



Antimicrobial Resistance in Aquaculture: Patterns of Use, Public Health Implications and Alternatives to Antibiotics

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Bacterial diseases are a major cause of loss in aquaculture, and antibiotics have been widely used to treat them and, in some systems, to improve fish performance [1]. Resistant bacteria can have negative effects on production, on consumers and on aquatic environments [1]. Non-prudent use of antibiotics in aquaculture and other animal farming increases the risk that resistance emerges, because bacteria that survive exposure pass on their resistance traits [2]. Resistance is a concern beyond the farm because water connects aquaculture to wild aquatic life and to people. This is why AMR in aquaculture is discussed within the One Health framework, which treats animal, human and environmental health as interdependent [4]. This article reviews the evidence for resistance in aquaculture and the practical alternatives that are available or under development.

How resistance develops and spreads

Resistance arises when bacteria carrying resistance genes survive antibiotic exposure and multiply, so that resistant strains become more common. Resistance genes can also be transferred between bacteria, including between species, on mobile genetic elements such as plasmids. In aquaculture, antibiotics given in feed or water can reach sediments and surrounding water, where bacteria from many sources come into contact. This is general microbiological background rather than a finding specific to the sources cited here.

Intensive systems add further risk. Overcrowding and stress make fish more susceptible to infection, which increases the demand for treatment [1]. For this reason the strategic use of probiotics, vaccines and better husbandry is considered an effective route to reducing reliance on antibiotics and thereby limiting the emergence of AMR [1].

Evidence of resistance in farmed species

Catfish aquaculture

A global review of catfish aquaculture found that resistant bacteria are highly prevalent in catfish farming in developing countries, that a range of resistance genes are present in farming systems, and that beta-lactamase resistance genes are the most commonly identified [3]. The authors concluded that future work should develop affordable vaccines and probiotics to reduce antimicrobial use [3]. The review is specific to catfish and its findings should not be generalised to other species or regions without further data.

Research trends

A bibliometric analysis of the literature on antibiotic resistance in aquaculture, covering 2000 to 2025, identified key research areas, leading contributors, emerging challenges and alternative solutions [1]. It concluded that future research should emphasise interdisciplinary collaboration, novel antimicrobial alternatives and global monitoring approaches [1]. Bibliometric analyses show where research effort is concentrated, but do not by themselves measure the level of resistance on farms.

Case study: Chilean salmon aquaculture

Chile is a major salmon producer, and its industry faces persistent challenges from bacterial pathogens, particularly *Piscirickettsia salmonis*, which has led to substantial antimicrobial use, reported as 351.1 tonnes in 2024 [4]. A workshop of 27 experts was convened to develop a roadmap for prudent antimicrobial stewardship, intended to inform public policy and industry practice [4]. The workshop recognised aquaculture's dual role in AMR development, which means that the sector can both be affected by resistance and contribute to it. It highlighted the need for international collaboration, proactive policy design, and comprehensive One Health surveillance systems guided by expert committees [4]. It also acknowledged that vaccines against *P. salmonis* have limitations, and that no effective vaccine is yet available to control piscirickettsiosis [4]. The authors concluded that antimicrobial use remains essential for controlling bacterial disease for now, but that the emergence of resistance and its effects on environment, animals and people call for a change in approach [4]. The case is instructive because it shows a dependency: where preventive tools are inadequate for a major pathogen, antibiotics continue to be used at large scale, so the priority becomes stewardship (using the right drug, at the right dose, only when necessary) and investment in better vaccines.

Alternatives to antibiotics

Table 1 summarises the main options and their limitations according to the sources reviewed.

Table 1. Alternatives to antibiotics in aquaculture, summarised from the sources cited.

Alternative	Potential benefit	Main limitation	Source
Vaccination	Prevents disease before infection; critical for fish disease control	Mass vaccination is difficult and costly; does not work at all life stages or in invertebrates	[5]
Probiotics, prebiotics, synbiotics	Influence gut microbiome; improve growth, feed use, immunity and disease resistance	Effects vary by species, strain and system	[5,6]
Bacteriophage therapy	Viruses that lyse specific bacteria	Still at an early stage of development	[5]
Quorum quenching	Reduces bacterial virulence by disrupting communication	Largely experimental	[5]
Medicinal plants	Antimicrobial, immunostimulant or stress-reducing compounds	Standardisation and dosing; evidence mixed	[5]
Selective breeding	Sustainable, heritable resistance	Progress can be slow	[5]
Antimicrobial peptides, bacteriocins	Natural antimicrobial molecules	Cost and delivery; early-stage	[2]

Vaccines

Vaccines are central tools for preventing and controlling fish diseases, although their use has been limited by the practical and logistical challenges of mass vaccination and by cost-effectiveness [5]. Approved commercial inactivated fish vaccines can prevent infections caused by pathogens including *Lactococcus*, *Streptococcus* and *Aeromonas* [2]. Live attenuated vaccines, which use bacteria or viruses with reduced pathogenicity, are used against diseases such as furunculosis, vibriosis and *Edwardsiella* infections [2]. Where several pathogens are present, multivalent vaccines are considered a highly cost-effective approach [2]. In catfish, inactivated vaccines are common but their limited protective efficacy makes effective adjuvants necessary [3].

