MEDWIN PUBLISHERS
Committed to Create Value for Researchers

International Journal of Zoology and Animal Biology
ISSN: 2639-216X

Antimicrobial Stewardship in Aquaculture: a One Health Perspective on Antimicrobial Use, Resistance, and Sustainable Disease Management

Bireshwar B*

Associate Professor, Department of Zoology, St. Joseph's College (Univ. Section), India

***Corresponding author:** Bireshwar Bera, Associate Professor, Department of Zoology St. Joseph's College, North Point, Darjeeling-734104, West Bengal, India.

Research Article

Volume 9 Issue 4

Received Date: July 31, 2026

Published Date: August 21, 2026

DOI: 10.23880/izab-16000695

Abstract

Aquaculture is the world's fastest-growing food-production sector and plays an indispensable role in ensuring global food and nutritional security. However, the rapid intensification of aquatic animal farming has been accompanied by extensive antimicrobial use, creating strong selective pressure for the emergence and dissemination of antimicrobial-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) within aquatic ecosystems. These resistance determinants can spread through aquatic food webs, environmental reservoirs, and human exposure pathways, posing an increasingly significant threat to public health within the One Health framework.

This review critically synthesizes current evidence on antimicrobial use in aquaculture, the molecular mechanisms underlying antimicrobial resistance, environmental dissemination pathways, and the associated implications for animal, environmental, and human health. Recent evidence indicates that antimicrobial consumption remains highest in Asian aquaculture, particularly in shrimp, tilapia, catfish, and carp production systems, although substantial geographical variation exists owing to differences in disease burden, farming practices, regulatory frameworks, and antimicrobial stewardship policies. The review further examines the molecular epidemiology of clinically important resistance determinants, including extended-spectrum β-lactamases (ESBLs), carbapenemases, plasmid-mediated colistin resistance genes (mcr), integrons, transposons, and other mobile genetic elements that facilitate horizontal gene transfer within aquatic microbial communities.

Particular emphasis is placed on antimicrobial stewardship strategies encompassing integrated surveillance, veterinary oversight, prudent antimicrobial use, farm biosecurity, vaccination, rapid diagnostics, and sustainable alternatives such as probiotics, prebiotics, bacteriophages, immunostimulants, phytotherapeutics, quorum-quenching approaches, and precision aquaculture technologies. Recent regulatory initiatives in India and other major aquaculture-producing countries are critically evaluated alongside persistent implementation challenges, particularly among small-scale and resource-limited farming systems.

Despite substantial progress in developing antimicrobial stewardship frameworks, effective implementation continues to be constrained by inadequate surveillance systems, limited diagnostic capacity, inconsistent regulatory enforcement, and socioeconomic barriers. Strengthening integrated One Health governance, expanding antimicrobial resistance surveillance, promoting evidence-based disease prevention, and accelerating the adoption of sustainable aquaculture practices are essential to reduce antimicrobial dependence while safeguarding aquatic animal health, environmental integrity, food safety, and human health. Collectively, these measures provide a strategic roadmap for mitigating antimicrobial resistance and enhancing the long-term sustainability and resilience of global aquaculture systems.

Keywords: Antimicrobial Resistance; Antimicrobial Resistance Genes; Antimicrobial Stewardship; Aquaculture; Bacteriophage Therapy; Biosecurity; Food Safety; One Health; Probiotics; Sustainable Aquaculture

Introduction

Aquaculture has emerged as the fastest-growing food production sector globally and plays a pivotal role in ensuring food security, nutritional sustainability, and socioeconomic development. According to the latest global fisheries assessment, aquaculture produced more than 94 million tonnes of aquatic animals in 2022 and now supplies over half of the aquatic animal-derived foods consumed worldwide. Asia dominates global production, contributing approximately 91% of total aquaculture output [1]. Continued expansion of the sector is driven by increasing demand for high-quality animal protein, rapid population growth, urbanization, changing dietary preferences, and the stagnation of capture fisheries [1,2].

Despite its remarkable growth, aquaculture intensification has substantially increased the incidence and severity of infectious diseases. High stocking densities, deteriorating water quality, environmental degradation, climate variability, and the transboundary movement of aquatic animals have collectively heightened disease risks across diverse production systems [3,4]. Bacterial pathogens, including Vibrio spp., Aeromonas spp., Edwardsiella spp., Flavobacterium spp., Streptococcus spp., and Piscirickettsia salmonis, remain major causes of disease outbreaks in shrimp, salmon, tilapia, carp, and catfish aquaculture, resulting in considerable economic losses worldwide [5,6]. Consequently, antimicrobial agents have been extensively employed for therapeutic and metaphylactic purposes and, in certain regions, continue to be used prophylactically despite progressively stricter regulatory controls [1,2,7,8].

Although antimicrobials remain indispensable for disease management, their inappropriate and excessive use has accelerated the emergence and spread of antimicrobial resistance (AMR), which is now recognised as one of the most pressing threats to global health, food security, and sustainable development [7,9]. Unlike terrestrial livestock systems, aquaculture operates within open and highly interconnected aquatic environments where antimicrobial residues, antimicrobial-resistant bacteria (ARB), and antimicrobial resistance genes (ARGs) can readily disperse through water, sediments, biofilms, and aquatic organisms [10,11]. These ecosystems therefore serve as important environmental reservoirs of resistance determinants and facilitate horizontal gene transfer through plasmids, integrons, transposons, bacteriophages, and other mobile genetic elements, thereby contributing to the expansion of the aquatic resistome [12,13]. The implications of AMR in aquaculture extend well beyond aquatic animal production. Resistant microorganisms and ARGs may reach human populations through multiple interconnected pathways, including seafood consumption, occupational exposure among aquaculture workers, contaminated water bodies, wastewater discharge, wildlife-mediated dissemination, and interactions between environmental and clinically relevant bacterial populations [14,15]. Growing evidence therefore recognises aquatic ecosystems as integral components of the One Health continuum, linking environmental integrity, animal health, food safety, and human health [9,15,16,17].

In response to these challenges, international organisations—including the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO), the World Organisation for Animal Health (WOAH), and the United Nations Environment Programme (UNEP)—have advocated coordinated antimicrobial stewardship (AMS) programmes across all food-animal production sectors [7,16]. Within aquaculture, antimicrobial stewardship encompasses the prudent use of antimicrobials, veterinary oversight, integrated surveillance of antimicrobial use (AMU) and AMR, strengthened farm biosecurity, vaccination, rapid diagnostic testing, farmer education, and the adoption of sustainable alternatives such as probiotics, prebiotics, bacteriophages, phytobiotics, immunostimulants, and precision aquaculture technologies [5,8,16,18,19].

Recent advances in molecular biology, genomics, and digital technologies are reshaping disease surveillance and antimicrobial stewardship in aquaculture. Innovations such as whole-genome sequencing, metagenomics, resistome profiling, environmental DNA (eDNA)- based surveillance, portable molecular diagnostics, artificial intelligence-assisted disease prediction, and precision aquaculture platforms enable earlier pathogen detection, real-time monitoring of AMR, and more informed antimicrobial decision-making [1,13,20]. Collectively, these emerging technologies have considerable potential to reduce antimicrobial dependence while enhancing productivity, disease resilience, and environmental sustainability [21,22].

