

Antimicrobial Resistance in Aquaculture: The Silent Threat Beneath the Water

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Abstract

Aquaculture has emerged as one of the fastest-growing food production sectors and is essential for global food and nutritional security. However, the increasing use of antibiotics to control bacterial diseases has contributed to the emergence and spread of antimicrobial resistance (AMR), a major threat to aquatic animal health, environmental sustainability, and public health. Aquatic environments serve as important reservoirs of antibiotic residues, resistant bacteria, and resistance genes, facilitating their dissemination through water systems, seafood, and interactions between farmed and wild organisms. The rise of AMR compromises disease management, reduces treatment efficacy, and leads to significant economic losses in aquaculture. Moreover, the interconnected nature of humans, animals, and the environment highlights the need for a One Health approach to address this growing challenge. Sustainable alternatives, including vaccination, probiotics, improved biosecurity, and precision technologies, offer promising solutions to reduce antibiotic dependence. Combating AMR requires coordinated global efforts to ensure the long-term sustainability and resilience of aquaculture systems.

Keywords: Aquaculture, Antimicrobial resistance, Food security, Health

Introduction

Aquaculture is one of the fastest-growing food-producing sectors of the world and supplies more than half of the aquatic food consumed worldwide. Aquaculture is becoming a critical pillar of global food security in the face of a growing world population and increasing demand for high-quality protein. Fish, prawns and other aquatic organisms are a crucial source of nutrition and livelihood for millions of people worldwide. However, alongside this remarkable growth, the sector is facing an increasing challenge that

threatens not only aquaculture production, but human and environmental health as well antimicrobial resistance (AMR). Antimicrobial resistance (AMR), often referred to as the "silent pandemic," occurs when microorganisms, particularly bacteria, evolve the ability to survive exposure to antimicrobial agents that were once effective against them (Watts et al., 2017). Antimicrobial resistance (AMR) is a natural evolutionary process driven by selection pressure; however, the extensive use of antimicrobials and various aspects of modern human activities have significantly accelerated the emergence and spread of latent or precursor resistance genes in bacterial populations (Deng et al., 2025).

The spread of resistant microbes makes infections harder to treat, leading to higher mortality, increased healthcare costs and reduced effectiveness of life-saving medicines. AMR is often thought of as a human medicine problem, but aquatic environments have become significant reservoirs and transmission routes of antimicrobial resistance. The emergence of antimicrobial resistance in aquaculture is a multifaceted issue with ramifications for fish health management, environmental sustainability, food safety, and public health (Madhulika et al., 2025b). Understanding the ways in which resistance develops and spreads is essential to ensuring the long-term sustainability of aquaculture worldwide.

Why Are Antibiotics Used in Aquaculture?

Aquatic animals are also affected by infectious diseases due to their biological nature, as is true for any organism. Intensive production systems create conditions that put animals under stress, and as animals are stressed by living in high density, this creates favourable conditions for the spread of disease from one animal to another through the transmission of pathogens (bacteria) (Deng et al., 2025). When a disease outbreak occurs from a bacterial infection in aquaculture, there can be a significant economic loss, which leads to the use of antibiotics to help farmers treat or prevent diseases. In aquaculture, antibiotics are commonly administered through medicated feeds or by direct application to the culture water for the prevention and treatment of bacterial diseases (Pepi and Focardi, 2021). These methods are successful in preventing or controlling the spread of bacterial infection; however, there can be negative effects caused by overuse or misuse of antibiotics and/or failing to diagnose the cause of a disease. The use of antibiotics in aquatic systems has its own unique challenges compared to their use in land-based livestock systems. Antibiotics may enter subsystems of aquaculture (ponds, tanks, rivers, lakes, and coastal waters), and as they enter the aquatic environment, they may not only affect the bacteria that they are intended to treat, but also other microorganisms. The widespread

application of antibiotics in aquaculture creates an environment conducive to the selection, persistence, and dissemination of antibiotic-resistant bacteria (Watts et al., 2017).

