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## CURRENT CHALLENGES AND FUTURE PERSPECTIVES OF BACTERIAL INFECTIONS IN FRESHWATER FISH AQUACULTURE HEALTH

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### ABSTRACT

Bacterial infections are one of the main obstacles to freshwater fish culture and are related to health, efficiency, and economic weight of production. Microorganisms, including *Aeromonas*, *Flavobacterium*, *Streptococcus*, and *Vibrio*, are responsible for diseases such as bacterial gill disease, *hemorrhagic septicemia*, and *streptococcosis*, which affect numerous freshwater fish. These diseases have economic consequences, including high fatality rates, low growth rates, and treatment. Control of bacterial diseases such as antibiotics, and chemicals. But abuse have led to resistant strains, also threat to productivity and public health. Environmental concerns have been raised due to antibiotic and chemical effluent release into aquatic bodies, which affect non-target species and lead to regulatory restrictions. To overcome these problems, novel approaches have been investigated. Other possibilities, such as probiotics, prebiotics and immunostimulants, are being developed to possibly improve fish protection against bacteria in reducing infection. Vaccination provides selective protection against certain bacterial pathogens. Progress in diagnostics allows earlier discovery and better management of the disease. New Focus The present focus is toward sustainable disease management practices that support both fish health and environment conservation, while maintaining economic feasibility. The combination of biosecurity, good husbandry and new treatment methods will be vital in coping with bacterial infections in freshwater fish farming.

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## INTRODUCTION

Freshwater fisheries are important for the world in terms of food security, economics and environment as a whole. This is a major source of protein for human consumption and a way of life for millions worldwide. Global aquaculture production exceeded 114.5 million tons in 2018, according to a report from the Food and Agriculture Organization (FAO), with contribution from freshwater aquaculture amounting to approximately 51.3 million tons<sup>1, 2</sup>. This highlights the important contribution of freshwater aquaculture to the growing global demand for fish and fishery products.

**Economic and Ecological Significance:** Freshwater fish culture has significant economic importance and serves as an essential source of livelihood for small to medium farmers, especially in the developing countries. In nations like China, India, and Indonesia, freshwater fish culture is an essential contributor to national economy, rural upliftment and earning foreign exchange<sup>3,4,5</sup>. It also offers employment along the supply chain ranging from hatchery through farming, processing and marketing. From an environmental point of view freshwater farming can act as a means of protecting wild fish

populations, for example by reducing the amount of fish caught. But it also presents threats such as habitat alteration, water contamination and the addition of invasive species. The application of sustainable management practices is of paramount importance for minimizing the environmental impact of freshwater aquaculture and to preserve the health of aquatic ecosystems<sup>4,6,7</sup>.

**Bacterial Infections as a Key Health Issue:** Bacterial diseases are one of the most serious health problems in freshwater fish culture because of both the effect on the health of fish and on the production economy. Different bacterial pathogens including *Aeromonas*, *Flavobacterium*, *Streptococcus* and *Vibrio* have been recognized as etiological agents for diseases like bacterial gill disease, *hemorrhagic septicemia*, *streptococcosis* etc., in the aquaculture<sup>8</sup>. These infections can lead to significant fish kills, reduced growth, and treatment and prophylactic costs. According to recent reports, the process of bacterial infections are contributing more in a problematic way in many aspects even<sup>9,10,11,12</sup>. The greater prevalence of aquaculture practices has created conditions that are conducive to transmitting pathogens. High stocking densities, bad water quality, and stress

factors resulting from intensive farming practices render fish more susceptible to bacterial disease.

**Challenges Associated with Bacterial Infections:** Antibiotics are extensively and misused in freshwater fish farming, leading to the development of antibiotic-resistant bacteria. This is not only a big threat to the aquaculture industry, but also to human lives. Antibiotic resistance has been singled out by the World Health Organization<sup>13, 14</sup> as among the most pressing threats to global health, food security and development. As a result, many countries have imposed restrictions on the use of antibiotics in aquaculture, making the control of bacterial diseases even more challenging<sup>15, 16</sup> (Figure-1). In addition to antibiotic resistance, concerns have risen following the release of antibiotics and chemicals into the aquatic environment. They may influence non-target species and unbalance the ecosystems. For example, antibiotic residues may affect microbial communities and disease treatment chemicals can be toxic to (in) aquatic invertebrates or other wildlife<sup>17</sup>.



it results in *streptococcosis* in freshwater fish. This condition is observed in the form of meningitis, septicemia, and loss of vision with often high lethality. These infections are common in high-density aquaculture, as they can often spread easily between hosts (due to intimate contact of the fish)<sup>24,25,26</sup>.

