DOI: https://doi.org/10.54083/978-81-980121-3-5_10

Pollution from Anthropogenic Sources: Challenges for Sustainable Aquaculture in Aquatic Ecosystems

Muthumannan Vishal[1*], Jebarson Solomon[2], Ganesh Kumar[3], Priyadharshini[4], Sudhanshu Raman[3] and Girija Saurabh Behere[3]

[1]*Dept. of Fisheries and Fishermen Welfare, Rameswaram, Tamil Nadu (623 526), India*
[2]*ICAR-Central Institute of Fisheries Education, Mumbai, Maharashtra (400 061), India*
[3]*Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh (284 003), India*
[4]*College of Fisheries, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Tuticorin, Tamil Nadu (628 008), India*

Abstract

Aquatic pollution is a critical challenge for aquaculture systems, affecting the health, growth and survival of cultured species. Contaminants such as heavy metals, pesticides, pharmaceuticals and organic pollutants accumulate in water bodies and sediments, disrupting the ecological balance and degrading water quality. The pollutants which arise from the anthropogenic activities were not removed efficiently in the wastewater treatment plant and find its occurrence in water-sediment matrices of natural aquatic ecosystem which are being primarily used as a water source for the aquaculture activities. These pollutants exert toxic effects on cultured aquatic organisms, impairing vital physiological processes like growth, reproduction and immunity. Addressing these challenges requires effective remediation strategies, including biological and chemical methods, soil vapor extraction and pump-and-treat systems, to manage and mitigate the impact of pollutants in aquaculture environments. This chapter summarizes the aquatic pollutants contaminating aquaculture waters, toxic effect on the cultured species and the remediation measures.

Keywords Aquaculture, Pollution, Remediation, Toxicity

1. Introduction

Aquaculture is the fastest-growing animal production sector and plays a key role in food security. It is projected to provide 62% of total fish consumption of human by 2030 (FAO, 2018). However, the rapid expansion of aquaculture to meet this demand has put significant pressure on available

[*]***Corresponding author's e-mail***: vishalmannan24@gmail.com

How to cite:

Vishal, M., Solomon, J., Kumar, G., Priyadharshini., Raman, S., Behere, G.S., 2025. Pollution from anthropogenic sources: challenges for sustainable aquaculture in aquatic ecosystems. In: *Aquaculture Reimagined: Modern Approaches to Sustainable Fish Farming*. (Eds.) Saini, V.P., Paul, T., Singh, A.K., Biswal, A. and Samanta, R. Biotica Publications, India. pp. 126-135. DOI: https://doi.org/10.54083/978-81-980121-3-5_10.

water resources. The success of aquaculture systems heavily depends on the quality and availability of water, which typically comes from natural sources like rivers, reservoirs, groundwater and ponds. Although freshwater ecosystems cover just 1% of the Earth's surface, they serve as the primary setting for aquaculture, with only limited activities extending to marine environments. As the global population has more than tripled since 1950, pressure on natural water resources has increased, leading to pollution and degradation, particularly in developing countries. Rapid urbanization and industrial growth have severely impacted aquatic systems, with untreated sewage and industrial waste often being discharged into natural water bodies. In India, for example, around 80% of natural water sources are polluted due to human and industrial activities and these polluted waters are frequently used in aquaculture, affecting the health of aquatic species and threatening sustainability. Additionally, climate change-related factors like monsoon failures and rising water temperatures have further degraded aquatic ecosystems, compounding the challenges faced by aquaculture. The pollution status of natural water bodies has significantly worsened, particularly after the COVID-19 pandemic, highlighting an urgent need for remedial action.

2. Water Source for Aquaculture

Aquaculture is practiced in marine, brackish and freshwater environments, using both open and closed systems. The most common method is pond culture, where water is contained in artificially constructed ponds or natural depressions in low-lying areas of a watershed. These ponds are typically smaller than other stagnant water bodies and may be made of earthen materials, cement, or lined with tarpaulin sheets, serving as enclosures for rearing finfish and shellfish. Water for these ponds are usually availed from a various source, including canals, rainwater, groundwater, or other local water bodies. The choice depends on the type of farm and the species being cultivated. For example, marine fish farms source water from the open ocean, brackish water farms use water from creeks and freshwater fish farms relies on rivers and canals. Most pond-based aquaculture systems utilize groundwater from borewells or canal water from rivers or lakes. Other forms of aquaculture, such as Recirculating Aquaculture Systems (RAS), biofloc technology and tank culture, primarily source water from borewells. Coastal aquaculture, practiced near shorelines, often uses pipelines to pump seawater from the open ocean into land-based ponds. Open water aquaculture systems like raceways, cage culture and pens are typically established in larger water bodies such as reservoirs, water barrages, lakes and marine territorial waters. However, in recent times, the diversity and quantity of pollutants in aquatic ecosystems have increased significantly. These pollutants are now widespread, contaminating natural water bodies and sediments, making many natural water sources unsuitable for aquaculture (Figure 1).

