



Aquaculture: sector-specific challenges and advances

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Summary

Antimicrobial resistance (AMR) represents a growing global health concern with major implications for aquaculture, the farming of aquatic animals and algae, such as fish, crustaceans, molluscs and seaweeds. Misuse and overuse of antibiotics in aquaculture can drive the emergence of resistant bacteria, threatening aquatic animal health and posing risks to human health through the food chain. Aquaculture's close connection to the aquatic environment makes it particularly vulnerable, as antibiotic residues and pollutants from aquaculture, agriculture and wastewater can enrich the resistome and promote the selection and spread of resistance genes in aquatic ecosystems.

The aquatic environment acts as both a reservoir and a vector for AMR, enabling dissemination not only through food, but also via occupational and recreational water exposure and wildlife contact. Addressing AMR in aquaculture requires a One Health approach that acknowledges the interdependence of human, animal and environmental health.

This article explores the historical emergence of AMR in aquaculture, focusing on the role of mobile genetic elements, such as plasmids, integrons and transposons, in horizontal gene transfer. It assesses trends in phenotypic resistance and presents a comprehensive overview of current surveillance and mitigation strategies aligned with One Health principles. International guidance from the World Health Organization, the Food and Agriculture Organization of the United Nations and the World Organisation for

Animal Health is discussed, with emphasis on harmonised antimicrobial use surveillance and improved transparency. Advances in antimicrobial susceptibility testing and molecular diagnostics, including whole genome sequencing, are presented as tools to enhance AMR surveillance. Key recommendations include strengthened, system-appropriate biosecurity and on-farm management to prevent disease introduction and reduce antimicrobial reliance. While vaccination has delivered sustained reductions in antimicrobial use in intensive finfish systems in high-income settings, notably Atlantic salmon, it remains unavailable for many species and production systems in low- and middle-income countries. In crustacean aquaculture, where vaccination is not feasible, there is a need for greater emphasis on affordable, validated non-antibiotic disease control approaches, including immunostimulants, probiotics and phage-based interventions, integrated within broader biosecurity frameworks.

Keywords

Antibiotic use – Antimicrobial resistance – Aquaculture – Mobile genetic elements – One Health – Surveillance.

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Introduction

Antimicrobial resistance (AMR) poses a significant threat to human, animal and plant health, with implications extending into aquaculture, defined as the farming of aquatic organisms such as fish, crustaceans, molluscs and aquatic plants. This article examines the development of AMR in aquaculture, its surveillance, and mitigation strategies.

Aquaculture is the fastest-growing food production sector globally, playing a vital role in enhancing food security, nutrition, livelihoods and economic growth. According to the 2024 State of World Fisheries and Aquaculture report [1], global aquaculture production reached 130.9 million tonnes in 2022, including 94.4 million tonnes of aquatic animals and 36.5 million tonnes of algae, with a farmgate value exceeding US\$ 330 billion. Today, aquaculture provides more than 57% of aquatic animal products for human consumption, a proportion that continues to rise.

This growth is driven by increasing global demand for sustainable protein sources, especially in Asia, Africa and Latin America [1]. However, the rapid intensification of production has led to higher stocking densities, elevating the risk of infectious disease outbreaks [2]. Disease is now considered the single greatest cause of economic loss in aquaculture globally [3].

In many regions and production systems, antibiotic use has become a routine response to disease challenges, contributing to the emergence of AMR in aquatic environments [4,5]. The spread of AMR threatens not only aquaculture sustainability, but also broader One Health initiatives aimed at safeguarding animal, human and environmental health.

Development of antimicrobial resistance: a One Health problem

The history of AMR development is closely linked to the widespread use of antibiotics in human medicine and agriculture, including the emergence of resistance in fish pathogens after antimicrobial use (AMU) began in aquaculture [6]. In aquaculture, antibiotics are used primarily for therapeutic purposes, particularly in Europe, where the use of antibiotics as growth promoters has been forbidden since 2006 [7]. However, they may also be used prophylactically and as growth promoters in certain parts of the world. When done indiscriminately, this use exerts selective pressure on bacteria, leading to the emergence and spread of resistant strains. AMR is a quintessential One Health issue, as resistant bacteria can transfer between animals, humans and the environment, complicating infection treatments across sectors [8].