How Does Antimicrobial Resistance Develop?

Bacteria have incredible flexibility in nature. The vast majority of the bacteria that have the potential to be impacted by antimicrobial treatment are destroyed; however, a select few will have some genetic ability to maintain their existence and continue to reproduce (Natrah et al., 2025). The use of antimicrobial agents promotes the spread of antimicrobial-resistant bacteria. The mechanisms by which microorganisms may develop resistance include natural mutations as well as gaining genes of resistance from others via conjugation, transformation, and transduction. In effect, within the microbial population, there is the capability of knowledge to be exchanged among bacteria, allowing for a rapid dissemination of resistant organisms throughout multiple environments and between species. The continuous exposure of antimicrobials upon bacteria fosters selective pressures to favour resistant organisms and hastens the development of antimicrobial resistance (Deng et al., 2025).

Aquatic Environments: A Reservoir for Resistance

Aquatic environments support extensive microbial growth and facilitate the widespread dispersal of microorganisms through water. When antibiotics are added to aquatic environments, residual antibiotics can remain in the sediment, water column and the surrounding environment. The presence of residual antimicrobials creates an environment for the persistence and growth of resistant microbes (Natrah et al., 2025). Fish farms typically support a large population of diverse microbes, including beneficial bacteria, opportunistic pathogens, and environmental microorganisms. The presence of antibiotics creates an opportunity for resistance genes to be exchanged between these groups of microbes, resulting in vast reservoirs of antimicrobial-resistant bacteria (Reverter et al., 2020). The issue of antimicrobial resistance is not limited to aquaculture facilities; the water that is discharged from aquaculture facilities can introduce resistant bacteria and resistance genes into rivers, lakes, estuaries and coastal ecosystems; therefore, the spread of antimicrobial resistance can occur well beyond the original point of antibiotic usage. This interconnectedness of the world indicates that the problem of antimicrobial resistance is a global environmental problem, not just a problem at the aquaculture farm level (fig. 1) (Watts et al., 2017).

The One Health Perspective

Modern strategies to prevent antimicrobial resistance are becoming more collaborative, integrating the idea of One Health into their strategy, which looks at how human beings,

animals, and the environment all interact with one another in ways that affect each other's health. Aquaculture provides opportunities for that interaction. Antimicrobial-resistant bacteria account for an estimated 35,000 annual deaths in the USA, 33,000 in the European Economic Area, and 58,000 in India, with potentially greater mortality in Southeast Asia; these numbers are expected to continue rising (Reverter et al., 2020).