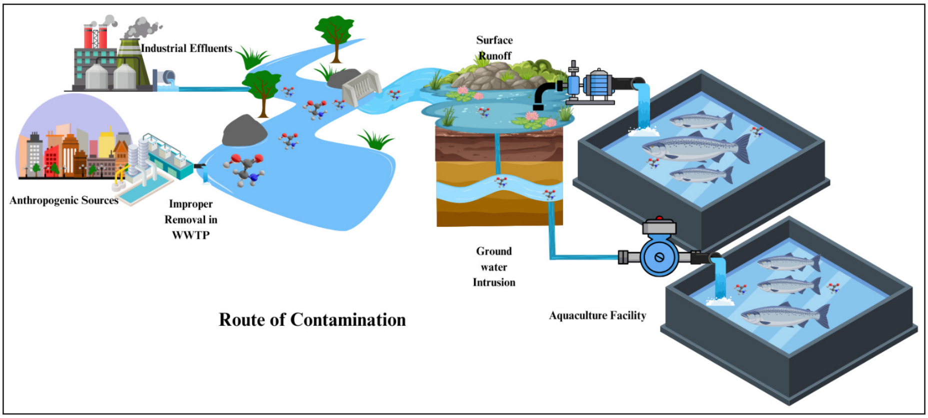

Figure 1: Route of pollutant contamination in aquaculture facility

3. Major Pollutants and its Occurrence

3.1. Heavy Metals

Heavy metal pollution has become an increasingly important environmental concern, especially with the rapid pace of industrialization and urbanization. These activities have significantly reduced the carrying capacity of water bodies, leading to widespread contamination by heavy metals. Human activities including logging and agriculture, as well as the release of household sewage are the primary causes of the increase in mercury (Hg) levels in natural waters. Mercury contamination is can also be caused by airborne deposition from mining, burning coal and oil, and incineration of trash. Also, rain and snowmelt can carry Hg-contaminated soil into nearby water bodies (Hassaan *et al.,* 2016). Industrial sources of mercury include chloralkali production, batteries, fluorescent lamps, thermometers and electronic switches. The chemical industry remains one of the largest global sources of mercury pollution. Nickel (Ni) pollution often results from corroded metal pipes and containers. Lead (Pb) enters aquatic systems through compounds in paints and gasoline additives, as well as aerosols from high-temperature industrial processes like coal burning, smelting and cement production. Cadmium (Cd) is introduced through industrial discharges and the breakdown of galvanized pipes, while phosphate fertilizers also contribute to cadmium pollution in water. Copper (Cu) typically comes from copper pipes, industrial waste and algal-control additives (copper sulphate). Iron (Fe) and manganese (Mn) pollution results from industrial effluents, acid mine drainage, sewage and landfill leachate (Pandey *et al.*, 2023). Chromium (Cr) pollution originates from industrial wastewater discharges in sectors like metallurgy, refractories, electroplating, tanning and pigment manufacturing. Arsenic (As) contamination comes from nonferrous mining, fossil fuel combustion, pesticides and animal feed additives, along with municipal and industrial waste incineration. Zinc (Zn) is introduced into water systems mainly through mining activities. A major contributor to heavy metal contamination is acid mine drainage (AMD), a serious environmental hazard caused by the oxidation of sulfide-bearing minerals exposed to weathering. AMD produces low-quality water characterized by acidic pH and high levels of dissolved metals (such as arsenic, cadmium, copper and zinc) and harmful anions like sulphates and carbonates (Kumar *et al.*, 2020).