Despite these advances, several important knowledge gaps remain. Most existing reviews address antimicrobial use, antimicrobial resistance, or alternative therapeutic strategies in isolation, whereas comparatively few provide an integrated synthesis encompassing antimicrobial consumption, resistance evolution, environmental dissemination, regulatory developments, socioeconomic constraints, stewardship interventions, and public health implications within a comprehensive One Health framework. Furthermore, rapid progress in global AMR surveillance, international regulatory policies, and innovative disease-control technologies necessitates an updated evaluation of the current evidence base [1,7,8].

Accordingly, this review critically synthesises current evidence on antimicrobial stewardship in aquaculture

Copyright© Bireshwar B.

through a comprehensive One Health perspective. Specifically, it evaluates (i) global patterns and key drivers of antimicrobial use; (ii) the molecular mechanisms, epidemiology, and dissemination of antimicrobial resistance; (iii) environmental, occupational, and foodborne transmission pathways relevant to human health; (iv) antimicrobial stewardship policies, governance, and regulatory frameworks; (v) emerging alternatives to conventional antimicrobial therapy; and (vi) future research priorities and policy directions for strengthening sustainable aquaculture and mitigating antimicrobial resistance at the human–animal–environment interface.

Methodology

Review Design

This review adopted a structured narrative review with a transparent evidence-synthesis approach to critically examine antimicrobial stewardship (AMS) in aquaculture within the broader One Health framework. The review integrates multidisciplinary evidence from aquaculture, aquatic animal health, veterinary medicine, environmental microbiology, antimicrobial resistance (AMR), food safety, molecular epidemiology, public health, environmental sciences, and international policy. Rather than undertaking a conventional narrative review, a systematic and reproducible methodology was employed to identify, evaluate, and synthesize the available scientific literature. The review incorporated the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses [23] to enhance transparency in literature identification, study selection, and evidence synthesis where applicable.

The review was designed to address the following research questions:

- What are the global patterns and major drivers of antimicrobial use in aquaculture?
- Which molecular mechanisms and antimicrobial resistance genes contribute to the emergence and dissemination of AMR in aquatic production systems?
- How do antimicrobial-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) move across environmental, animal, and human interfaces?
- Which antimicrobial stewardship interventions have demonstrated effectiveness in reducing antimicrobial use while maintaining aquatic animal health and productivity? Which emerging technologies and policy interventions have the greatest potential to strengthen antimicrobial stewardship within a One Health framework?

One Health Conceptual Framework

The review was guided by the One Health concept, which recognizes antimicrobial resistance as a complex ecological and public health challenge arising from interactions among humans, animals, and the environment. Evidence was therefore synthesized across interconnected systems involving aquaculture production, aquatic ecosystems, environmental reservoirs, wastewater, seafood supply chains, wildlife, occupational exposure, and clinical settings.

Particular attention was given to the movement of antimicrobial residues, resistant microorganisms, antimicrobial resistance genes, and mobile genetic elements between these interconnected sectors. This integrated framework enabled a comprehensive evaluation of how antimicrobial use in aquaculture influences environmental contamination, food safety, aquatic animal health, and human health simultaneously.

Literature Search Strategy

A comprehensive literature search was conducted to identify relevant peer-reviewed publications addressing antimicrobial stewardship and antimicrobial resistance in aquaculture. Multiple international bibliographic databases were searched to ensure broad coverage of the available scientific evidence.

1. The primary databases included:
2. Web of Science Core Collection
3. Scopus
4. PubMed/MEDLINE
5. Embase
6. ScienceDirect
7. Google Scholar

To complement the peer-reviewed literature, authoritative reports, technical documents, and policy guidelines were also retrieved from major international organizations, including the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO), the World Organisation for Animal Health (WOAH), the United Nations Environment Programme (UNEP), the European Food Safety Authority (EFSA), and the Codex Alimentarius Commission.

The literature search covered publications from January 2015 to June 2026, while earlier landmark studies were included where necessary to provide historical context and explain fundamental concepts related to antimicrobial resistance, horizontal gene transfer, aquatic microbial ecology, and antimicrobial stewardship.

Copyright© Bireshwar B.

Search strategies were developed using combinations of controlled vocabulary (Medical Subject Headings, where applicable) and free-text keywords linked by Boolean operators (AND, OR). Representative search terms included:

1. "aquaculture" AND "antimicrobial stewardship"
2. "aquaculture" AND "antimicrobial resistance"
3. "aquaculture" AND "One Health"
4. "aquaculture" AND "antimicrobial resistance genes"
5. "aquaculture" AND "resistome"
6. "aquaculture" AND "biosecurity"
7. "aquaculture" AND "surveillance"
8. "aquaculture" AND "whole-genome sequencing"
9. "aquaculture" AND "metagenomics"
10. "aquaculture" AND "environmental DNA"
11. "aquaculture" AND "food safety"
12. "aquaculture" AND "occupational exposure"
13. "aquaculture" AND "climate change"

Reference lists of all eligible publications were manually screened to identify additional relevant studies that may not have been captured through the electronic database search.

Eligibility Criteria

Studies were selected according to predefined inclusion and exclusion criteria to ensure consistency throughout the review process.

1. Publications were included if they:
2. investigated antimicrobial use in aquaculture;
3. reported antimicrobial-resistant bacteria or antimicrobial resistance genes;
4. described molecular mechanisms of antimicrobial resistance;
5. evaluated antimicrobial stewardship interventions;
6. examined environmental dissemination of antimicrobial resistance;
7. investigated food safety, occupational exposure, or environmental transmission pathways;
8. explored One Health implications of antimicrobial resistance;
9. evaluated surveillance systems or emerging diagnostic technologies; or
10. discussed national or international antimicrobial policies relevant to aquaculture. Eligible publications included original research articles, systematic reviews, meta-analyses, surveillance reports, governmental publications, international policy documents, consensus statements, and evidence-based guidelines.

Conference abstracts lacking sufficient methodological information, editorials, opinion papers, duplicate publications, studies unrelated to aquaculture, and non-English publications were excluded.

Study Selection

All retrieved records were exported into reference-management software, where duplicate publications were identified and removed. Study selection was conducted in two sequential stages. Initially, titles and abstracts were screened to identify potentially relevant publications. Subsequently, full-text articles were assessed against the predefined eligibility criteria. Where multiple publications reported similar datasets, the most comprehensive or recent study was included to avoid duplication of evidence.

Data Extraction

Relevant information from eligible publications was extracted using a standardized data collection framework to ensure consistency throughout the review.

The extracted information included publication year, geographical location, cultured species, aquaculture production system, antimicrobial classes investigated, antimicrobial use patterns, bacterial pathogens, antimicrobial resistance genes, resistance mechanisms, mobile genetic elements, surveillance approaches, molecular diagnostic techniques, stewardship interventions, environmental transmission pathways, One Health components, public health implications, policy recommendations, and principal findings.

Whenever available, quantitative information describing antimicrobial consumption, prevalence of antimicrobial resistance, stewardship effectiveness, surveillance outcomes, and intervention performance was also incorporated into the evidence synthesis.

Quality Assessment

The methodological quality of the included studies was critically evaluated according to their study design and scientific rigor. Particular consideration was given to methodological transparency, sample size, laboratory methodology, diagnostic reliability, statistical analysis, reproducibility, potential sources of bias, and consistency with existing scientific evidence. International reports and policy documents were evaluated based on institutional credibility, methodological transparency, scientific relevance, and their contribution to antimicrobial stewardship and One Health policy development.