**Vibrio spp.:** While *Vibrio* infections are more commonly associated with marine environments, they can also infect fresh water organisms. *Vibrio anguillarum* is well known for its ability to induce *Vibriosis*, it is characterized by hemorrhagesepticemia and skin lesions. This disease is commonly associated with some types of environmental stress such as temperature fluctuation or poor water quality. These bacterial pathogens are associated with bacterial gill disease, *hemorrhagic septicemia*, and *streptococcosis*, which may cause severe impacts on fish health and the productivity of aquaculture. Control of these infections is crucial for the sustainability of freshwater fish farming<sup>27, 28</sup>.



Figure 1. Major bacterial diseases affecting freshwater aquaculture species and causative agents

Table 1. Summarizing the major bacterial pathogens affecting freshwater fish aquaculture, their associated diseases

Pathogen	Disease	Symptoms	Key Reference
<i>Aeromonas spp.</i>	Motile Aeromonad Septicemia (MAS)	Hemorrhagic lesions, ulcers, septicemia	<sup>29</sup>
<i>Flavobacterium spp.</i>	Columnaris Disease	Necrotic lesions, gill necrosis	<sup>30</sup>
<i>Streptococcus spp.</i>	Streptococcosis	Meningitis, septicemia, ocular damage	<sup>31</sup>
<i>Vibrio spp.</i>	Vibriosis	<i>Hemorrhagic septicemia</i> , skin ulcers	<sup>32</sup>

**Major Bacterial Pathogens in Freshwater Fish Aquaculture:** Aquaculture production of freshwater fish is increasing rapidly, and bacterial diseases have become serious obstacles to the sustainable development of this industry. Of the numerous bacterial pathogens infecting freshwater fish, *Aeromonas*, *Flavobacterium*, *Streptococcus*, and *Vibrio* are most prevalent. These bacteria are associated with several severe diseases, and cause enormous economic losses (Table-1).

***Aeromonas spp.* :** The *Aeromonas* genus are comprised of diverse species, including *Aeromonas hydrophila* which is a major pathogenic agent causing motile aeromonad septicemia (MAS) in fish. There is bleeding, ulcers, and septicemia and frequently high mortality. In intensive aquaculture systems, such as those in the southern parts of China (e.g., Gunagdong province), where over-crowding and poor water quality are prevalent, the infection rapidly spreads<sup>18,19,20</sup>.

***Flavobacterium spp.*:** Columnaris (e) disease, is an infection of the skin and gills of fish caused by the bacterium *Flavobacterium columnare* in warm-blooded animals which may result in necrotic lesions of affected tissues, and gill necrosis. It is a warm water bacterium and a serious problem for a number of species of freshwater fish. *Flavobacterium* infections often occur in stress conditions, such as handling and transportation<sup>21, 22, 23</sup>.

***Streptococcus spp.*:** Streptococcal infection, such as *Streptococcus iniae* and *Streptococcus agalactiae*, is of particular importance in that

**Current Challenges in Managing Bacterial Diseases:** With the development of freshwater aquaculture, the outbreak of bacterial diseases has been increasing, posing a dangerous threat to fish health and farm management. Issues that I'm dealing with are just a bit more difficult than they have been in the past and that's due to a combination of biological issues, environmental issues and operational issues. Five key difficulties are presented below.

**Mis- and Overprescribing Antibiotics:** Antibiotics have been widely used for both therapy and prophylaxis in the aquaculture industry. However, their widespread and indiscriminate use is a key driver of antimicrobial resistance (AMR). In many places, antibiotics are used some quaquaversally without any consultation with a vet nor do food product withdrawal times are respected, which in-turn has led to antibiotic residue in the aquatic products and habitats<sup>33, 34</sup>. Furthermore, uneaten medicated feed and fish waste have been documented to contribute to antibiotic accumulation in sediments, maintaining selective pressure on microbial communities<sup>35</sup>.

**Multidrug-Resistant (MDR) Bacterial Strains Have Arisen:** The prolonged use of broad-spectrum antibiotics in aquaculture has given rise to multi-drug resistant pathogens such as *A. hydrophila*, *E. tarda*, and *F. columnare*<sup>36, 37</sup>. The MDR strains create additional burden for treatment leading to prolonged infections and mortality. Furthermore, resistance genes are often located on mobile genetic elements, which increases the possibility of horizontal gene transfer among aquatic bacteria<sup>38</sup>.