National action plans for AMR vary significantly in their inclusion of aquaculture, with a 2023 study by Caputo *et al.* [9] revealing that 37% of 95 countries' national action plans fail to address aquaculture despite its role in global food production and AMR risk. Many countries overlook the sector's contribution to AMR, particularly in low- and middle-income nations, where antimicrobial access, antimicrobial use and enforcement of controls in aquaculture can be limited [10]. The One Health approach, integrating human, animal and environmental health, is inconsistently applied, with gaps in governance, surveillance and research hindering effective AMR mitigation.

Antimicrobial use in aquaculture

AMU in aquaculture varies significantly by region, species and production system [5]. Global consumption was estimated at 10,259 tons in 2017, with a projected 33% increase by 2030 due to intensification and disease pressures. This use is heavily concentrated in China and other Asian countries [11]. However, these estimates are subject to substantial uncertainty due to sparse and heterogeneous primary data, reliance on point-prevalence surveys, and assumptions of constant use intensity across species and regions [11]. In regulated regions such as the European Union, the United States of America and Canada, antibiotic use is restricted to agents such as oxytetracycline and florfenicol, requiring veterinary prescriptions and oversight. The European Union mandates annual AMU data reporting by species under Regulation (EU) 2019/6, covering antibiotics, antivirals, antifungals and antiprotozoals. Prescription as well as sales data are also increasingly being incorporated, allowing more accurate estimation of standardised metrics, such as milligrams of active ingredient per kilogram of biomass, to enable cross-country comparisons [12]. Conversely, in major aquaculture regions like Asia, where smallholder farms dominate, broader and often unregulated antibiotic use prevails due to limited access to veterinary services [5]. The World Organisation for Animal Health (WOAH) prioritises AMU surveillance, collecting data from 152 countries, though only 39 provide quantitative data publicly, limiting transparency [13]. WOAH's ANIMUSE database facilitates standardised reporting of import and sales data, adjusted for animal biomass, to estimate usage patterns [13]. Challenges include inconsistent reporting, lack of species-specific data, and limited capacity in low-income countries. In Asia and Africa, small-scale farmers often use antibiotics without guidance, complicating data collection [14,15]. Initiatives like Vietnam's mobile applications for tracking antibiotic use in shrimp farms enhance data accuracy and farmer engagement [16]. The InFARM system of the Food and Agriculture

Organization of the United Nations (FAO) is expanding to include aquaculture AMU monitoring, integrating data from sentinel sites to inform targeted interventions [17].

Emergence of antibiotic-resistant pathogens

The use of antimicrobials in aquaculture has contributed to the development of resistant fish pathogens. Studies in Japan during the 1970s identified transferable R-plasmids in fish pathogens, associating AMU with resistance spread [6]. Bacterial genera, such as *Aeromonas* and *Vibrio* spp., developed resistance to antibiotics including oxytetracycline and sulfonamides, reducing treatment effectiveness [18]. In Asia, the leading aquaculture region, intensive and often poorly regulated AMU in smallholder systems promotes resistance. For instance, *Aeromonas hydrophila* isolates from tilapia farms in Thailand and Vietnam carry resistance genes for tetracyclines and sulfonamides [19]. Similarly, *Vibrio* spp. from shrimp farms in Asia exhibit resistance to multiple antibiotics, complicating disease management in penaeid shrimp culture [20]. Metagenomic analyses in China and Vietnam indicate shared resistance gene pools between aquaculture bacteria and human clinical isolates, suggesting potential cross-sectoral transmission [21].

Mobile genetic elements and horizontal gene transfer

AMR in aquaculture is often facilitated by mobile genetic elements. Tetracycline resistance genes, such as tetA, tetB, tetE and tetG, in fish pathogens are highly similar to those in terrestrial bacteria, indicating horizontal gene transfer between aquatic and terrestrial environments [22,23]. By the 1990s, Class 1 integrons with gene cassettes (e.g. aadA for streptomycin, dfr for trimethoprim and cat for chloramphenicol resistance) were common in fish pathogen isolates [23,24]. Conjugative plasmids, such as IncA/C in *Aeromonas salmonicida*, encode resistance to antibiotics including florfenicol, tetracycline, sulfonamides, streptomycin and β -lactams (e.g. blaCMY-2) and are found across human, animal and aquaculture pathogens [25,26]. Identical Tn1721 transposons carrying tetA have been detected in *Aeromonas* spp. from fish farms and clinical bacteria, evidencing genetic exchange [27]. Integrative and conjugative elements (ICEs), such as the SXT/R391 family in *Vibrio* spp., confer resistance to antibiotics including sulfamethoxazole, trimethoprim, chloramphenicol and streptomycin [28]. *Shewanella algae* isolates from aquaculture harbour ICE-like elements (~200 kb) with resistance to heavy metals (e.g. mercury) and antibiotics such as kanamycin, sulfonamides and rifampin [29].