Because of the diversity of study designs included in this review, formal numerical quality scoring was not considered appropriate. Instead, greater emphasis was placed on the methodological robustness, consistency, and relevance of the available evidence.

Copyright© Bireshwar B.

Evidence Synthesis

The considerable heterogeneity among the included studies with respect to geographical location, aquaculture species, farming systems, laboratory methodologies, surveillance strategies, and reported outcomes precluded quantitative meta-analysis.

Accordingly, a thematic narrative synthesis was undertaken. Evidence was organized into major thematic areas including global antimicrobial use, drivers of antimicrobial consumption, antimicrobial resistance mechanisms, resistance genes, multidrug-resistant pathogens, horizontal gene transfer, environmental resistomes, surveillance technologies, foodborne transmission, occupational exposure, regulatory frameworks, antimicrobial stewardship interventions, biological alternatives, emerging technologies, precision aquaculture, policy implementation, and future research priorities.

Comparative evaluation across studies facilitated the identification of consistent findings, regional differences, emerging trends, knowledge gaps, and future research needs.

Integration of the One Health Perspective

A central objective of this review was to evaluate antimicrobial resistance through an integrated One Health perspective. Evidence was synthesized to examine interactions among aquatic animal health, environmental ecosystems, food safety, and human health. Particular emphasis was placed on the dissemination of antimicrobial resistance genes within aquatic ecosystems, transmission of resistant bacteria through seafood and environmental pathways, occupational exposure, wastewater-mediated dissemination, wildlife interfaces, environmental reservoirs, climate-related influences on antimicrobial resistance ecology, integrated surveillance systems, governance, and antimicrobial stewardship interventions. This interdisciplinary approach enabled identification of intervention strategies capable of simultaneously improving aquaculture productivity, environmental sustainability, food safety, and public health.

Limitations of the Review

Several limitations should be acknowledged. The review was restricted to publications available in English, which may have excluded relevant evidence published in other languages. Owing to the broad scope of the review and the heterogeneity of the included studies, quantitative meta-analysis was not feasible. In addition, publication bias and differences in study methodologies, surveillance systems, and reporting standards may have influenced the interpretation of available evidence. Nevertheless, the inclusion of diverse study designs, international policy documents, and multidisciplinary literature provides a comprehensive overview of current knowledge regarding antimicrobial stewardship in aquaculture.

Reporting Standards

The review was prepared in accordance with internationally accepted recommendations for transparent reporting of evidence syntheses and incorporated relevant PRISMA 2020 principles to improve transparency in literature identification, study selection, and evidence synthesis. Scientific terminology, nomenclature, and concepts were harmonized with guidance published by the WHO, FAO, WOAH, and other internationally recognized authorities to ensure consistency with the interdisciplinary scope and reporting standards of One Health Advances.

The Global Expansion of Aquaculture and the Need for Stewardship

The rapid global expansion of aquaculture has substantially increased the demand for effective disease management strategies. Consequently, antimicrobial use (AMU) has become an integral component of many intensive production systems where infectious diseases remain a major constraint to productivity. Although antimicrobials are primarily administered for therapeutic purposes, metaphylactic treatment remains common, and prophylactic use continues in certain regions despite progressively stricter regulatory oversight.

Global Trends in Antimicrobial Use

The remarkable expansion of aquaculture over the past three decades has transformed the sector into the world's fastest-growing source of animal-derived food, making it indispensable for global food security, nutritional well-being, and economic development. This rapid intensification, however, has been accompanied by an increased burden of infectious diseases arising from high stocking densities, environmental degradation, climate variability, and the globalization of aquatic animal trade. Consequently, antimicrobial use (AMU) has become an integral component of disease management in many aquaculture systems, particularly where preventive health measures remain insufficient or disease outbreaks result in substantial economic losses [1,7,18].

In aquaculture, antimicrobials are primarily administered to treat clinically diagnosed bacterial infections. Nevertheless, metaphylactic administration remains common in many intensive production systems, and

Copyright© Bireshwar B.

prophylactic use continues to occur in some regions despite increasingly stringent international recommendations and national regulatory controls [7,8]. Although these practices may provide short-term protection against disease outbreaks, inappropriate or excessive antimicrobial use creates strong selective pressure that accelerates the emergence, persistence, and dissemination of antimicrobial-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) within aquatic environments. Unlike terrestrial livestock systems, aquatic production systems permit the direct release of antimicrobial residues, resistant microorganisms, and mobile genetic elements into surrounding water bodies, sediments, and associated microbial communities, thereby amplifying the environmental resistome and facilitating the spread of resistance across interconnected ecological compartments.

Global estimates indicate that aquaculture consumed approximately 10,259 tonnes of antimicrobials in 2017, and under a business-as-usual scenario, consumption could increase to nearly 13,600 tonnes by 2030, representing an increase of approximately 33% [24]. Although these estimates remain subject to uncertainty because of incomplete reporting, informal veterinary drug markets, and differences in national surveillance systems, they clearly demonstrate the growing contribution of aquaculture to global antimicrobial consumption. More recent international assessments further emphasize that improving surveillance of antimicrobial use is essential for generating reliable estimates and informing evidence-based stewardship policies [1,19].

The Asia–Pacific region accounts for more than 90% of global aquaculture production and therefore represents the largest consumer of veterinary antimicrobials. China remains the dominant producer, followed by India, Indonesia, Vietnam, and Bangladesh. Variations in antimicrobial consumption among countries largely reflect differences in production intensity, disease prevalence, veterinary governance, and national regulatory frameworks [1,24]. In many low- and middle-income countries, limited access to rapid diagnostics, inadequate biosecurity, unrestricted antimicrobial availability, and financial constraints encourage empirical antimicrobial use, often without laboratory confirmation of bacterial infection.

Conversely, experiences from several high-income countries demonstrate that intensive aquaculture does not inevitably require extensive antimicrobial use. Norway provides one of the most compelling examples of successful antimicrobial stewardship. Since the late 1980s, antimicrobial consumption in Norwegian salmon aquaculture has declined by more than 99%, largely through the combined implementation of effective vaccination programmes, strict veterinary prescription policies, comprehensive disease surveillance, selective breeding, improved farm management, and enhanced biosecurity [8,25]. This experience illustrates that sustained productivity and profitability can be achieved while maintaining exceptionally low antimicrobial dependence, providing an internationally recognized model for responsible aquaculture management.

Antimicrobial use also varies considerably among aquaculture production systems. Traditional extensive systems generally require relatively limited antimicrobial intervention because lower stocking densities reduce pathogen transmission. In contrast, intensive pond culture, cage farming, and highly concentrated commercial production systems often experience greater disease pressure and consequently higher antimicrobial use. Emerging production technologies such as recirculating aquaculture systems (RAS) offer important opportunities to reduce antimicrobial dependence by maintaining superior water quality, minimizing pathogen introduction, improving environmental control, and strengthening farm biosecurity [1,26]. These technological advances illustrate how engineering innovations can complement antimicrobial stewardship by addressing the underlying drivers of infectious disease rather than relying solely on therapeutic interventions.

From a One Health perspective, patterns of antimicrobial use in aquaculture have implications that extend well beyond aquatic animal production. Antimicrobial residues released into aquatic environments may alter microbial community structure, promote the selection of resistant bacteria, and facilitate the persistence and horizontal transfer of ARGs among environmental microorganisms. These resistance determinants may subsequently disseminate through aquatic food webs, seafood products, wildlife, wastewater systems, and human occupational exposure, creating interconnected pathways that link aquatic ecosystems with human and animal health. Consequently, responsible antimicrobial use should be regarded not merely as a veterinary practice but as a fundamental component of integrated environmental management, food safety, and public health protection.