A review of the shift from antibiotics to vaccine prophylaxis notes that earlier fish vaccine studies often lacked assessment of efficacy across different environments and species and tended to focus on single pathogens, leaving the influence of pathogen interactions poorly understood [9]. It also describes the progression from traditional vaccines to newer generations, including DNA, monovalent and polyvalent vaccines [9]. This indicates that vaccine performance under commercial conditions is still a research need.

Probiotics, prebiotics and plant-derived products

Probiotics defend against pathogens by producing antimicrobial metabolites and by stimulating immune responses [6]. Examples from recent studies include *Bacillus* strains that improved resistance of shrimp to *Vibrio parahaemolyticus*, the cause of AHPND, and reduced disease in experimental trials [1]. A systematic review of probiotics and prebiotics reported that fermented seaweed improved fish health and performance and showed resistance against the pathogens *Vibrio harveyi* and *Aeromonas hydrophila* [6]. A European review similarly reports that probiotics combined with plant products can improve growth, immune response and disease resistance in farmed fish and crustaceans [8]. Most of these findings come from experimental or small-scale studies, so the results need confirmation on commercial farms. Some reviewers are optimistic but cautious. One review of the peer-reviewed literature concluded that the alternatives it covered have great potential, with some already showing proven benefits while others remain experimental, and that targeted research funding is needed to advance them [7].

Phage therapy, quorum quenching and breeding

Bacteriophages are promising but still at an early stage of development, and quorum quenching aims to reduce the pathogenicity of bacteria by disrupting their signalling [5]. Selective breeding for disease resistance offers a durable option that works with other measures, although progress is slow [5]. These approaches are best seen as longer-term contributions to an integrated programme.

An integrated stewardship pathway

Stewardship means using antimicrobials responsibly so that they remain effective. In aquaculture it can be organised as a continuous cycle (Figure 1): prevent disease through husbandry and immunisation, diagnose accurately before treatment, treat only when necessary and under veterinary supervision, monitor use and resistance, and review practice and policy in light of the data.

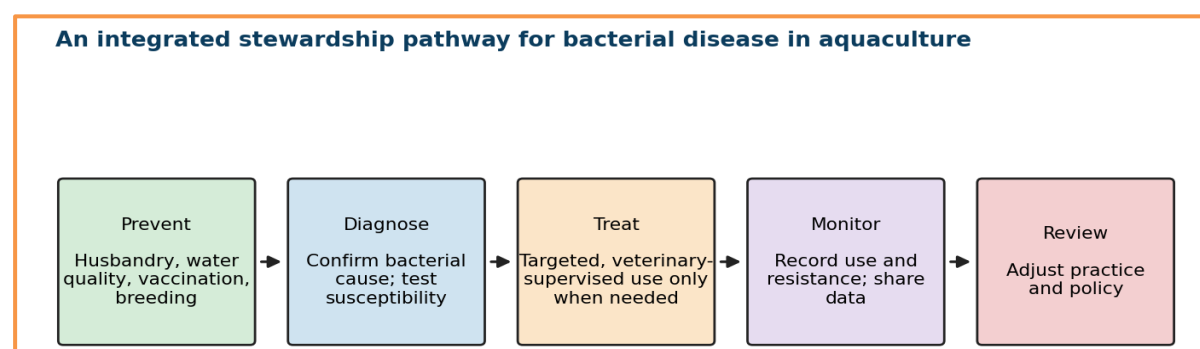


Figure 1. Stewardship cycle for bacterial disease in aquaculture (schematic prepared for this article, based on [1,4,5]).

Surveillance is the weakest link in many countries. Without records of what is used and what resistance is present, neither farmers nor regulators can judge whether policies work. The Chilean workshop explicitly called for comprehensive surveillance systems [4], and the catfish review stressed the need for up-to-date species-specific data on AMR trends [3].

Discussion

Three conclusions follow from the evidence. First, prevention should come first: improved husbandry, water quality and vaccination reduce the number of disease episodes that require treatment. Second, alternatives to antibiotics vary in maturity. Vaccines and probiotics are in

use but have limits, while phages and quorum quenching are earlier-stage options. Third, the evidence base is uneven, with gaps in resistance data for many species and for low- and middle-income countries, where much aquaculture is concentrated [3].

This review is limited by its reliance on secondary sources and by the heterogeneity of studies. Reported figures of antimicrobial use (such as that for Chile) are specific to one industry and year, and should not be extrapolated to other settings.

Priorities for research and policy

- Develop affordable, effective vaccines for major bacterial pathogens that currently lack them, such as *P. salmonis*.
- Test probiotics and plant-derived products under commercial conditions and across life stages.
- Establish surveillance of antimicrobial use and resistance in aquaculture within One Health frameworks.
- Strengthen veterinary oversight and diagnostic capacity so that treatment is based on confirmed bacterial infection.
- Support breeding programmes for disease resistance as a long-term preventive tool.

Conclusion

AMR in aquaculture is a shared problem for animal, human and environmental health. Antibiotics remain necessary for some bacterial diseases, but dependence on them can be reduced by a combination of preventive husbandry, vaccination, probiotics, breeding and other emerging tools. Progress requires investment in research, particularly on vaccines for difficult pathogens, and in surveillance systems that allow policy to be judged against data.

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