Antimicrobial resistance in the ornamental fish trade

AMR in ornamental fish is also a concern due to widespread and poorly regulated antibiotic use in this sector. The global ornamental fish trade involves over 1.2 billion fish annually, with approximately 80–90% bred in Asia and exported worldwide [30]. Verner-Jeffreys *et al.* [30] demonstrated the presence of multidrug-resistant *Aeromonas* spp. in imported ornamental species, often carrying transferable resistance genes. Other studies have confirmed that bacteria associated with ornamental fish may be highly resistant and have found antibiotics in their carriage water or in pet shop aquariums, raising risks of environmental dissemination and zoonotic transmission [31,32].

Phenotypic resistance trends and management

In the late 1980s, multidrug-resistant *A. salmonicida* subsp. *salmonicida* caused furunculosis outbreaks in Atlantic salmon farms in Norway and Scotland, leading to investments in vaccines and improved biosecurity, which reduced AMU by the 1990s [33]. In Chile, intensive salmon farming and prophylactic AMU have led to resistance in *Piscirickettsia salmonis* to florfenicol and oxytetracyclines, with challenges exacerbated by limited vaccine efficacy [34,35]. *Flavobacterium psychrophilum* also shows reduced susceptibility to most antimicrobials, complicating treatment in trout and salmon farms [36]. In Asia, which is responsible for over 90% of global aquaculture production, resistance to antibiotics such as oxytetracycline, sulfonamides and fluoroquinolones is widespread, with median AMR prevalence exceeding 33% across species [11]. Aquaculture environments, including ponds and hatcheries, serve as reservoirs for resistance genes, facilitating potential cross-sectoral transfer [8]. For example, multidrug-resistant *Vibrio parahaemolyticus* in shrimp farms poses food safety concerns, as these strains can cause human infections through contaminated seafood.

Developing an antimicrobial resistance surveillance programme

Effective AMR surveillance is essential for monitoring trends, informing policy and guiding interventions [9]. The World Health Organization's Global Antimicrobial Resistance and Use Surveillance System (GLASS), FAO's regional AMR guidelines and WOAHA's *Aquatic Animal Health Code* advocate for harmonised surveillance methods to ensure data comparability [37-39]. The European Union is conducting a baseline survey on AMR in *Aeromonas* spp., *Escherichia coli*, *Enterococcus* spp. and *Vibrio* spp. from key European aquaculture production species, such as salmon, seabass, trout and mussels, to support One Health objectives [40].

Surveillance programmes must determine whether to target organisms associated with cultured species or pathogenic bacteria. Some bacteria, such as *E. coli*, largely reflect environmental AMR contamination through wastewater output and other human activity, while pathogens such as many *Vibrio* spp. directly impact animal health [37]. For freshwater aquaculture, *Aeromonas* species can serve as a useful indicator due to their ubiquity, propensity to readily acquire and transfer mobile genetic elements, and pathogenic potential. Chapter 6.4. of WOA's *Aquatic Animal Health Code* [13] together with FAO's regional guidelines [37] provide detailed criteria for designing AMR surveillance programmes, including sampling strategies, target species and data management.

The main challenges for AMR surveillance in aquaculture include i) inconsistent methodologies, ii) gaps in interpretive criteria for aquatic bacteria and iii) limited resources in low-income countries.

Addressing challenges of inconsistent methodologies

Harmonised protocols, as advocated by the Clinical and Laboratory Standards Institute (CLSI) and FAO, are essential for generating comparable data [41]. CLSI provides standardised antimicrobial susceptibility testing (AST) protocols for aquatic bacteria at temperatures below 35°C, tailored to species such as *Aeromonas* and *Vibrio* [41]. Despite this, many studies on aquatic bacteria fail to adhere to standardised AST protocols, hindering data comparability ([Table I](#)). An investigation of 200 studies on *Vibrio* spp. found that 99.5% lacked evidence of standard protocol adherence, with modifications undermining data utility [42]. To address these issues, Smith [43] proposed eight recommendations aimed at improving data quality, including the use of harmonised testing protocols and transparent reporting.

Volume 3 of FAO's regional AMR guidelines provides detailed recommendations for conducting AST in aquatic bacteria, emphasising standardised conditions [37]. Sustained advocacy through regional and international conferences on AMR in aquaculture represents a critical mechanism for raising awareness and promoting laboratory adoption of standard AST methodologies. Technical workshops providing practical training and resources, supported by organisations such as FAO and partner AMR Reference Centres, would also be useful in advancing methodological standardisation and building laboratory capacities in this area.