3.2. Pesticides

Pesticide pollution has become a significant global concern, particularly due to its impact on aquatic ecosystems and resources crucial for aquaculture. The extensive use of agrochemicals in agriculture, especially in the last few decades has led to a dramatic increase in pesticide contamination of aquatic systems. The scale of pesticide use is staggering, with approximately 4.6 million tons of pesticides sprayed globally each year. However, only a small fraction (around 0.1%) of these chemicals reaches their intended target pests, while the remaining 99.9% enters the environment, contaminating soil, air and water. Herbicides account for 47.5% of global pesticide use and pose particular challenges for aquatic ecosystems. These chemical contaminations often impair photosynthesis in aquatic plants, reducing oxygen levels and degrading water quality, which in turn affects the growth and survival of farmed species in aquaculture systems. Insecticides, which make up 29.5% of pesticide use, are also a major concern, as they have a high affinity for aquatic sediments and can remain toxic for extended periods. Most of these pesticides, such as insecticides (malathion, endosulfan, diazinon) and herbicides (atrazine, glyphosate), are persistent chemicals that do not easily degraded (Saleh *et al.*, 2020). They remain in aquatic environments for long periods, affecting fish and other aquatic organisms through acute and chronic health impacts. These chemicals find their way into water bodies via various pathways, including agricultural runoff, industrial waste discharge and atmospheric deposition. Pesticide pollution level on the environment can be ranked as cropland > field ditch water > run off > pond water > ground water > river water > deep ground water > sea water. Pesticides undergo biotransformation in rivers, lakes, ponds and estuaries and the bio transformed product accumulate in sediments and water columns. Studies have shown that pesticides can persist in sediments for decades, continuing to pose a threat to aquatic life long after their initial application. This persistence is particularly problematic in lentic (still water) ecosystems, where pollutants can accumulate in the water-sediments matrices, affecting nutrient cycling and water quality. In addition to surface water contamination, groundwater systems are also at risk (Vandermaesen *et al.*, 2016). Pesticides can leach from agricultural soils into groundwater and persist due to the low organic content and reduced microbial activity in ground water aquifers. Groundwater pollution takes longer to manifest but can persist for decades, as contaminants move slowly through aquifers (Malyan *et al.*, 2019). This presents a long-term threat to aquaculture systems that rely on groundwater for water supply. Additionally, excessive use of pesticides combined with nutrient pollution from fertilizers, exacerbates the issue of water pollution in aquaculture environments. Nitrogen and phosphorus runoff from fertilizers contributes to harmful algal blooms, creating hypoxic conditions that suffocate aquatic organisms and further degrade water quality. These combined pollutants disrupt the ecosystems that aquaculture operations depend, leading to reduced productivity, poor health and increased mortality in farmed species (Rad *et al.*, 2022).

3.3. Personal Care Products and Pharmaceuticals

Pharmaceuticals and personal care products (PPCPs) encompass a wide range of substances, including prescription and non-prescription drugs, disinfectants, body lotions and even illicit drugs. Once consumed or applied, these compounds elicit biological responses before being excreted from the body, either unchanged or as metabolites. Studies have shown that approximately 10-90% of the administered dose is excreted in its original form. These residues are discharged into wastewater systems, where they reach wastewater treatment plants (WWTPs). However, WWTPs are often ineffective in fully removing these substances, allowing both raw and treated effluent to enter groundwater, rivers, lakes, oceans and soils, contributing to environmental contamination (Kumar *et al.*, 2024).

Pharmaceuticals and personal care products (PPCPs) have been detected in aquatic environments since the 1970s and continue to be found in surface water, groundwater and oceans worldwide. Human activities, such as discharges from pharmaceutical industries, households, hospitals, landfills and veterinary clinics, are the main pathways through which these contaminants enter aquatic ecosystems. Municipal and hospital sewage, as well as septic tanks, contain pharmaceutical residues from human waste and expired medications, making them significant contributors. Agricultural runoff and animal farming also play a role, as veterinary antibiotics, hormones and growth promoters used in livestock enter the environment through manure, often applied as fertilizer. Similarly, sewage sludge used in agriculture contains PPCP residues, which can leach into groundwater or run off into surface water. In addition, landfills without proper sealing, illegal dumps and industrial waste lagoons contribute to PPCP contamination by allowing harmful compounds to enter leachates that eventually reach water bodies. Personal care products, such as cosmetics and detergents, are also sources of PPCP pollution, entering water systems through everyday activities like bathing, where residues are washed off and discharged into wastewater. Recreational activities in coastal areas further release these products into seawater, adding to the contamination. These compounds can be toxic to aquatic organisms and promote the development of resistance in pathogens. Some PPCPs are classified as endocrine-disrupting chemicals, interfering with hormonal systems in both wildlife and humans, leading to reproductive disorders and developmental issues (Wang and Wang, 2016). Natural processes such as photolysis, biodegradation, chemical transformation, hydrolysis, volatilization, sorption onto particles and dilution can influence the extent of PPCP contamination. However, many PPCPs are resistant to these degradation processes and conventional wastewater treatment methods often fail to remove them completely. As a result, PPCP residues persist in water systems, including drinking water sources (Cizmas *et al.*, 2015).