Collectively, current evidence indicates that antimicrobial consumption is influenced less by production intensity alone than by the effectiveness of disease prevention, veterinary governance, surveillance capacity, and stewardship implementation. Countries that have invested in preventive health management, vaccination, biosecurity, and evidence-based antimicrobial policies consistently report substantially lower antimicrobial use than those relying primarily on therapeutic interventions. Strengthening these integrated stewardship measures will therefore be essential

Copyright© Bireshwar B.

for reducing antimicrobial dependence while supporting resilient aquaculture systems, protecting environmental integrity, and mitigating the global spread of antimicrobial resistance within the One Health framework.

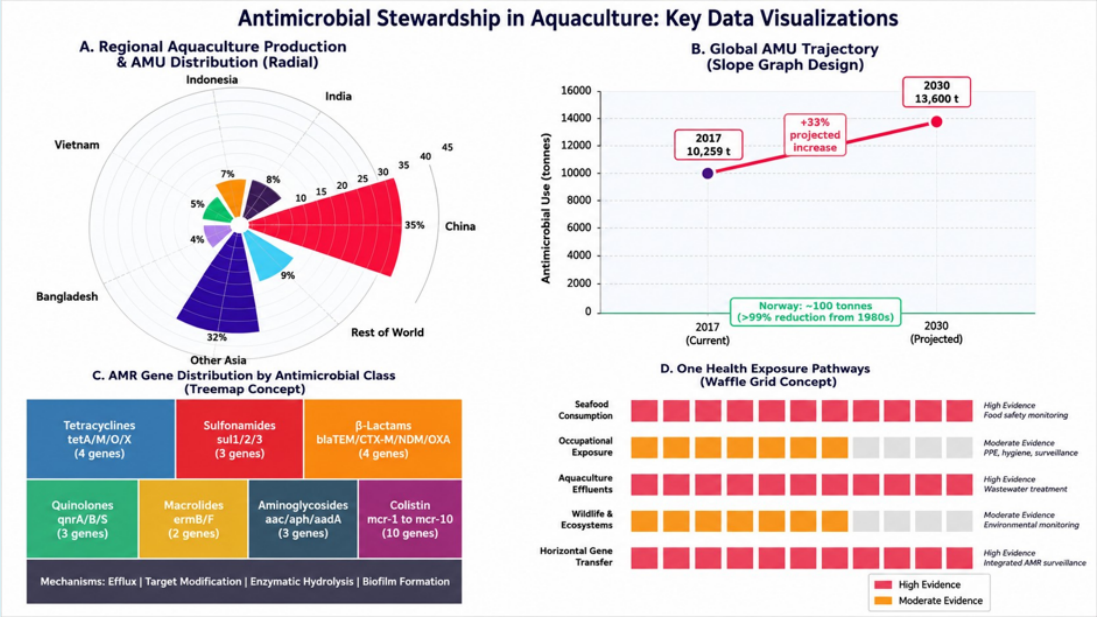


Figure 1: Global AMU Overview & Key Metrics

Panels:

A. Global antimicrobial use projection (2017: 10,259 tonnes → 2030: 13,600 tonnes, +33%) with Norway's >99% reduction benchmark; B. Regional distribution pie chart showing Asia >90% dominance (China 35%, India 8%, Indonesia 7%, etc.); C. Major AMR genes identified in aquaculture (Table 3 data) — horizontal bar chart with gene names and mechanisms; D. Human health risk exposure pathways (Table 9 data) — evidence levels with mitigation strategies

Major Classes of Antimicrobials Used in Aquaculture

Aspect	Current status	Major concern	Key references
Major producing regions	Asia (>90% of global aquaculture production)	Highest antimicrobial consumption	[1]
Principal cultured species	Shrimp, tilapia, carp, catfish, salmon	Disease susceptibility varies among species	[24;1]
Common antimicrobial classes	Tetracyclines, florfenicol, sulfonamides, quinolones	Selection pressure for AMR	[1]
Major drivers	Disease outbreaks, stocking density, poor water quality, inadequate biosecurity	Excessive antimicrobial use	[18]
Best practice example	Norwegian salmon farming	Vaccination and biosecurity reduced AMU by >99%	[25]

Table 1: Global patterns of antimicrobial use in aquaculture.

The diversity of bacterial pathogens affecting aquaculture has resulted in the widespread use of a relatively limited number of antimicrobial classes across freshwater, brackish water, and marine production systems. Although the specific agents employed vary according to cultured species, disease epidemiology, national regulations, and drug availability, a small group of antimicrobial classes accounts for most veterinary antimicrobial consumption worldwide. Their continued use has significantly improved disease control and production efficiency; however, prolonged and

Copyright© Bireshwar B.

often inappropriate application has also imposed substantial selective pressure for the emergence and dissemination of antimicrobial resistance (AMR) within aquatic ecosystems [6,18].

The World Health Organization (WHO) classifies several antimicrobials commonly used in aquaculture as Critically Important Antimicrobials (CIAs) for human medicine, underscoring the need for prudent use and strengthened stewardship to preserve their therapeutic efficacy [19]. The extensive use of these agents in aquatic food production has heightened concerns regarding the selection of antimicrobial-resistant bacteria (ARB), enrichment of antimicrobial resistance genes (ARGs), and subsequent transmission through aquatic environments, seafood products, and the broader food chain. Tetracyclines Among all antimicrobial classes, tetracyclines remain the most extensively used in global aquaculture. Oxytetracycline is particularly favoured because of its broad-spectrum antibacterial activity, relatively low cost, wide commercial availability, and established efficacy against numerous Gram-positive and Gram-negative bacterial pathogens. It is routinely administered to control diseases such as vibriosis, motile aeromonad septicaemia, bacterial gill disease, and columnaris disease in finfish and crustacean production systems [18].

Despite these advantages, the prolonged use of tetracyclines has contributed to the widespread dissemination of tetracycline resistance genes, including tet(A), tet(B), tet(M), tet(O), and tet(X), which are frequently associated with plasmids, transposons, and integrative conjugative elements. These mobile genetic elements facilitate horizontal gene transfer among environmental and pathogenic bacteria, increasing the persistence of resistance within aquaculture environments. Consequently, tetracycline resistance has become one of the most prevalent forms of antimicrobial resistance reported in aquatic microbial communities worldwide.

Amphenicols

Florfenicol has become one of the principal antimicrobial agents used in modern aquaculture following the global prohibition of chloramphenicol in food-producing animals because of its association with idiosyncratic aplastic anaemia in humans. Compared with chloramphenicol, florfenicol offers a more favourable safety profile while maintaining broad-spectrum activity against several economically important fish pathogens, including Aeromonas, Edwardsiella, Flavobacterium, and Vibrio species.

Nevertheless, increasing use of florfenicol has been accompanied by the emergence of florfenicol resistance genes, particularly floR, fexA, and related determinants that are frequently carried on transferable plasmids. Although chloramphenicol is prohibited in aquaculture in most countries, sporadic detection of illegal residues in internationally traded seafood continues to be reported, highlighting persistent weaknesses in regulatory compliance and residue monitoring in some production regions [27]. These findings emphasise the need for strengthened surveillance systems and harmonised international food safety regulations.

