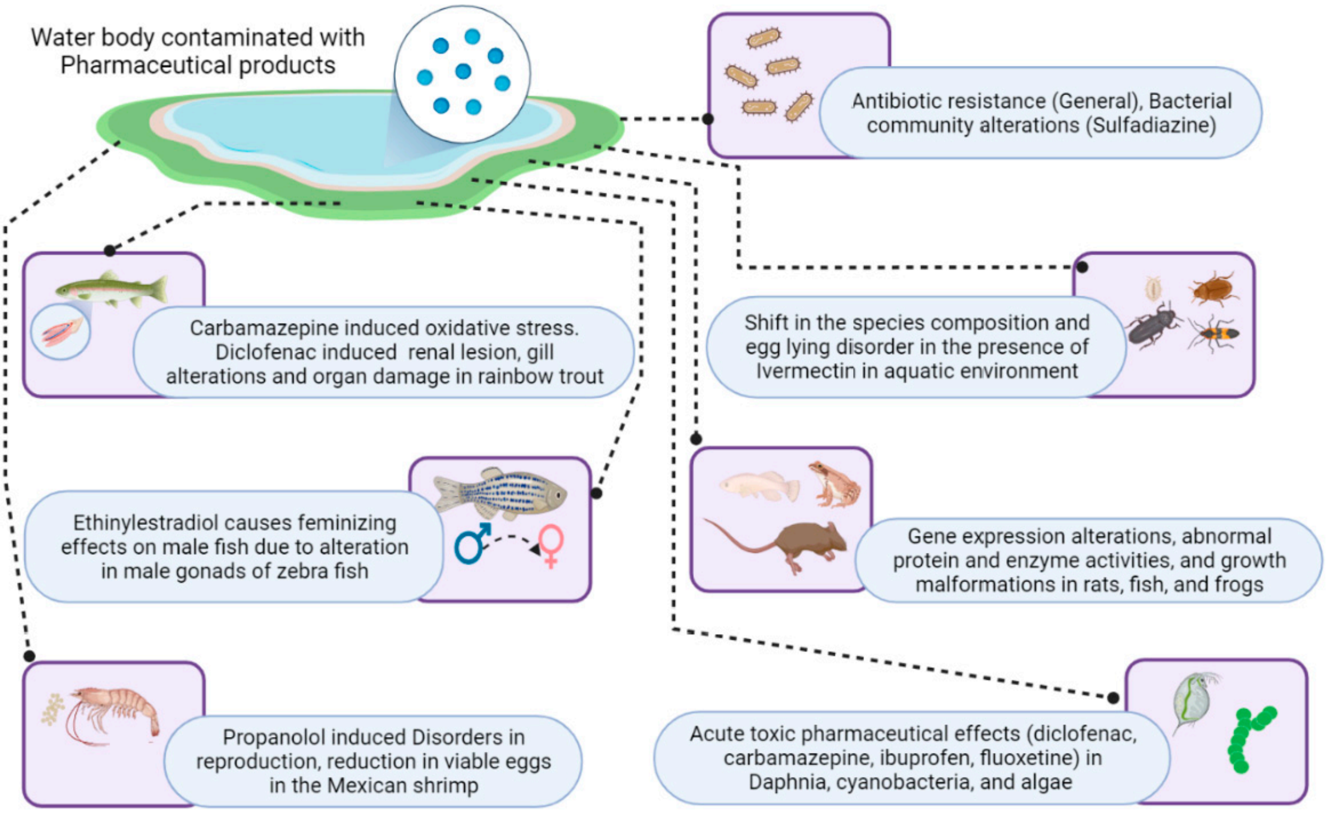

Figure 3. Toxic Effects of Pharmaceuticals on the Nontarget Organisms in the Environment (data extracted from Patel et al. [15]).

5. Methods of Choice for the Management of Pharmaceutical Pollution in Water

There are several pharmaceutical remediation methods currently in use for treating pharmaceutical products in aquatic environments. These methods include biological treatments such as activated sludge, bioremediation, phytoremediation, and nutrient removal [42]. Other physical remediation methods include adsorption, absorption, and membrane filtration [43]. Chemical treatments such as oxidation, chlorination, and ozonation may also be used [44]. New research is also being conducted to develop novel remediation technologies, such as engineered nanomaterials and biosystems used for the adsorption of antibiotics, which hold promise for treating contaminated waters [45,46]. At present, a few of these systems are in the research stage and need thorough evaluation before commercial application. Biological treatments are often preferred for the treatment of pharmaceutical products in aquatic environments because they can be more cost-effective compared with physical or chemical treatments, and they typically result in lower residual impact. Bioremediation uses bacteria, fungi, algae, or plants to degrade or transform toxins in the environment [47–50]. However, the risk of antibiotic resistance and the emergence of super tolerant microbial bugs are among the most prominent obstacles to the use of microbial-based bioremediation technologies. Other biological treatments include oyster culture, marsh wetlands, and constructed wetlands, which use plants and animals to filter out contaminants. Such treatments must be carefully managed to ensure that the water is safe for human and aquatic life.