Addressing challenges from a lack of interpretive criteria

Clinical breakpoints developed for human and terrestrial bacteria are often unsuitable for aquatic species due to differences in pharmacokinetics and testing conditions [44]. The lack of interpretive criteria for aquatic animals may have both hampered AMR surveillance for aquatic animal health purposes and contributed to the use of non-standard AST and result interpretation methods. In addressing the challenges stemming from a lack of interpretive criteria for aquatic animals, recent efforts have established epidemiological cut-off values for key aquaculture pathogens, including *Vibrio harveyi* [45], *Vibrio anguillarum* [46], *Vibrio cholerae* non-O1/non-O139 [47], *V. parahaemolyticus* [48], *Yersinia ruckeri* [49] and *A. salmonicida* [50]. These cutoffs, submitted to CLSI, support harmonised surveillance by distinguishing non-wildtype from wildtype populations. Recently Smith *et al.* [51] suggested that epidemiological cut-off values designed to be applied to all members of the genus *Aeromonas* would not be inherently unreliable.

Surveillance of antimicrobial resistance in limited-resource settings

Volume 3 of FAO's regional guidelines [37] provides systematic guidance on surveillance design, sampling approaches and priority aquaculture pathogens and antimicrobials, enabling countries to develop targeted AMR surveillance programmes aligned with national priorities. The guidelines promote a pragmatic, capacity-appropriate approach, encouraging implementation at whatever level is currently feasible for the country, while adhering to standardised AST methodologies.

Internationally recognised AST methods include disc diffusion, broth dilution and agar dilution. Disc diffusion remains the most accessible option due to its simplicity and low operational cost. Broth microdilution offers greater precision and reproducibility and is the preferred AST method but requires tailored 96-well minimum inhibitory concentration (MIC) panels and higher upfront costs. Baron *et al.* [52] provide a template MIC panel for *Vibrio* spp. that can be adapted to other aquatic bacteria, with careful consideration of antimicrobial concentration ranges and cost-effectiveness. Regional standardisation of MIC panels could further reduce costs through economies of scale [37]. Panels targeting oxytetracycline, florfenicol and sulfonamides are particularly relevant for aquaculture due to their widespread use. Access to cost-effective, standardised AST methodologies is therefore critical for enabling robust AMR surveillance in resource-limited settings.

Antimicrobial resistance data management

Comprehensive data management systems are essential for handling large surveillance datasets, including sample metadata, resistance profiles and AMU data. Platforms such as the World Health Organization's GLASS and WHONET, FAO's InFARM and the European Food Safety Authority's Data Collection Framework facilitate data collection, analysis and sharing [53]. Harmonised data formats are critical for multisectoral analyses and cross-border comparisons. For example, InFARM enables countries to share AMU and AMR data with controlled privacy settings, supporting regional surveillance in Asia [17]. The freely available WHONET software is widely used in low-resource settings for its adaptability to veterinary data and integration with GLASS. Most platforms accommodate for consolidation of data from multiple surveillance programmes, including aquatic AMR surveillance. For instance, InFARM has specific data entry variables for healthy and diseased aquatic animals. Laboratories are encouraged to consolidate all surveillance data under a unified system instead of maintaining separate databases, in order to preserve data integrity and facilitate meaningful cross-sectoral analyses.

Challenges in data management include inconsistent formats, incomplete datasets and limited interoperability between human and animal health systems. Efforts to address these issues include developing standardised data templates and training programmes for data entry. Major data management platforms have also been accommodating for interoperability solutions; for example, AMR data files adhering to InFARM framework specifications can be generated by WHONET and BacLink [17].

The systematic collection of required metadata is important to complete data entry on preferred management platforms and for comprehensive capture of surveillance information. Templates or checklists of the required information should be developed to ensure all critical information is collected for meaningful data analysis and interpretation. Additional information specific to aquatic AMR surveillance may be required, such as example temperature and salinity conditions of the aquatic environment, production system, host animal species (genus and species), life stage and health status. This information would be essential for data traceability, comparative analyses across studies, and supporting future investigations that might require species-specific or environment-specific resistance profiling.