Quinolones and Fluoroquinolones

Quinolones and fluoroquinolones, particularly enrofloxacin and ciprofloxacin, are widely recognised for their excellent tissue penetration, broad-spectrum activity, and effectiveness against severe bacterial infections. These characteristics have contributed to their extensive application in intensive aquaculture systems, particularly in Asia.

However, these compounds are designated by WHO as Highest Priority Critically Important Antimicrobials for human medicine because they are indispensable for treating serious bacterial infections. Their continued use in aquaculture has therefore generated considerable concern regarding the emergence of fluoroquinolone-resistant pathogens. Increasing resistance among Vibrio, Aeromonas, Edwardsiella, and members of the family Enterobacteriaceae has been linked to chromosomal mutations within quinolone resistance- determining regions as well as plasmid-mediated resistance genes such as qnr, aac(6')-Ib-cr, and qepA. The environmental dissemination of these resistance determinants further illustrates the interconnected nature of AMR across human, animal, and environmental health sectors [19].

Sulfonamides

Sulfonamides, frequently administered in combination with trimethoprim, continue to be widely used in freshwater aquaculture because they are relatively inexpensive, readily available, and effective against a broad range of bacterial pathogens. These combinations have historically played an important role in controlling systemic bacterial infections in cultured fish.

Nevertheless, resistance to sulfonamides has become increasingly widespread in aquaculture- associated bacterial populations. Resistance is commonly mediated by sul1, sul2, and sul3 genes, which are frequently embedded within class 1 integrons and other mobile genetic elements capable of rapid dissemination among environmental bacteria. Because

Copyright© Bireshwar B.

integrons often carry multiple antimicrobial resistance genes simultaneously, the continued use of sulfonamides may contribute not only to sulfonamide resistance but also to the co-selection of multidrug-resistant bacterial populations [6].

Emerging Concerns Regarding Critically Important Antimicrobials

Growing evidence indicates that the continued use of antimicrobials classified as critically important for human medicine presents challenges that extend beyond aquaculture production. Residues released into aquatic ecosystems can exert selective pressure on indigenous microbial communities, promoting the persistence and dissemination of ARGs in environmental reservoirs. These resistance determinants may subsequently spread through water, sediments, aquatic organisms, seafood products, wildlife, and wastewater systems, creating multiple exposure pathways that connect aquaculture with clinical settings under the One Health framework.

Consequently, international organisations increasingly advocate restricting the routine use of critically important antimicrobials in aquaculture while promoting preventive health management, vaccination, enhanced biosecurity, rapid diagnostics, antimicrobial susceptibility testing, and evidence-based prescribing. Such stewardship strategies not only reduce antimicrobial consumption but also preserve the effectiveness of essential therapeutic agents for both veterinary and human medicine.

Critical Perspective

Although antimicrobial therapy remains indispensable for managing bacterial diseases in aquaculture, sustainable production cannot rely on antimicrobial treatment as the primary disease-control strategy. The future of aquatic animal health increasingly depends on integrated stewardship programmes that combine prudent antimicrobial use with preventive disease management, continuous surveillance, molecular diagnostics, vaccination, selective breeding, improved farm management, and innovative biological alternatives. Adopting this holistic approach will reduce selective pressure for AMR while enhancing aquaculture productivity, food safety, environmental sustainability, and the long-term effectiveness of life-saving antimicrobials within a comprehensive One Health framework.

Species-Specific Patterns of Antimicrobial Use in Aquaculture

Antimicrobial use in aquaculture varies considerably among cultured species because of differences in production systems, disease susceptibility, environmental conditions, management practices, and regulatory oversight. Species-specific husbandry requirements influence pathogen exposure, disease epidemiology, and treatment strategies, resulting in distinct patterns of antimicrobial consumption across global aquaculture. Understanding these variations is fundamental for designing targeted antimicrobial stewardship (AMS) programmes that reduce antimicrobial dependence while maintaining animal health, productivity, and food safety.

Shrimp Aquaculture: Shrimp farming represents one of the most economically valuable sectors of global aquaculture and is also among the most vulnerable to infectious disease outbreaks. High stocking densities, fluctuating environmental conditions, and the absence of a fully developed adaptive immune system make cultured shrimp particularly susceptible to bacterial diseases caused by Vibrio species, including Vibrio parahaemolyticus, the causative agent of acute hepatopancreatic necrosis disease (AHPND), as well as V. harveyi and V. alginolyticus. Historically, these challenges resulted in extensive antimicrobial use, particularly in many Asian and Latin American production systems [1,18]. Over the past decade, however, shrimp aquaculture has undergone a substantial transition from antimicrobial-dependent disease control to preventive health management. Commercial producers increasingly rely on improved biosecurity, specific pathogen-free (SPF) broodstock, enhanced water-quality management, probiotics, prebiotics, phytogenic feed additives, immunostimulants, and bacteriophage-based interventions to reduce disease incidence and antimicrobial use. The adoption of molecular diagnostics, environmental monitoring, and precision farming technologies has further strengthened disease prevention by enabling early detection and timely management of disease outbreaks.

Despite these advances, antimicrobial misuse continues to be reported among small-scale farming systems where limited diagnostic facilities, unrestricted antimicrobial access, and inadequate veterinary support encourage empirical treatment. Consequently, strengthening farmer education, laboratory diagnostic capacity, and regulatory compliance remains essential for improving antimicrobial stewardship within the shrimp industry.

Salmon Aquaculture: Atlantic salmon farming provides one of the most successful examples of antimicrobial stewardship in modern food-animal production. During the 1980s, bacterial diseases such as furunculosis caused extensive production losses and necessitated substantial antimicrobial use. The subsequent introduction of highly effective vaccination programmes, combined with selective breeding, comprehensive disease surveillance, improved

Copyright© Bireshwar B.

husbandry, and strict veterinary oversight, resulted in a dramatic reduction in antimicrobial consumption. Norway has demonstrated that intensive aquaculture can achieve high productivity while maintaining exceptionally low antimicrobial use. Antimicrobial consumption has declined by more than 99% since the late 1980s, despite continuous growth in production volume. This remarkable achievement highlights the effectiveness of integrated disease prevention strategies and provides an internationally recognised model for sustainable aquaculture management [8,25].

Nevertheless, antimicrobial use remains necessary under specific disease conditions, particularly in regions affected by bacterial kidney disease, tenacibaculosis, and piscirickettsiosis. In Chile, for example, persistent outbreaks of Piscirickettsia salmonis continue to drive comparatively high antimicrobial consumption, illustrating how regional epidemiology, pathogen biology, and regulatory environments influence stewardship outcomes.

Tilapia Aquaculture: Tilapia has become one of the world's most widely cultured freshwater fish because of its rapid growth, efficient feed conversion, environmental adaptability, and broad consumer acceptance. However, increasing production intensity has been accompanied by a rising incidence of bacterial diseases, particularly infections caused by Streptococcus agalactiae, Streptococcus iniae, Aeromonas hydrophila, and Francisella orientalis.

Antimicrobial use in tilapia farming varies substantially among countries and production systems. Commercial farms operating under veterinary supervision increasingly employ vaccination, improved biosecurity, water-quality management, and routine health monitoring to minimise antimicrobial use. In contrast, small-scale operations frequently rely on empirical antimicrobial treatment because of limited access to diagnostic laboratories and aquatic animal health services.