3.4. Antibiotics

Antibiotics are natural, synthetic, or semi-synthetic compounds capable of killing or inhibiting the growth of microorganisms. They possess biologically active molecules with antibacterial, antifungal and antiparasitic properties, primarily designed as medicines to treat bacterial infections in both humans and animals. The global use of antibiotics is rising because of population growth and better access to medicines. Additionally, the increasing demand for animal protein leads to more intensive food production, which depends on greater use of antibiotics and growth promoters. In aquaculture, the incidence of diseases caused by various pathogens has limited production. It had prompted farmers and hatchery operators to use a range of remedial measures, including antibiotics and other chemicals for disease control. The frequency of antibiotic use is generally higher in hatcheries and scientific farms compared to traditional farms (Gothwal and Shashidhar, 2015). The US Food and Drug Administration (FDA) reported that in 2009, a total of 13.1 million kilograms of antimicrobial drugs were sold for use in food animals. Over the years, a wide array of antibiotics has been introduced in veterinary medicine, including chloramphenicol, oxytetracycline, kanamycin, nifurprazine, oxolinic acid, flumequine and ciprofloxacin. These antibiotics are further classified into categories such as antibacterials, antivirals, antifungals, antiprotozoans, anti-metazoan preparations, probiotics, immunostimulants, vaccines, bacterins, hormones, growth stimulants, anesthetics and bioremediators (Baquero *et al.*, 2008).

Despite the extensive use of antibiotics, approximately 70% of these compounds are excreted unchanged into wastewater. This persistent input has resulted in the accumulation of antibiotics in the environment. In fact, the amount of antibiotics consumed by the general population exceeds that used in hospitals, leading wastewater treatment plants (WWTPs) to become hotspots for antibiotic contamination. Veterinary antibiotics may also enter the environment through various routes, including manufacturing plants, process effluents, runoff from fields treated with agricultural waste and improper disposal. WWTPs play a critical role in collecting and removing antibiotics from wastewater; however, many existing treatment systems, including those that use flocculation, sedimentation, active sludge treatment and some advanced methods like disinfection and ultrafiltration, are often ineffective at completely removing antibiotics. As a result, antibiotics can still be released into aquatic systems. Furthermore, contaminated surface water may infiltrate groundwater systems, compounding the problem of environmental contamination (Zeng *et al.*, 2022).

4. Toxicological Impact of Pollutants

Heavy metal pollution poses a significant threat to aquatic environments and organisms, particularly when concentrations exceed safe limits. These metals induce toxicity in fish by generating reactive oxygen species (ROS), leading to oxidative stress and cellular damage. Exposure results in hematological alterations, including changes in blood parameters and enzyme activities, which serve as critical indicators of toxicity. Additionally, heavy metals compromise immune function, increasing susceptibility to diseases (Pandey *et al.*, 2023). Pesticides exert a range of harmful effects on fish in aquatic systems, including acute toxicity that can lead to immediate death. Chronic exposure can induce oxidative damage, impairing metabolic functions, while also inhibiting key enzymes such as acetylcholinesterase, which affects energy metabolism and nervous system function. Most of the PPCPs are increasingly recognized as endocrine disruptors in fish, affecting their hormonal systems and reproductive health. These compounds can interfere with the normal functioning of hormones by mimicking or blocking their natural action, leading to altered growth, development and reproductive behavior in aquatic organisms (Kumar *et al.*, 2024). For example, substances like synthetic estrogens and other endocrine-active chemicals can disrupt the endocrine pathways, resulting in feminization of male fish, impaired spawning and changes in secondary sexual characteristics. The presence of antimicrobial drug residues in source water can lead to allergies, toxic effects, alterations in intestinal microbial flora and the development of drug