Antimicrobial resistance surveillance using molecular methods

Molecular methods, including hybridisation, nucleic acid amplification (e.g. polymerase chain reaction), immunoassays and sequencing (e.g. whole genome sequencing, metagenomics), complement phenotypic AST [54]. Whole genome sequencing enables high-resolution identification of pathogens and resistance genes, tracing transmission patterns and mobile genetic elements. Metagenomics, being culture-independent, profiles resistomes in complex samples, such as pond water and sediment, aiding environmental AMR monitoring [55].

Challenges include variable genotype–phenotype concordance, as some resistance genes may not be expressed, and reliance on curated AMR gene databases, which may miss novel genes. Long-read sequencing, such as PacBio or Oxford Nanopore, improves plasmid and mobile genetic element resolution with accuracies up to 99.9%, but high costs limit adoption in low- and middle-income countries [56]. Emerging approaches, such as metatranscriptomics, which profiles mRNA to reveal active resistance genes, could address genotype–phenotype discordances but face challenges, such as RNA instability and limited reference databases. Molecular methods are increasingly integrated into national surveillance programmes, particularly in high-income countries.

Integration of aquaculture antimicrobial use and resistance into One Health frameworks

Countries such as Chile, Thailand and the United Kingdom exemplify the integration of aquaculture AMU and, to a more limited extent, AMR data into One Health surveillance frameworks, with further expansion anticipated as surveillance capacity develops. In Chile, the National Fisheries and Aquaculture Service monitors AMU in salmon farming and reports data to national authorities in alignment with international standards [57]. Notably, its Programme for the Optimisation of Antimicrobial Use, a voluntary certification scheme promoting good sanitation and responsible AMU, achieved a 93.7% reduction in the Antimicrobial Consumption Index compared to the national average [57].

Thailand's Thai AMR Watch integrates AMU and AMR data from humans and food-producing animals, supporting national risk assessment and cross-sectoral trend analysis. While currently displayed aquaculture data are limited to AMU, the platform architecture enables straightforward incorporation of aquaculture AMR data as it becomes available [58], illustrating how existing One Health infrastructure can be adapted to emerging surveillance needs.

In the United Kingdom, the Veterinary Antimicrobial Resistance and Sales Surveillance (VARSS) framework includes AMU data from salmon and trout production, providing transparency on AMU trends in aquaculture [59]. The 2024 VARSS report also included AMR data from a pilot clinical surveillance in trout, in which high meropenem resistance was detected in *A. salmonicida* isolates, prompting investigation due to potential One Health implications.

Collectively, these examples demonstrate how integrated surveillance can support evidence-based policy development, regulatory oversight and antimicrobial stewardship. However, extending similar systems to low- and middle-income countries remains constrained by laboratory capacity, data completeness and digital infrastructure, underscoring the need for scalable, context-appropriate surveillance technologies.

Climate change and aquaculture

Climate change profoundly impacts aquaculture by altering water quality parameters, such as temperature, pH and oxygen levels, increasing fish susceptibility to diseases, and expanding the range and density of pathogens, such as *Vibrio*, *Aeromonas* and *Lactococcus* spp. [60,61]. Rising sea temperatures, particularly in regions such as the Baltic Sea, have been associated with increased *Vibrio* infections in humans, highlighting environmental and public health risks [62]. Warmer waters enhance bacterial proliferation and facilitate resistance gene transfer, exacerbating AMR risks. For instance, elevated temperatures have been linked to a higher prevalence of multidrug-resistant *V. parahaemolyticus* in shrimp farms, increasing the risk of human infections through contaminated seafood consumption [63].

Climate-induced changes such as ocean warming and acidification also affect pathogen virulence and host immune responses, complicating disease management [60]. For example, warmer waters reduce dissolved oxygen levels, stressing aquatic organisms and increasing their susceptibility to bacterial infections, which often necessitates antibiotic use, thereby intensifying AMR pressures [61].

Mitigation strategies

Biosecurity

Biosecurity is vital for disease prevention, reducing pathogen spread and antibiotic reliance. Aligned with the WOA's *Aquatic Animal Health Code*, biosecurity practices include risk assessments, quarantine, disinfection and disease surveillance [39]. In

intensive aquaculture industries, such as salmon farming in Norway and Scotland and sea bass/sea bream production in Mediterranean countries (e.g. Spain, Greece, Turkey), key measures involve sourcing certified disease-free stock, water treatment via filtration, ozonation or ultraviolet sterilisation, and area-based management plans with 'all-in, all-out' stocking, active sampling and syndromic surveillance. Government regulations such as Norway's coordinated management areas, Scotland's disease control framework and Spain's aquaculture zoning enforce synchronised production cycles and mandatory health monitoring to limit disease transmission [64-66].