Recent advances in selective breeding, genomic surveillance, and precision aquaculture offer promising opportunities to reduce disease susceptibility while supporting more targeted and evidence-based antimicrobial use. These developments are expected to play an increasingly important role in future stewardship programmes.

Carp Aquaculture: Carp farming accounts for a substantial proportion of global freshwater aquaculture, particularly throughout Asia, where carp species contribute significantly to regional food security and rural livelihoods. Traditional polyculture systems generally exhibit lower disease pressure than intensive monoculture operations owing to lower stocking densities and greater ecological stability.

However, intensification of carp production has increased the prevalence of bacterial diseases caused by Aeromonas, Edwardsiella, Flavobacterium, and Pseudomonas species, resulting in greater antimicrobial use in some commercial operations. Environmental stressors, including poor water quality, seasonal temperature fluctuations, eutrophication, and inadequate farm hygiene, further increase disease susceptibility.

Improved pond management, integrated fish health programmes, vaccination, probiotics, and environmental monitoring have demonstrated considerable potential for reducing antimicrobial dependence while maintaining production efficiency. These preventive measures are particularly important for smallholder farming systems that dominate carp production in many developing countries.

Catfish Aquaculture: Catfish farming has expanded rapidly across Asia, Africa, and North America, driven by increasing consumer demand and favourable production characteristics. Major bacterial pathogens affecting catfish include Edwardsiella ictaluri, Aeromonas hydrophila, Flavobacterium columnare, and Edwardsiella tarda, all of which can cause substantial economic losses.

Disease outbreaks are frequently associated with elevated water temperatures, high organic loading, poor water quality, transportation stress, and intensive production practices. These factors often increase reliance on antimicrobial therapy, particularly during seasonal disease outbreaks.

The implementation of improved farm biosecurity, regular health surveillance, rapid diagnostic testing, and evidence-based treatment protocols has reduced unnecessary antimicrobial use in several commercial production systems. Nevertheless, strengthening veterinary extension services and antimicrobial stewardship remains a priority in regions where antimicrobials remain readily accessible without appropriate professional oversight.

Comparative Perspective Across Aquaculture Species: Although antimicrobial use differs among aquaculture species, several common patterns emerge across production systems. Intensive farming, high stocking densities, environmental deterioration, climate-related stress, and inadequate biosecurity consistently increase disease risk and antimicrobial consumption irrespective of species. Conversely, production systems that prioritise preventive health management—including vaccination, selective breeding, biosecurity, improved nutrition, environmental monitoring, and early disease detection— consistently report lower antimicrobial use while maintaining productivity. These

Copyright© Bireshwar B.

observations demonstrate that antimicrobial consumption is influenced less by the cultured species itself than by the effectiveness of disease prevention, farm management, veterinary governance, and surveillance capacity.

Critical Perspective

Species-specific differences in antimicrobial use underscore the importance of developing tailored antimicrobial stewardship programmes rather than adopting uniform management approaches across all aquaculture sectors. While the biological characteristics of individual species influence disease susceptibility, the greatest determinants of antimicrobial consumption remain production intensity, management quality, diagnostic capacity, regulatory enforcement, and farmer awareness.

From a One Health perspective, reducing antimicrobial use across all cultured species requires an integrated strategy that combines preventive health management, rapid diagnostics, molecular surveillance, vaccination, environmental monitoring, precision aquaculture, and evidence-based veterinary oversight. Such an approach not only improves aquatic animal health and farm profitability but also limits the environmental dissemination of antimicrobial resistance genes, protects food safety, and reduces the risk of resistant pathogens entering the human population. Consequently, species-specific stewardship programmes should form a central component of national and international strategies aimed at preserving antimicrobial efficacy and ensuring the long-term sustainability of global aquaculture.

Beyond production characteristics, antimicrobial use is also shaped by ecological, socioeconomic, and governance factors that collectively determine antimicrobial selection pressure across the human–animal–environment interface.

Drivers of Antimicrobial Use in Aquaculture: The use of antimicrobials in aquaculture is shaped by a complex interplay of biological, environmental, technological, socioeconomic, and regulatory factors. Rather than being driven solely by the occurrence of infectious diseases, antimicrobial use (AMU) reflects the interaction between farm management practices, pathogen dynamics, production intensity, governance frameworks, and access to veterinary services. Understanding these interconnected drivers is fundamental for designing effective antimicrobial stewardship (AMS) programmes that reduce antimicrobial dependence while maintaining aquatic animal health, production efficiency, and environmental sustainability.

From a One Health perspective, these drivers operate across the human–animal–environment interface, influencing not only disease occurrence within aquaculture systems but also the emergence, persistence, and dissemination of antimicrobial-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) in aquatic ecosystems.

Disease Burden and Production Intensification: Infectious diseases remain the principal reason for antimicrobial administration in aquaculture. The rapid expansion of intensive farming systems has substantially increased stocking densities, creating favourable conditions for pathogen transmission and disease outbreaks. High biomass, frequent animal handling, transportation stress, and suboptimal water quality collectively weaken host immunity, increasing susceptibility to bacterial infections.

Major bacterial pathogens, including Vibrio spp., Aeromonas spp., Edwardsiella spp., Flavobacterium spp., Streptococcus spp., and Piscirickettsia salmonis, continue to cause substantial economic losses in shrimp, salmon, tilapia, carp, and catfish farming worldwide. Under such circumstances, antimicrobials are often used to minimise mortality and maintain production, particularly where rapid diagnostic facilities are unavailable or disease outbreaks require immediate intervention [6,18]. However, reliance on antimicrobial therapy alone rarely addresses the underlying causes of disease. Farms that implement comprehensive health management programmes—including improved biosecurity, vaccination, water-quality management, and nutritional optimisation— consistently report lower disease incidence and reduced antimicrobial consumption.

Environmental and Climatic Drivers: Aquatic environmental conditions exert a profound influence on pathogen ecology and antimicrobial use. Poor water quality, elevated organic loading, eutrophication, hypoxia, inappropriate pH, salinity fluctuations, and excessive nutrient accumulation increase physiological stress in cultured organisms and favour the proliferation of opportunistic bacterial pathogens.

Climate change further compounds these challenges. Rising water temperatures, altered rainfall patterns, flooding, droughts, and extreme weather events influence pathogen distribution, host susceptibility, and disease seasonality. Warmer aquatic environments often accelerate bacterial growth rates and may expand the geographical range of several economically important pathogens.

Climate-induced environmental disturbances can therefore indirectly increase antimicrobial consumption by elevating disease pressure within aquaculture systems. Consequently, climate adaptation strategies—including improved environmental monitoring, ecosystem- based management, and climate-resilient farming practices—

Copyright© Bireshwar B.

should be considered integral components of antimicrobial stewardship within the One Health framework [1,28].

Socioeconomic and Management Factors: Socioeconomic conditions strongly influence antimicrobial use, particularly in low- and middle-income countries where small-scale aquaculture dominates production. Many producers operate with limited financial resources, restricted access to veterinary expertise, inadequate diagnostic facilities, and insufficient technical training. Under these circumstances, empirical antimicrobial treatment is frequently adopted in preference to laboratory-based diagnosis.

The widespread availability of veterinary antimicrobials through informal distribution networks further contributes to inappropriate antimicrobial use. Self-prescription, incorrect dosage, incomplete treatment courses, and prophylactic administration remain common challenges in several regions.