5.1. Phytoremediation of Pharmaceutics

Among the biological methods, phytoremediation is the method of choice for the removal of pharmaceutical compounds from aquatic environments. The prime reason for this is that it can counter the menace of antibiotic resistance in pathogenic and opportunistic bacteria [51]. Phytoremediation is a type of biological treatment that uses plants and plant-associated microbial communities to degrade or transform pollutants in the environment [52,53]. It is a cost-effective and ecologically sustainable approach to treating wastewater and contaminated soils. The technology is based on the concept of bioaccumulation or bioretention, where the plants absorb, accumulate, or retain the contaminants from the water or sediment [54–56]. The plants then either store, degrade, or metabolize the pollutants and thus reduce their concentrations in the environment [57,58]. Plants possess the ability to heal damaged ecosystems, making them a possible solution in constructed wetlands (CWs) as an added treatment method for wastewater treatment plants. The utilization of CWs for wastewater treatment has become a well-liked and innovative technique for environmental protection and rehabilitation [59].

These wetlands have exhibited their ability to successfully treat wastewater that contains various pollutants, including pharmaceutical products. CWs have become a popular technology due to their advantages such as low cost, ease of operation, high removal capacity, and significant potential in recycling water and nutrients [60]. Having introduced this, the plants can be used to remove pharmaceutical contaminants from the environment by absorbing them into their cells, thereby decreasing the concentration of the pollutants. Phytoremediation can also be applied directly to the water. Plants such as duckweed and pondweed have been used to reduce concentrations of pharmaceuticals in aquatic systems [61]. In combination with other biological treatments, they can be used to treat wastewater and other polluted waters.

Pharmaceutical phytoremediation in the aquatic environment can be impacted by several factors, including the type of pharmaceutics to be treated, species of plants used for phytoremediation, environmental conditions, bioavailability of targeted compound, water flow rates, presence of other contaminants, and duration of treatment. Different types of pharmaceuticals have varying levels of persistence and toxicity, and higher concentrations of pollutants can reduce the effectiveness of phytoremediation [58]. For instance, when the phytoremediation is performed using constructed wetland, as a primary treatment method, over 98% of caffeine, acetaminophen, ibuprofen, naproxen, and triclosan were removed from the influent. However, for trimethoprim, gemfibrozil, and carbamazepine, the removal values were even negative, indicating that their concentrations increased in the treated effluent [62]. This could be due to evapotranspiration by the plants, which reduced the volume of exiting effluent. Plant species selection is also important, as some plants are better at absorbing and degrading pharmaceuticals than others. A study conducted by Brunhoferova et al. [63] proposed similar results using *Phragmites australis*, *Iris pseudacorus*, and *Lythrum salicaria*, against 27 micropollutants. Among these micropollutants, the pharmaceuticals included were atenolol, bezafibrate, carbamazepine, clarithromycin, ciprofloxacin, cyclophosphamide, diclofenac, erythromycin, ketoprofen, lidocaine, metoprolol, propranolol, n-acetyl sulfamethoxazole, and sulfamethoxazole. It was proposed that compared to *P. australis* and *I. pseudacorus*, *L. salicaria* showed higher phytoremediation potential, as the removal efficiency was higher than 20% for most micropollutants, including pharmaceuticals in aquatic conditions. Apart from this, the configuration in which the wetland is designed also plays a significant role in the removal of certain pharmaceuticals [64]. de Oliveira et al. [65] analysed ibuprofen and caffeine removal under two different settings (vertical flow and free-floating) using *Heliconia rostrata*. Removal efficiencies were more than 80% for both ibuprofen and caffeine. However, removal efficiencies in the vertical flow constructed wetlands were 97 and 90%, while in the free-floating constructed wetland system were 94 and 89%, for caffeine and ibuprofen, respectively. Similarly, in another study conducted by Chen et al. [18] *Thalia dealbata* Fraser and *Iris tectorum* Maxim were exposed to various antibiotics, including erythromycin-H_2O, monensin, clarithromycin, leucomycin, sulfamethoxazole, trimethoprim, sulfamethazine, and sulfapyridine. Similarly, the researchers investigated the effects of antibiotics on these plant species. It was reported that horizontal subsurface flow CW using either of these plants resulted in higher removals (up to 95%) using either studied antibiotic compared with the vertical flow or free flow system [18].