In small-scale aquaculture in the Global South, biosecurity must address resource constraints and limited infrastructure. Cost-effective measures include sourcing certified disease-free seed to prevent pathogen introduction (e.g. *Vibrio* spp. in shrimp farming), maintaining water quality through organic waste removal and aeration, and using affordable disinfectants like lime [20]. Community-based training, supported by local authorities or non-governmental organisations, can promote disease awareness, teaching early detection, water quality monitoring and safe biosecurity practices. Simple record-keeping and cooperative seed-sourcing initiatives enhance sustainability and reduce AMR risks, aligning with smallholder farmers' needs.

Vaccination

Vaccines are critical for disease prevention in aquaculture and have contributed substantially to reductions in AMU in intensive finfish systems. They are widely deployed in sea bass, sea bream, rainbow trout and Atlantic salmon aquaculture, with marked impacts in well-regulated industries in Norway, Scotland and Spain [67]. In Norwegian Atlantic salmon farming, vaccination programmes targeting bacterial pathogens such as *Aeromonas salmonicida* reduced antibacterial use from a peak of approximately 48 tonnes in 1987 to around six tonnes by 1993, following widespread adoption of injectable vaccines administered intraperitoneally to larger fish (>5 g) [67]. National surveillance data indicate that antibacterial use in Norwegian salmon aquaculture has since remained at historically low levels – typically below 1 tonne per year – despite a substantial increase in production from approximately 200,000 tonnes in the late 1980s to over 1.5 million tonnes in 2022 [1], representing a reduction of more than 99% from peak use [68,69].

In Mediterranean aquaculture, vaccines against *Vibrio anguillarum* and *Photobacterium damsela* are widely used in sea bass and sea bream production (e.g. Spain and Greece), although levels of protection vary by pathogen and species [69].

In contrast, vaccine adoption in small-scale aquaculture in the Global South remains limited due to barriers including inadequate cold-chain infrastructure, limited access to licensed products, cost constraints and the absence of vaccines adapted to local species and production systems [70,71]. For lower value, smaller fish and early life stages, immersion and oral vaccination approaches are particularly attractive because of their scalability and ease of administration, although their field-level efficacy is often more variable than injectable vaccines. Recent work in Asian seabass (*Lates calcarifer*) provides a useful illustration of how research is increasingly focused on improving the performance of these delivery routes, including through nanoparticle-based vaccine systems designed to enhance mucosal and systemic immune responses [71]. While seabass is used here as an example, these research directions are broadly applicable across tropical and subtropical aquaculture species.

Alternative control methods

Non-antibiotic interventions can reduce AMR risks and support sustainable aquaculture. These include the use of probiotics, phage therapy and phytochemicals. Probiotics, administered via feed or water, enhance disease resistance and improve water quality [72]. Probiotics are live non-pathogenic microorganisms, usually bacteria, that serve to maintain a healthy microbial balance in the gastrointestinal tract. In doing so, probiotics prevent disease by inhibition and competitive exclusion of pathogenic microorganisms [72]. Phage therapy targets specific pathogens, offering a precise alternative to antibiotics. While phage therapy has been shown to be effective in production systems and commercially available products exist, bacteriophages have complex interactions with the bacterial host that mitigate their sustained effectiveness, and these challenges must be overcome for sustainable application [72]. Phytochemicals derived from herbs and spices, including herbs used in traditional medicine, have been shown to contain antimicrobial and immunostimulant properties. The ease of application, lower environment impact and cost-effectiveness of phytochemicals are currently being studied and offer some promise for wider commercial application [72].

Conclusion

Addressing AMR in aquaculture requires approaches that explicitly reflect the sector's distinctive characteristics, including open and highly connected aquatic environments, diverse farmed species and a predominance of small-scale production in many regions. Prudent AMU needs to be supported by surveillance systems capable of capturing resistance not only in cultured animals but also in the wider aquatic environment, which

can act as sink and reservoir for AMR bacteria and determinants. A One Health perspective is particularly relevant for aquaculture, as water systems act as a direct vehicle linking farmed animals, natural ecosystems and human exposure pathways. Strengthened biosecurity and husbandry, vaccination in intensive finfish systems, and the development of non-antibiotic disease control options for species such as shrimp and prawns represent the most effective routes to reducing antimicrobial dependence. These efforts will need to be adaptive, as climate-driven changes in temperature and water quality increasingly influence disease dynamics and AMR risks in aquatic production.