Farmer education plays a pivotal role in promoting responsible antimicrobial use. Studies consistently demonstrate that producers with greater awareness of disease prevention, antimicrobial resistance, withdrawal periods, and biosecurity practices are significantly more likely to adopt stewardship principles than those lacking formal training.

Strengthening extension services, continuing education programmes, and farmer participation in antimicrobial stewardship initiatives therefore represents a cost-effective strategy for reducing unnecessary antimicrobial consumption.

Veterinary Services and Diagnostic Capacity: Timely disease diagnosis is essential for evidence-based antimicrobial therapy. Nevertheless, many aquaculture-producing regions continue to face substantial limitations in laboratory infrastructure, diagnostic technology, and access to aquatic animal health professionals. In the absence of reliable diagnostic confirmation, antimicrobials are frequently administered empirically based on clinical signs rather than pathogen identification or antimicrobial susceptibility testing. Such practices increase the likelihood of ineffective treatment and accelerate the selection of resistant bacterial populations.

Recent advances in molecular diagnostics—including quantitative PCR, loop-mediated isothermal amplification (LAMP), whole-genome sequencing, metagenomics, and environmental DNA (eDNA)-based surveillance—offer unprecedented opportunities for rapid pathogen detection and antimicrobial stewardship. Combined with antimicrobial susceptibility testing and digital disease surveillance platforms, these technologies facilitate targeted therapeutic decisions while reducing unnecessary antimicrobial exposure.

Regulatory and Governance Factors: National regulatory frameworks exert a major influence on antimicrobial consumption in aquaculture. Countries with comprehensive legislation governing antimicrobial approval, veterinary prescription, residue monitoring, surveillance, and farm certification generally report substantially lower antimicrobial use than regions where regulatory oversight remains limited.

Successful examples from Norway, Denmark, and several European countries demonstrate that integrated governance combining legislation, surveillance, vaccination, biosecurity, and farmer education can dramatically reduce antimicrobial consumption without compromising production performance.

Conversely, inconsistent regulatory enforcement, unrestricted antimicrobial sales, counterfeit veterinary medicines, and weak surveillance systems continue to undermine antimicrobial stewardship in several developing countries. Addressing these governance gaps requires coordinated action involving governments, regulatory agencies, researchers, veterinarians, producers, and international organisations.

Technological Innovation and Precision Aquaculture: Technological innovation is rapidly transforming disease management in aquaculture. Precision aquaculture combines sensor technologies, artificial intelligence, machine learning, automated feeding systems, remote environmental monitoring, and predictive analytics to optimise farm management and improve disease prevention.

Real-time monitoring of water quality, fish behaviour, feeding activity, and environmental conditions enables producers to identify disease risks before clinical outbreaks occur. Early intervention reduces the need for antimicrobial treatment while improving productivity and animal welfare.

The integration of genomic surveillance, resistome monitoring, portable sequencing technologies, and digital decision-support systems further enhances antimicrobial stewardship by providing rapid information on pathogen identity, antimicrobial susceptibility, and resistance gene distribution.

Copyright© Bireshwar B.

These emerging technologies represent a paradigm shift from reactive disease treatment towards predictive, preventive, and precision-based health management.

One Health Perspective on Antimicrobial Use Drivers: The drivers of antimicrobial use should not be considered independently because they interact across ecological and socioeconomic systems. Disease outbreaks, environmental degradation, climate change, inadequate governance, socioeconomic constraints, and limited diagnostic capacity collectively determine antimicrobial selection pressure within aquaculture. Importantly, the consequences of these drivers extend beyond farm boundaries. Antimicrobial residues, resistant bacteria, and antimicrobial resistance genes released into aquatic environments may persist in sediments, wastewater, wildlife, and seafood supply chains, facilitating transmission across environmental, animal, and human populations. Consequently, antimicrobial stewardship requires coordinated action that simultaneously addresses disease prevention, environmental management, veterinary governance, food safety, and public health. Such integration represents the fundamental principle of the One Health approach and provides the most sustainable pathway for mitigating antimicrobial resistance.

Critical Perspective

Current evidence clearly demonstrates that antimicrobial consumption in aquaculture is primarily determined by the quality of disease prevention rather than disease treatment itself. Farms that invest in biosecurity, vaccination, environmental monitoring, precision farming, rapid diagnostics, and veterinary oversight consistently achieve lower antimicrobial use while maintaining productivity and profitability.

Future antimicrobial stewardship programmes should therefore shift from a treatment- oriented model towards an integrated preventive framework supported by robust surveillance, evidence-based policy, climate-resilient production systems, and international collaboration. Embedding these measures within a comprehensive One Health strategy will be essential for preserving antimicrobial efficacy, protecting aquatic ecosystems, ensuring food safety, and safeguarding human health in an increasingly interconnected world.

Emerging Trends in Responsible Antimicrobial Use and Antimicrobial Stewardship

The escalating threat of antimicrobial resistance (AMR) has fundamentally transformed approaches to disease management in aquaculture. Whereas antimicrobial therapy was historically regarded as the primary means of controlling bacterial diseases, contemporary aquaculture increasingly emphasizes prevention, surveillance, and evidence-based health management as the cornerstones of sustainable production. This transition reflects growing recognition that antimicrobial stewardship (AMS) extends beyond reducing antimicrobial consumption; it seeks to preserve the long-term efficacy of life-saving antimicrobials while simultaneously protecting aquatic animal health, environmental integrity, food safety, and public health. Contemporary antimicrobial stewardship increasingly prioritizes disease prevention rather than therapeutic intervention. This shift reflects growing recognition that sustainable aquaculture depends on integrated health management systems capable of minimizing antimicrobial exposure while maintaining productivity, animal welfare, environmental integrity, and food safety.

Within the One Health framework, antimicrobial stewardship is recognised as a multidisciplinary strategy integrating veterinary medicine, aquatic animal health, environmental management, microbiology, epidemiology, public health, and regulatory governance. Effective stewardship therefore requires coordinated interventions throughout the aquaculture value chain, from hatcheries and grow-out farms to processing facilities and aquatic ecosystems, ensuring that disease prevention and responsible antimicrobial use are addressed simultaneously.

Critical Synthesis

Ultimately, antimicrobial stewardship should not be viewed solely as a veterinary intervention but as a comprehensive One Health strategy that integrates disease prevention, environmental management, regulatory governance, surveillance, innovation, and responsible antimicrobial use. Coordinated implementation of these measures will be fundamental to preserving antimicrobial efficacy while supporting resilient aquaculture systems, ecosystem health, food security, and public health.

Copyright© Bireshwar B.