Table 1: Toxicological effect of pollutants

Pollutants	**Examples**	**Toxicological effect**
Heavy Metals	Mercury, Cadmium, Lead and Arsenic	Brain lesions, spinal cord degeneration and central nervous system dysfunctions; Damage the integrity of tissue structure and function, antioxidant defense system, reproductive regulation system and immune system.
Pesticides	Chlorpyrifos, Endosulfan, Malathion, Atrazine, Diazinon, Glyphosate and Cypermethrin	Oxidative stress; Enzyme alterations in fish, leading to reduced Acetylcholinesterase activity; Increased protein carbonyl levels.
Personal care products and pharmaceuticals	Carbamazepine, Triclosan, Caffeine and Parabens	Endocrine disruption; Impairs fatty acid synthesis in phytoplankton.
Antibiotics	Tetracyclines, Sulfonamides, Nitrofurans and Fluoroquinolones	Development of antimicrobial resistance; Endocrine disruption; Residue accumulation in fish tissue and harms humans.

resistance. For instance, residues of chloramphenicol in food consumed by humans can result in a plastic anemia in cultured organisms. Additionally, nitrofuran antibiotics have been linked to cancer and numerous other health defects (Baquero *et al.*, 2008) (Table 1).

5. Remediation

Remediation of aquatic pollutants in aquaculture systems is crucial for protecting both the environment and the health of aquatic organisms. Several strategies can be employed to effectively manage and degrade pollutants, utilizing both biological and chemical methods tailored to the specific challenges of aquaculture. Biological treatment methods, such as in situ bioremediation, harness naturally occurring microbial populations to break down contaminants in the environment. These methods can be optimized by introducing additional nutrients, oxygen and water to enhance microbial activity, promoting faster and more efficient degradation. However, biological treatments can face limitations when pollutant concentrations are high, as toxic levels may inhibit microbial function and the time required for effective biodegradation can be considerable. In contrast, chemical remediation techniques, such as *in situ* chemical oxidation (ISCO), offer a more immediate solution for sites with severe contamination. The Fenton reaction, which generates hydroxyl radicals through the reaction of hydrogen peroxide with iron, effectively decomposes organic pollutants. Alternatively, sulfate radicals can be produced by activating persulfate, providing another powerful means of degradation. The effectiveness of these chemical reactions is highly dependent on the pH of the environment, requiring careful management to optimize conditions for pollutant breakdown. Additional remediation methods, such as soil vapor extraction (SVE) and air sparging, enhance the volatilization of pollutants from contaminated soils (Rathfelder *et al.*, 1995). SVE works by introducing fresh air through a vacuum, continuously extracting non-aqueous phase liquids (NAPL) and dissolved contaminants while preserving sediment structure. Air sparging, on the other hand, injects air into the saturated zone to facilitate both the volatilization of contaminants and the growth of aerobic bacteria that contribute to degradation. This technique can be implemented through in-well aeration or direct air injection, promoting the movement of contaminants toward the surface for extraction. The pump and treat method are another effective approach for managing contaminated groundwater in aquaculture systems. This technique involves extracting groundwater through wells and treating it using various methods such as air stripping or activated carbon filtration (Njoku *et al.*, 2021). While pump and treat systems can enhance pollutant removal, their effectiveness may be diminished in low-permeability aquifers, often necessitating long-term management strategies to ensure comprehensive remediation. Vacuum-enhanced systems can improve the recovery rate of pollutants by simultaneously removing soil vapors and contaminated groundwater, though careful monitoring is essential to prevent rapid water table drawdown and potential contaminant smearing.

6. Conclusion

The growth of aquaculture is increasing the demand for fish, but this expansion brings significant challenges related to water quality. Pollution from heavy metals, pesticides, pharmaceuticals and antibiotics threatens aquatic ecosystems and the safety of aquaculture products. Addressing these issues requires better waste management, sustainable agricultural practices and stronger regulations to protect water resources. By prioritizing water quality and reduction of anthropogenic activities and the development of effective remediation, can ensure the sustainability of aquaculture and secure food resources for the future.

7. References

Baquero, F., Martínez, J.L., Cantón, R., 2008. Antibiotics and antibiotic resistance in water environments. *Curr. Opin. Biotechnol.* 19(3), 260-265. DOI: https://doi.org/10.1016/j.copbio.2008.05.006.