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Aquaculture : les défis et les avancées spécifiques de ce secteur

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Résumé

La résistance aux antimicrobiens (RAM), sujet de préoccupation de plus en plus pressant à l'échelle mondiale, a des implications majeures pour les secteurs de l'aquaculture (élevage d'animaux aquatiques tels que poissons, crustacés et mollusques) et de l'algoculture (culture d'algues). L'une des conséquences des utilisations infondées ou excessives d'antibiotiques en aquaculture est de favoriser l'émergence de bactéries résistantes, ce qui menace directement la santé des animaux aquatiques et représente également un risque pour la santé humaine via la chaîne alimentaire. Le lien très étroit entre l'aquaculture et l'environnement aquatique rend celui-ci particulièrement vulnérable, dans la mesure où les résidus d'antibiotiques et de polluants issus de l'aquaculture, de l'agriculture et des eaux usées viennent renforcer le résistome bactérien et favorisent la sélection des gènes de résistance et leur propagation dans les écosystèmes aquatiques.

Le milieu aquatique fait office à la fois de réservoir et de vecteur pour la RAM, car la dissémination des bactéries résistantes n'est pas seulement d'origine alimentaire mais passe aussi par l'exposition à ces bactéries présentes dans l'eau lors d'activités professionnelles ou de loisir, ou par contact avec la faune sauvage. Le traitement de la RAM en aquaculture nécessite une approche « Une seule santé », c'est-à-dire des interventions qui prennent en compte l'interdépendance entre la santé humaine, la santé animale et celle de l'environnement.

Cet article explore les toutes premières modalités d'émergence de la RAM en aquaculture et décrit le rôle joué par les éléments génétiques mobiles tels que les plasmides, les intégrons et les transposons dans le transfert horizontal de gènes. Il relève la dynamique des résistances non héréditaires (phénotypiques) et propose un panorama exhaustif des stratégies actuelles de surveillance et d'atténuation suivant l'approche « Une seule santé ». Les orientations internationales fournies par l'Organisation mondiale de la santé, l'Organisation des Nations unies pour l'alimentation et l'agriculture et l'Organisation mondiale de la santé animale y sont discutées, particulièrement celles portant sur une surveillance harmonisée de l'utilisation des antimicrobiens et sur une meilleure transparence en la matière. Certains outils tels que les tests de sensibilité aux antimicrobiens et les méthodes de diagnostic moléculaire

comme le séquençage du génome entier ont enregistré des avancées notables qui permettent d'améliorer la surveillance de la RAM. Parmi les principales recommandations figurent le renforcement de la biosécurité en tenant compte des particularités de chaque système de production, et une gestion appropriée des exploitations afin de prévenir l'introduction des maladies et de moins dépendre des antimicrobiens. La solution de la vaccination a permis de réduire durablement l'usage d'antimicrobiens dans les systèmes piscicoles intensifs des pays à revenu élevé (en premier lieu les élevages de saumon atlantique), mais elle ne s'applique pas à nombre d'espèces et de filières des pays à revenu faible et intermédiaire. Dans le secteur de production de crustacés, la vaccination n'est pas envisageable et il convient donc de remplacer l'antibiothérapie par d'autres méthodes abordables et validées de lutte contre les maladies, par exemple le recours aux immunostimulants, aux probiotiques et aux bactériophages, en les intégrant dans des cadres de biosécurité plus larges.

Mots-clés

Aquaculture – Éléments génétiques mobiles – Résistance aux antimicrobiens – Surveillance – Une seule santé – Utilisation des antimicrobiens.

Acuicultura: retos y avances específicos del sector

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Resumen

La resistencia a los antimicrobianos (RAM) constituye un problema de salud mundial cada vez mayor con importantes repercusiones para la acuicultura, la cría de animales acuáticos y algas, como peces, crustáceos, moluscos y algas marinas. El uso indebido y excesivo de antibióticos en la acuicultura puede estimular la aparición de bacterias resistentes, lo que amenaza la sanidad de los animales acuáticos y supone riesgos para la salud humana a través de la cadena alimentaria. Debido a su estrecha relación con el medio acuático, la acuicultura es particularmente vulnerable, ya que los residuos de antibióticos y los contaminantes procedentes de la acuicultura, la agricultura y las aguas residuales pueden enriquecer el resistoma y favorecer la selección y propagación de genes de resistencia en los ecosistemas acuáticos.