### Challenges in Early Diagnosis and Deficiency of Rapid Detection Tools:

Both timely and accurate diagnosis are critical elements of disease management, yet many farms lack the rapid, sensitive, economic diagnostics required. Diagnosis is often symptomatic and subjective. While advanced molecular methods (such as PCR and qPCR) can be utilised in a research setting<sup>39, 40</sup>, they are not commonly used on-farm for practical reasons (e.g. expense, technical requirements and lack of infrastructure).

**Shortage of Effective Vaccines:** Although vaccination is potentially a good prophylactic method, vaccine for freshwater fish pathogens is rarely developed. In the processes of constructing vaccines, the heterogeneity of bacterial strains, antigen variation, and species-specific immune responses make it difficult to establish universal vaccines. Injection, immersion, or oral administration as delivery approaches are frequently impractical or ineffective in the handling of a large number of juvenile fish in a commercial hatchery<sup>41</sup>.

tissues, water, and sediment, especially when it comes to early detection of pathogens like *Aeromonas hydrophila*, *Edwardsiella tarda*, and *Flavobacterium columnare*<sup>49, 50</sup>. PCR assays are highly sensitive and qPCR allows pathogen quantification<sup>51</sup>. Loop-mediated isothermal amplification (LAMP) is a rapid, cost-effective alternative to PCR and facilitates on-the-spot diagnosis within an hour<sup>52</sup>. New pathogens in aquaculture systems can be discovered using metagenomic approaches, such as next-generation sequencing (NGS)<sup>53</sup>. Biosensors technology is advancing for point-of-care (POC) applications and immunosensors and NABS for real-time detection<sup>54</sup>. However, affordable, field-friendly diagnostic instruments are still required for farmers who are not professionals of this area. Current molecular tools are too costly often, especially for smaller setups such as those in developing countries. The emphasis should be on streamlining detection systems without compromising on accuracy.

**Table 2. Overview of Antibiotic Resistance in Freshwater Aquaculture and Its Public Health Implications**

Key Issue	Description	Examples / Notes	References
Horizontal Gene Transfer (HGT)	Movement of resistance genes between bacteria via plasmids, integrons, or transposons in aquatic environments.	Enables spread of resistance from environmental bacteria to fish or human pathogens.	34
Presence of ARGs in Aquatic Systems	ARGs detected in fish tissues, pond water, sediments, and farm discharge.	Common genes include <i>tetA</i> , <i>sul1</i> , <i>blaTEM</i> .	48
Human Health Risks	Transmission of ARGs through fish consumption, water contact, or environmental runoff.	Potential colonization or infection with resistant bacteria.	47
Environmental Persistence	ARGs and resistant bacteria can remain in the environment long after antibiotic exposure.	Facilitates long-term ecological impact.	48
Antibiotic Misuse	Use without diagnosis, improper dosing, or non-compliance with withdrawal periods.	Contributes to resistance development.	33,34
Need for Stewardship	Implementation of responsible antibiotic practices and promotion of alternatives.	Probiotics, vaccines, immunostimulants, and regulation of drug use.	34

**Environmental stress causing disease:** Environmental stressors, such as poor water quality, the temperature gradient, heavy stocking density and organic load are some of the predisposing factors of fish to a disease outbreak. These stress factors suppresses the immune system of fish, making it more susceptible to opportunistic pathogens<sup>42</sup>. Moreover, increased temperatures resulting from climate change can affect pathogen virulence, disease timing, host susceptibility and thus also the susceptibility to diseases<sup>43</sup>.

**Resistance Phenomena and Public Health Issues:** The tremendous application of these components in freshwater aquaculture, for prophylaxis and treatment, has caused the diffusion of antibiotic resistance phenomena, a serious public health issue considering the link between natural freshwater ecosystems and human populations. HGT supports transfer spread of resistance in aquatic systems by conjugation, transformation and transduction between bacterial species. ARGs are disseminated among bacterial species by mobile genetic elements such as integrons, plasmids, and transposons<sup>44,45</sup>. ARGs also exist in fish tissues, water columns, and sediments, as well as biofilms in aquaculture systems. The tetracyclines (*tetA*, *tetM*), sulfonamides (*sul1*, *sul2*), and  $\beta$ -lactams (*blaTEM*, *blaCTX-M*), resistance genes are prevalent in antibiotic-applied aquaculture waters. These components remain after antibiotics stop use of drugs, which indicates their resistance in the environment. ARGs released from aquaculture could be taken up by humans in the process of contacting with the contaminated water, eating the contaminated fish or due to environmental runoff. Bacteria associated with fish could act as ARG reservoirs transferring ARG to human pathogens and potentially impacting global antimicrobial resistance (AMR)<sup>46, 47</sup>.