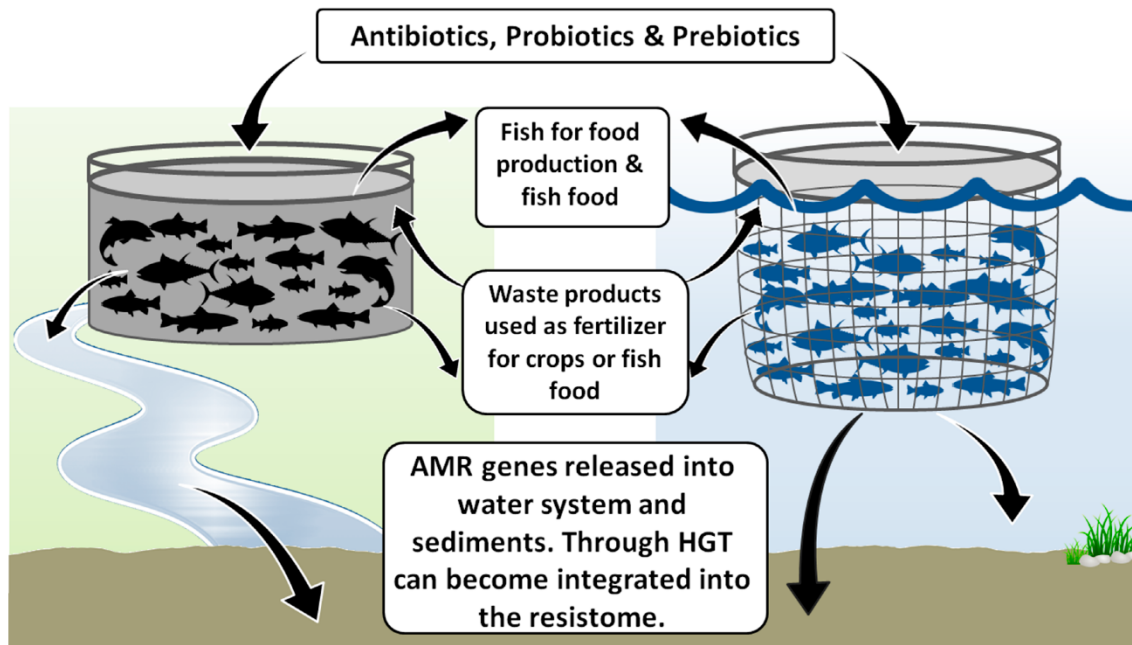


Fig. 1 Pathways of antimicrobial resistance (AMR) in aquaculture. Figure taken from Watt et al. (2017), under CC BY 4.0.

Fish farms are located in close proximity to natural bodies of water, allowing microorganisms to transmit between fish that are raised in aquaculture and those in the wild, as well as to and from freshwater and saltwater bodies, the environment, and humans. For example, bacteria that have become resistant to antimicrobials will typically enter the human food chain through seafood. Furthermore, resistance genes can be spread through water systems, thereby potentially affecting humans, livestock, and wildlife. Additionally, resistant bacteria from hospitals and agricultural runoff can also infiltrate aquatic systems and, therefore, impact the microorganisms that are present in aquaculture establishments (Watts et al., 2017). As a result, the transfer of microorganisms will continue to occur on a global scale; therefore, no one sector can prevent the emergence of antimicrobial resistance on its own. The only way to stop antimicrobial resistance is through coordinated action among human health, veterinary medicine, agriculture, aquaculture, and environmental management.

Consequences for Aquaculture

Antimicrobial resistance is becoming an increasing threat to aquaculture. As bacteria develop

resistance to traditional antibiotics, it becomes more challenging for farmers to manage outbreaks of these diseases. Because of this, farmers may experience larger numbers of fish lost due to disease, poor growth rates and economic losses associated with reduced productivity (Madhulika et al., 2025b). In addition, the lack of efficacy of currently used antimicrobial treatments limits management options. In difficult situations, resistant bacteria can spread rapidly through a farm's production cycle, which jeopardises the entire production cycle. Higher therapy costs and reduced productivity may make aquaculture farms less financially viable. In addition, the concern about antimicrobial resistance can create a negative impact on consumers' trust and trade internationally. Many countries have established strict limits on residues of antibiotics and the use of antimicrobials in seafood. Failure to comply with these regulations can limit access to markets and result in financial losses to producers (Natrah et al., 2025).

Environmental Impacts

There are still many ways that the effects of antimicrobial resistance on the water environment can be impactful. One of these includes impacts due to antibiotics being introduced into aquaculture facilities. When antibiotics are placed into the water, they will change the microbial communities and ecological processes of that aquatic ecosystem (Reverter et al., 2020). Over time, microorganisms that provide nutrient cycling, decomposition of organic material, and ecosystem functioning can be impacted by long-term exposure to antibiotics. Sediments will collect and hold both the antibiotic residues and resistance-gene building blocks over time. The sediment provides a good environment for genetic exchange between all of the microorganisms which contributes to the persistence and spread of resistance. In addition to these things, the spread of antibacterial resistance into the aquatic environment is of great concern in regard to the conservation of biodiversity (Pepi and Focardi, 2021). Wild fish and other aquatic organisms could be exposed to pathogens that are resistant to available antibiotics, which will likely have negative effects on the health of the ecosystem and its ability to recover after disruption