El medio acuático actúa como reservorio y vector de la RAM, haciendo posible su propagación no solo a través de los alimentos, sino también por la exposición al agua en los ámbitos laboral y recreativo, así como por el contacto con la fauna silvestre. Para abordar la RAM en la acuicultura, es necesario adoptar un enfoque «Una sola salud» que reconozca la interdependencia entre la sanidad animal, la salud humana y la medioambiental.

En este artículo se explora la aparición histórica de la RAM en la acuicultura, haciendo hincapié en el papel de los elementos genéticos móviles, como plásmidos, integrones y transposones, en la transferencia horizontal de genes. Se evalúan las tendencias en la resistencia fenotípica y se presenta un panorama completo de las estrategias actuales de vigilancia y mitigación conformes con los principios del enfoque «Una sola salud». Se analizan las directrices internacionales de la Organización Mundial de la Salud, la Organización de las Naciones Unidas para la Alimentación y la Agricultura y la Organización Mundial de Sanidad Animal, haciendo énfasis en la vigilancia armonizada del uso de antimicrobianos y una mayor transparencia. Los avances en las pruebas de susceptibilidad a los antimicrobianos y el diagnóstico molecular, incluida la secuenciación del genoma completo, se presentan como herramientas para mejorar la vigilancia de la RAM. Algunas de las recomendaciones clave son una bioseguridad reforzada y adecuada al sistema, y una gestión en las explotaciones para prevenir la introducción de enfermedades y reducir la dependencia de los antimicrobianos. Si bien

la vacunación ha permitido reducir de forma sostenida el uso de antimicrobianos en los sistemas intensivos de cría de peces de aleta en lugares de ingresos altos, en particular en el salmón del Atlántico, aún no está disponible para muchas especies y sistemas de producción en países de ingresos bajos y medios. En la acuicultura de crustáceos, en la que no es posible aplicar la vacunación, es necesario hacer un mayor énfasis en enfoques asequibles y validados de control de enfermedades sin antibióticos, incluidos los inmunoestimulantes, los probióticos y las intervenciones basadas en fagos, integrados en marcos de bioseguridad más amplios.

Palabras clave

Acuicultura – Elementos genéticos móviles – Resistencia a los antimicrobianos – Una sola salud – Uso de antimicrobianos – Vigilancia.

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Table I

General considerations, challenges and advancements on phenotypic antimicrobial susceptibility testing methods for bacteria isolated from aquatic animals

Considerations	Challenges	Advancements	References and further reading
Internationally accepted methods	<ul style="list-style-type: none"> • Many studies conducting AST with deviations from standard methods • Unable to consolidate and compare data from different studies, hampering advancement of the field of aquatic animal AST 	<ul style="list-style-type: none"> • Publication of consolidated guidelines for AST in aquatic animals [37] and recommendations to harmonise methods and improve data reporting 	[41]
Quality control (QC)	<ul style="list-style-type: none"> • Lack of appropriate QC values for antimicrobials for certain testing conditions • Studies conducted without QCs • Unable to verify validity of AST data 		[44]
Interpretive criteria	<ul style="list-style-type: none"> • Lack of internationally harmonised interpretive criteria for most aquatic bacteria to be tested under standard conditions of <35°C • Unable to accurately interpret AST results 	<ul style="list-style-type: none"> • Epidemiological cut-off values have recently been developed for <i>Vibrio harveyi</i> [45], <i>Vibrio anguillarum</i> [46], <i>Vibrio cholerae</i> non-O1/non-O139 [47], <i>Vibrio parahaemolyticus</i> [48], <i>Yersinia ruckeri</i> [49] and <i>Aeromonas salmonicida</i> [50] 	[41,44]
AST where there are no established standards	<ul style="list-style-type: none"> • Studies conducted using differing methods, complicating subsequent efforts in protocol and data harmonisation 	<ul style="list-style-type: none"> • Ongoing efforts to optimise methods for certain gram-positive bacteria in the CLSI Veterinary AST Working Group on Aquatic Animals 	[41]

Considerations	Challenges	Advancements	References and further reading
Conducting AST in resource-limited settings	<ul style="list-style-type: none"> • Developing suitable surveillance programme within resource limits • High cost of preferred AST method (broth microdilution) 	<ul style="list-style-type: none"> • Guidelines on developing targeted AMR surveillance that focuses resources on addressing national priorities • Template for designing cost-effective MIC panels • Developing and supporting standardised panels to reduce costs through economies of scale 	[37,52]

AMR: antimicrobial resistance
 AST: antimicrobial susceptibility testing
 CLSI: Clinical and Laboratory Standards Institute
 MIC: minimum inhibitory concentration