Environmental parameters, including temperature, light, pH, and nutrients can severely affect plant growth and survival, which in turn can impact the plant's competence to grow and remove pharmaceuticals present in the water [66]. One such consideration is also related to the transformation of pharmaceutical compounds, resulting in highly toxic products [67,68]. For instance, Carpinteiro et al. [69] identified that diazepam's reaction with chlorine produces more mutagenic and toxic derivatives than the precursor drug. The bioavailability of pharmaceuticals in aquatic environments can be affected by pH, salinity, and the presence of other organic matter, which can also impact the effectiveness of phytoremediation [16,70]. Vascular plant roots, such as cattails (*Typha* sp.), are highly effective at absorbing compounds with a log K_{ow} (Octanol-water partition coefficient) value ranging from 1 to 3.5 [71]. The reason for this is that these substances possess sufficient lipophilicity to permeate the lipid bilayer of plant cell membranes, while also being soluble in water, which enables them to enter the cell, making them highly bioavailable. Water flow rate can affect the contact time between water and plants, while the presence of other contaminants, such as heavy metals or pesticides, can interact with pharmaceuticals and impact their bioavailability and toxicity [72]. The efficiency of constructed wetlands planted with *Scirpus grossus* (a pilot-scale vertical subsurface flow CW with an aeration system) was assessed by Falahi et al. [16]. The objective was to evaluate the capability of this system to simultaneously remove ibuprofen, chemical oxygen demand, and nutrients from domestic wastewater. Similarly, in another study, Falahi et al. [73] reported that the HRT impacts the removal of ibuprofen and paracetamol and proposed that a prolonged HRT improved the removal efficiency of pharmaceuticals using *Scirpus grossus*. Hence it can be concluded that the duration of phytoremediation of pharmaceuticals can also impact the competence of plants to eliminate pollutants from water.

5.2. Advanced Oxidative Processes for Treatment of Pharmaceuticals

Advanced oxidative processes (AOPs) are a type of chemical treatment used for the elimination of toxic impurities present in the water. These processes utilize oxidizing chemicals such as ozone, hydrogen peroxide, and ultraviolet light to break down the contaminants into harmless by-products. The highly reactive species that occur due to AOPs in the aqueous phase are $HO^{\bullet}$, $O_2^{\bullet}$, and $HO_2^{\bullet}$ [15]. These free radicals are highly reactive and have the capacity to oxidize a large range of pollutants (organic and inorganic) with great efficiency due to their high reaction rate constants. AOPs are particularly efficient at removing pharmaceuticals. A few examples of different AOPs used for the treatment of pharmaceuticals in water bodies are based on O_3 alone, O_3 in combination with UV/H_2O_2, O_3/H_2O_2, Fe^{2+}/H_2O_2, photo-Fenton oxidation, and electro-Fenton degradation [74–78]. These processes can be scaled up for use in real-world applications, typically by increasing the size and complexity of the equipment used to generate and operate the AOPs. Additionally, the process can be enhanced through the addition of catalysts and adsorbents to speed up reaction rates, reduce wastewater volume, and improve the efficiency of contaminant removal.

Like phytoremediation, there are numerous considerations that can impact the removal rates of pharmaceuticals in aquatic systems using AOPs. These include the type of pharmaceutical compound, its concentration in the water, and the type of oxidant used [79]. For example, some pharmaceuticals are more resistant to oxidation than others, and higher concentrations of pharmaceuticals may require higher concentrations of the oxidant or longer reaction times. Serna-Galvis et al. [80] conducted an experiment that examined the effectiveness of sonochemical advanced oxidation processes in treating pharmaceutical compounds such as azithromycin, carbamazepine, ciprofloxacin, clarithromycin, clindamycin, diclofenac, erythromycin, irbesartan, losartan, metronidazole, norfloxacin, sulfamethoxazole, trimethoprim, valsartan, and venlafaxine. According to the results, it appears that the removal of pollutants through ultrasonic means is influenced by parameters such as concentration and hydrophobicity. In addition, the degradation of all the compounds was significantly improved by complementary processes, with the sono-photo-Fenton/oxalic acid process showing the highest enhancement, followed by the sono-photo-Fenton and sono-Fenton processes, while sonochemistry exhibited the lowest enhancement. The type of oxidant used can also affect the efficiency of the process [80,81]. Hydroxyl radicals are highly reactive oxidants commonly used in AOPs, but their reactivity can be reduced by the presence of other species in the water or wastewater matrix, such as dissolved organic matter [78,82].