**Advances in Disease Detection and Diagnosis:** Accurate diagnosis of bacterial diseases is crucial for controlling outbreaks in freshwater fish farms. Conventional diagnostic methods, such as culture-based identification, are the most reliable methods, but are time-consuming and labour-consuming. These and similar molecular-based and biosensor technologies have significantly advanced the speed and resolution of aquatic disease diagnosis. Polymerase chain reaction (PCR) and quantitative real-time PCR (qPCR) are the most commonly used techniques for testing bacterial DNA from fish

**Future Perspectives:** The challenge of fisheries in fighting bacterial infections demands a forward-looking approach which integrates technology, environmental sustainability and global health. Precision aquaculture applies real-time monitoring, artificial intelligence (AI) and automated diagnostics to detect early signals of diseases as well as improve water quality and fish health parameters. These systems offer disease prediction/prophylaxis, and lead to less reliance on antibiotics and fewer illness episodes<sup>55</sup>. Ingenious options to traditional antibiotics, such as bacteriophage therapy and nanotechnology, have been developed. Targeting the entire microorganism (nanoparticles, antimicrobial agents, vaccines) Nanoparticles can deliver the antimicrobial agents or vaccines of interest for increased effectiveness and stability<sup>56</sup>. Even though Phage therapy—the application of bacteriophages for targeting pathogenic bacteria – has demonstrated success in trial aquaculture situations, it provides a species-specific strategy to address MDR strains<sup>57</sup>. In a changing climate, it's important to build robust aquaculture systems. Warming water and altered hydrology stress fish and enhance pathogen virulence. Strategies include IMTA, RAS and stress-resistant breeds of fish<sup>58</sup>.

## DISCUSSION

Bacterial diseases still constitute a major problem for freshwater fish farming around the world. Due to the advent of intensive culture conditions and pollution of the environment, infections caused by bacteria (such as *Aeromonas*, *Edwardsiella*, *Flavobacterium*, and *Streptococcus*) lead to severe mortality and economic loss. Such infections are aggravated by unfavorable water conditions, overpopulation, or a temperature drop which increases bacterial colonization due to poor hygiene and/or immune suppression in fish<sup>59</sup>. An important aspect is the high antibiotic consumption that has led to the emergence of multidrug-resistant (MDR) strains. Antibiotic residues and resistance genes have been detected in aquaculture systems as well as surrounding environment, causing concern about their resistance in the environment and subsequent transfer to humans through the food chain [Banerjee et al 2024]. In addition, lateral gene transfer between aquatic bacteria further enhances the distribution of

resistance characteristics, thus complicating disease management. This role of nonclinical environments in the spread of resistance may also apply to freshwater in which resistance genes that have a possible impact on human pathogens have recently been discovered<sup>60</sup>. Flaws in existing diagnostic techniques also hinder early disease interventions. Classical bacteriological methods are slow and labour-intensive. Despite the fact that molecular diagnostics, such as qPCR, LAMP, and CRISPR based approaches show promise, their high costs and technical complexity preclude their application in small holder farms<sup>61</sup>. In this sense, novel approaches such as probiotics, immunostimulants and phage therapy are emerging as environmentally friendly options to antibiotics. Furthermore, use of nanoparticle mediated drug delivery and precision aquaculture approaches may also provide hope in terms of early disease detection and focused treatment<sup>62</sup>. Given weak enforcement of regulations, particularly in developing countries, however, few if any countries live up to this ideal. Prompt, coordinated disease surveillance, enhanced vaccination campaigns and farmer access to knowledge are urgently required. A holistic One Health model, taking into account the aquatic, environmental, and public health perspectives, is required to address and control antimicrobial resistance and promote the sustainability of aquaculture. Further research should target climate-resilient agriculture, host-pathogen interaction, and the creation of affordable diagnostics and vaccines.

## CONCLUSION

Bacterial infections remain a significant threat to freshwater fish aquaculture, affecting the health of fish, farm productivity, and economic sustainability. The rise of multidrug-resistant pathogens, primarily due to excessive antibiotic use and inadequate biosecurity measures, has intensified the challenge of managing diseases. The current limitations in diagnostics and treatment effectiveness necessitate a move towards sustainable, science-driven solutions. Progress in molecular diagnostics, immunoprophylaxis, and the application of probiotics and nanotechnology presents promising alternatives to traditional antibiotic treatments. However, their effective adoption requires improved regulatory systems, farmer education, and greater accessibility, especially in areas with limited resources. A One Health strategy is crucial to tackle the interconnected risks of antimicrobial resistance across aquatic, environmental, and human sectors. Future research should prioritize the development of cost-effective vaccines, climate-adaptive farming practices, and integrated disease monitoring tools.

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