Climate Change and Antimicrobial Resistance

Research is growing into how climate change could complicate the problem of antimicrobial resistance even more. Higher water temperatures will allow many different types of bacterial pathogens to grow and spread more rapidly. In addition, higher temperatures may alter the make-up of microorganisms (microbial community composition) and increase the chances of transferring resistance genes (Pepi and Focardi, 2021). Natural disasters, such as floods and

storms, can also spread more resistant bacteria and antibiotic contamination among the different parts of a waterway. As climate change creates additional stresses for aquatic organisms, they may be more likely to contract diseases that will result in the greater use of antibiotics (Madhulika et al., 2025a). The relationship between climate change and antimicrobial resistance contributes to the need for integrated and forward-thinking management strategies.

Alternatives to Antibiotics

While we've made progress in the development of alternatives to decrease the reliance on antimicrobial treatments for aquaculture, it is more recent vaccinations that are now considered the most successful disease prevention method in aquatic animal production. Vaccination is effective because vaccines stimulate the development of protective immunity in the host, which decreases the incidence of diseases and rightfully reduces the need for antimicrobial treatment (Madhulika et al., 2025a). Probiotics are live microorganisms that improve gut health and improve the resistance of animals to disease. Probiotics help the host animal to resist infection from pathogens, enhance the immune response of the animal, and create a healthy balance of the resident microbiota of the animal. Prebiotics are non-digestible substances that specifically encourage the growth of beneficial gut microorganisms. Synbiotics are a combination of prebiotics and probiotics, so therefore maximize the health effects of both types of additives. Synthetic pre-and-probiotic feed additives are becoming increasingly popular as sustainable alternatives to antimicrobials (Natrah et al., 2025). Phytogetic Compounds (plant-derived bioactive compounds) possess antimicrobial, antioxidative, and immune-stimulating properties and therefore, a great deal of research is currently being conducted on the use of herbal extracts and essential oils as natural alternatives for disease management. Improving management practices is the key to preventing diseases in aquaculture. Proper stocking density, improved water quality, biosecurity measures, and proper nutrition are all important ways to reduce the incidence of diseases and the reliance on antibiotics to treat those diseases (Madhulika et al., 2025b).

Challenges and Recommendations

Antimicrobial resistance is an example of a global health issue that calls for collaboration; this includes input from all stakeholders, farmers, scientists, regulators, industry partners and consumers) (Natrah et al., 2025). Promoting responsible antibiotic use can be achieved by educating and creating awareness of proper use among all stakeholders involved. Strengthening regulations through surveillance systems to monitor antimicrobial use and the patterns of

resistance can improve data collection efforts. Investing in research to develop new ways to prevent AMR and understand the novel mechanisms for developing AMR is critical to succeeding with AMR issues (Deng et al., 2025). Finally, aquaculture must shift from a treatment-based management strategy to a preventative management strategy by concentrating on fish health, environmental sustainability and ecosystem resilience.

Conclusion

Antibiotic overuse and misuse significantly threaten modern aquaculture technologies, but they have historically provided effective ways to control bacterial diseases. Due to misuse and overuse, antibiotic-resistant microorganisms have developed that threaten animal health, environmental sustainability, and public health. Also, the challenge of AMR goes far beyond aquatic animal farming as these interconnected ecosystems are impacted through many complex pathways. The expansion of the global aquaculture industry further emphasizes the need for effective sustainable disease management strategies. Sustainable aquaculture management of AMR in addition to developing globally sustainable food production systems will be developed by adopting responsible antibiotic use, building strong biosecurity protocols, vaccinating fish, nutritionally balancing fish diets through functional feeds, utilizing advanced technologies, and developing a One Health approach. The issue of antimicrobial resistance will not be resolved through one solution but by developing a coordinated approach to protect all components of our planet's ecosystems: aquatic livestock, ocean ecosystems, and humans, now and in the future. Responsible AMR management is an imperative for the future of sustainable aquaculture.

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