Cizmas, L., Sharma, V.K., Gray, C.M., McDonald, T.J., 2015. Pharmaceuticals and personal care products in waters: Occurrence, toxicity and risk. *Environ. Chem. Lett.* 13, 381-394. DOI: https://doi.org/10.1007/s10311-015-0524-4.

Gothwal, R., Shashidhar, T., 2015. Antibiotic pollution in the environment: A review. *Clean-Soil, Air, Water* 43(4), 479-489. DOI: https://doi.org/10.1002/clen.201300989.

Hassaan, M.A., El Nemr, A., Madkour, F.F., 2016. Environmental assessment of heavy metal pollution and human health risk. *Am. J. Water Sci. Eng.* 2(3), 14-19. DOI: https://doi.org/10.11648/j.ajwse.20160203.11.

Kumar, G., Kumar, S., Paul, T., Pal, P., Shukla, S.P., Kumar, K., Jha, A.K., Pradeep, S., 2024. Ecotoxicological risk assessment of triclosan, an emerging pollutant in a riverine and estuarine ecosystem: A comparative study. *Mar. Pollut. Bull.* 205, 116667. DOI: https://doi.org/10.1016/j.marpolbul.2024.116667.

Kumar, V., Sharma, A., Kumar, R., Bhardwaj, R., Kumar Thukral, A., Rodrigo-Comino, J., 2020. Assessment of heavy-metal pollution in three different Indian water bodies by combination of multivariate analysis and water pollution indices. *Hum. Ecol. Risk Assess.* 26(1), 1-16. DOI: https://doi.org/10.1080/10807039.2018.1497946.

Malyan, S.K., Singh, R., Rawat, M., Kumar, M., Pugazhendhi, A., Kumar, A., Kumar, V., Kumar, S.S., 2019. An overview of carcinogenic pollutants in groundwater of India. *Biocatal. Agric. Biotechnol.* 21, 101288. DOI: https://doi.org/10.1016/j.bcab.2019.101288.

Njoku, V.O.N., Arinze, C., Chizoruo, I.F., Blessing, E.N., 2021. A review: Effects of air, water and land dumpsite on human health and analytical methods for determination of pollutants. *Anal. Methods Environ. Chem. J.* 4(03), 80-106. DOI: https://doi.org/10.24200/amecj.v4.i03.147.

Pandey, S., Kumari, N., 2023. Impact assessment of heavy metal pollution in surface water bodies. *Metals Water,* 129-154. DOI: https://doi.

org/10.1016/B978-0-323-95919-3.00004-5.

Rad, S.M., Ray, A.K., Barghi, S., 2022. Water pollution and agriculture pesticide. *Clean Technol.* 4(4), 1088-1102. DOI: https://doi.org/10.3390/cleantechnol4040066.

Rathfelder, K., Lang, J.R., Abriola, L.M., 1995. Soil vapor extraction and bioventing: Applications, limitations and future research directions. *Rev. Geophys.* 33(S2), 1067-1081. DOI: https://doi.org/10.1029/95RG00402.

Saleh, I.A., Zouari, N., Al-Ghouti, M.A., 2020. Removal of pesticides from water and wastewater: Chemical, physical and biological treatment approaches. *Environ. Technol. Innov.* 19, 101026. DOI: https://doi.org/10.1016/j.eti.2020.101026.

Vandermaesen, J., Horemans, B., Bers, K., Vandermeeren, P., Herrmann, S., Sekhar, A., Seuntjens, P., Springael, D., 2016. Application of biodegradation in mitigating and remediating pesticide contamination of freshwater resources: State of the art and challenges for optimization. *Appl. Microbiol. Biotechnol.* 100, 7361-7376. DOI: https://doi.org/10.1007/s00253-016-7709-z.

Wang, J., Wang, S., 2016. Removal of pharmaceuticals and personal care products (PPCPs) from wastewater: A review. *J. Environ. Manage.* 182, 620-640. DOI: https://doi.org/10.1016/j.jenvman.2016.07.049.

Zeng, Y., Chang, F., Liu, Q., Duan, L., Li, D., Zhang, H., 2022. Recent advances and perspectives on the sources and detection of antibiotics in aquatic environments. *J. Anal. Methods Chem.* 2022(1), 5091181. DOI: https://doi.org/10.1155/2022/5091181.