In addition to these factors, other considerations must be considered when applying AOPs to the treatment of pharmaceuticals in aquatic systems. For example, the potential for the formation of toxic intermediates or by-products during the oxidation process must be carefully evaluated to ensure that the treatment is not creating a new set of contaminants that could be harmful to aquatic organisms or humans [83]. For instance, the decomposition of pharmaceutical compounds (diclofenac and ibuprofen sodium salt solutions) during the UV/TiO_2 process resulted in the formation of toxic transformation products [84]. Additionally, the cost and feasibility of implementing AOPs as a treatment method must be investigated in the context of existing wastewater treatment infrastructure and regulatory requirements. Overall, AOPs have shown promise as an effective method for the removal of pharmaceuticals from aquatic systems, but careful consideration of the factors that can affect their efficiency and effectiveness is essential to ensure safe and sustainable treatment.

5.3. Comparison of Benefits and Limitations of Phytoremediation and AOPs

AOPs are relatively new and rapidly evolving processes that use chemical, ultraviolet, and/or other energy-activated oxidants to remove pharmaceuticals from water and land-based sources [78]. AOPs are often effective for a wide range of contaminants and for dissolved as well as particulate pollutants, they often reduce contaminants to non-detectable levels, AOPs can be placed in existing treatment installations where the space is available; however, high costs of maintenance, operation, and investment, possible susceptibility to wastewater matrix changes, including pH, temperature, and chemical concentrations, and unused chemical reactants can cause water-quality problems [75–80]. Phytoremediation is a process that utilizes plants to remove pollutants from solid and water sources [56]. The benefits of phytoremediation include: (1) it is a natural process that decreases the risk of discharging harmful effluents into the environment, (2) it has low cost and maintenance due to the lack of specialized equipment, and (3) it can be used to remove pollutants from land and water bodies alike [85]. However, it is limited for use against contaminants with low bioavailability, its applicability is limited to certain environments, and it is slow and can therefore be impractical for large-scale removal of pharmaceuticals from water if the clean-up is needed instantaneously [86,87]. AOPs are relatively new and expensive, and their installation and ongoing operation can be high. Phytoremediation, on the other hand, is relatively low-cost since it requires minimal equipment or infrastructure. Furthermore, since it is a natural process, it can be conducted cheaply and with limited resources. Thus, phytoremediation is more cost-effective when it comes to scaling up.

6. Conclusions

Based on the published findings, it can be determined that the impact of pharmaceutical products on hydrobiology is significant. While the immediate effects of pharmaceuticals on aquatic ecosystems may seem limited to aquatic life, their potential to impact human beings by bypassing the trophic levels due to the emergence of resistant microorganisms is significant. In order to fully evaluate and address the impact of pharmaceuticals on aquatic ecosystems, it is imperative that extensive research is conducted to gain a deeper understanding of the complex and intricate chemical interactions that occur within these unique systems. Only with a comprehensive understanding of these chemical interactions can effective measures be taken to mitigate the impact of pharmaceuticals on these delicate ecosystems, ensuring their long-term sustainability and health. Cutting-edge analysis and further studies must be conducted to accurately measure the extent of the impact of pharmaceuticals on aquatic ecology and develop better management and regulatory practices with a focus on sustainability. Through collaboration between scientists, policymakers, business leaders, and local communities, we can reduce the potential for negative environmental impacts from pharmaceuticals and take proactive steps to protect and restore healthy aquatic ecosystems for future generations.

Author Contributions: Conceptualization, A.H.A.K. and R.B.; software, R.B.; writing—original draft preparation, A.H.A.K. and R.B.; writing—review and editing, A.H.A.K. and R.B.; visualization, A.H.A.K.; rebuttal and revision, A.H.A.K. and R.B., supervision, R.B.; funding acquisition, R.B. All authors have read and agreed to the published version of the manuscript.

Funding: The authors want to acknowledge the funding received under GREENER and BIOSYSMO projects. The GREENER project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No. 826312, while the BIOSYSMO project is funded by the European Union under the Grant Agreement No. 101060211.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the use of Bio Render software for the preparation of figures.

Conflicts of Interest: The authors declare no conflict of interest.

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