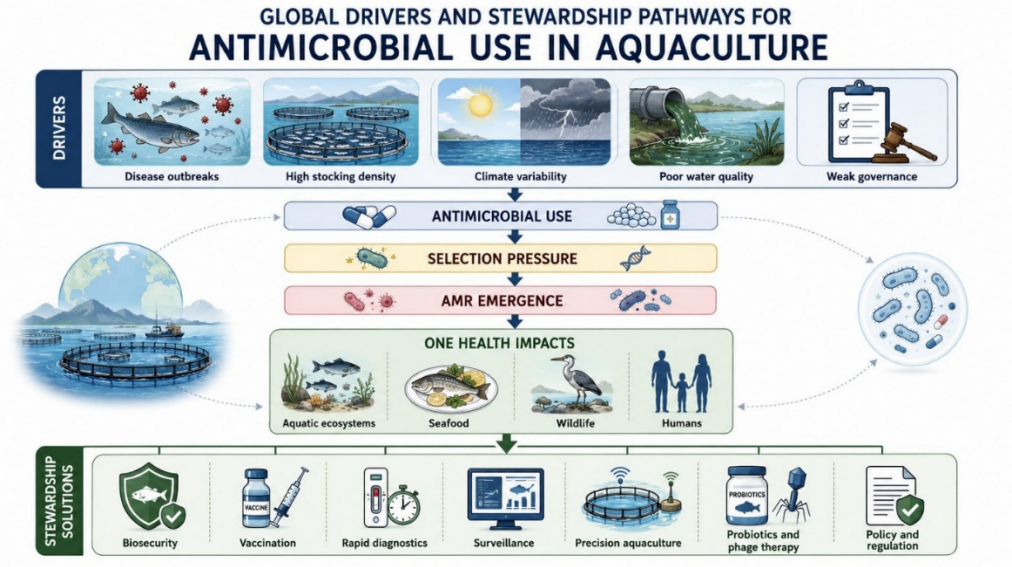


Figure 2: Global Drivers and Stewardship Pathways for Antimicrobial Use in Aquaculture.

Preventive Health Management

Disease prevention represents the most effective strategy for reducing antimicrobial dependence in aquaculture. Numerous studies demonstrate that farms implementing comprehensive preventive health programmes consistently require fewer antimicrobial treatments than farms relying primarily on therapeutic interventions.

Preventive health management encompasses biosecurity, optimized nutrition, vaccination, water-quality management, stress reduction, environmental monitoring, selective breeding for disease resistance, and routine health surveillance. These integrated measures improve host immunity, reduce pathogen transmission, and minimize disease outbreaks before antimicrobial treatment becomes necessary.

Successful examples from salmon aquaculture in Norway and other countries illustrate that comprehensive preventive programmes can achieve substantial reductions in antimicrobial consumption without compromising productivity or animal welfare [8,25].

Biosecurity as the Foundation of Stewardship: Biosecurity has emerged as one of the most cost-effective components of antimicrobial stewardship. Effective biosecurity minimizes pathogen introduction, limits disease transmission, and reduces environmental contamination, thereby decreasing the need for antimicrobial intervention.

Essential biosecurity measures include:

1. use of certified disease-free broodstock and seed;
2. quarantine of newly introduced animals;
3. routine health monitoring;
4. disinfection of equipment and production facilities;
5. water treatment and filtration;
6. control of vectors and predators;
7. appropriate stocking densities;
8. proper disposal of mortalities and farm waste.

Improved biosecurity also reduces the environmental release of pathogens, antimicrobial residues, and antimicrobial-resistant microorganisms, thereby contributing to ecosystem health and reducing the risk of resistance dissemination beyond farm boundaries.

Vaccination and Host Immunoprophylaxis

Vaccination remains one of the most successful interventions for reducing antimicrobial use in commercial aquaculture. Modern vaccines have substantially decreased bacterial disease incidence in several cultured species, particularly Atlantic salmon, where vaccination programmes have almost eliminated routine antimicrobial use.

Recent advances in recombinant vaccines, DNA vaccines, subunit vaccines, nanoparticle- based delivery systems, and mucosal immunization offer promising opportunities to improve disease prevention in a broader range of cultured fish species. Continued research into shrimp immunology, oral vaccine delivery, and species-specific vaccine development is expected to further strengthen antimicrobial stewardship.

Although vaccination is not universally applicable to all aquaculture species, particularly crustaceans with limited

Copyright© Bireshwar B.

adaptive immune responses, advances in immunostimulants and immune-priming strategies continue to expand preventive disease management options.

Rapid Diagnostics and Precision Medicine

Accurate diagnosis is fundamental to responsible antimicrobial prescribing. Historically, antimicrobials were frequently administered empirically because conventional diagnostic methods required several days to identify bacterial pathogens.

Rapid molecular diagnostics now allow earlier and more precise disease detection. Technologies including quantitative PCR, loop-mediated isothermal amplification (LAMP), whole-genome sequencing, metagenomic sequencing, environmental DNA (eDNA) surveillance, biosensors, and portable sequencing platforms enable rapid pathogen identification together with characterization of antimicrobial resistance genes. When integrated with antimicrobial susceptibility testing, these technologies facilitate evidence-based therapeutic decisions while minimizing unnecessary antimicrobial exposure. Such precision-based approaches improve treatment success, reduce production losses, and limit selective pressure for resistance development.

Alternatives to Conventional Antimicrobials:

The search for sustainable alternatives to conventional antimicrobials has accelerated considerably during the past decade. Rather than directly replacing antimicrobial therapy, these approaches aim to enhance host immunity, suppress pathogen virulence, improve microbial balance, and strengthen ecosystem resilience.

Among the most promising alternatives are:

Probiotics, which improve intestinal microbial balance, enhance immune function, and competitively exclude pathogenic bacteria.

1. Prebiotics, which selectively stimulate beneficial microbial communities and improve gut health.
2. Synbiotics, combining probiotics and prebiotics to maximize beneficial microbial interactions.
3. Bacteriophage therapy, providing highly specific pathogen control while minimizing disruption of commensal microbiota.
4. Phytotherapeutics and plant-derived bioactive compounds, offering antimicrobial, antioxidant, and immunomodulatory activities.
5. Quorum-quenching technologies, which inhibit bacterial communication and virulence without exerting strong selective pressure for resistance.
6. Antimicrobial peptides, RNA-based therapeutics, CRISPR-assisted antimicrobial technologies, and microbial engineering, which represent emerging frontiers in precision disease control.
7. Although many of these approaches remain under commercial evaluation, accumulating evidence suggests that integrated application of multiple non-antibiotic strategies can substantially reduce antimicrobial dependence in aquaculture.

Digital Technologies and Precision Aquaculture

Digital transformation is reshaping aquatic animal health management. Artificial intelligence (AI), machine learning, Internet of Things (IoT) sensors, autonomous monitoring systems, remote sensing, and cloud-based decision-support platforms enable continuous monitoring of environmental conditions and animal health.

These technologies facilitate early disease prediction through analysis of water quality, feeding behaviour, swimming activity, and environmental variables. Predictive analytics allows farmers to intervene before clinical disease develops, thereby reducing antimicrobial use while improving production efficiency.

Integration of precision aquaculture with genomic surveillance and real-time resistome monitoring represents an important step toward predictive antimicrobial stewardship and evidence-based farm management.

Strengthening Governance and Global Stewardship: Technological innovation alone cannot achieve sustainable antimicrobial stewardship without effective governance. National AMR action plans, veterinary prescription systems, antimicrobial surveillance programmes, residue monitoring, farmer education, certification schemes, and international regulatory harmonization are equally important components of stewardship.

International organisations, including the WHO, FAO, WOAH, and UNEP, advocate integrated governance that combines surveillance of antimicrobial use, resistance monitoring, environmental protection, and food safety within a unified One Health framework [8,16,19].

Countries that have successfully implemented coordinated stewardship programmes consistently report lower antimicrobial consumption, improved compliance with residue regulations, and enhanced export competitiveness. These experiences demonstrate that responsible antimicrobial use is both a public health priority and an economically advantageous strategy for sustainable aquaculture.

Future Directions: Future antimicrobial stewardship programmes are expected to become increasingly predictive,

Copyright© Bireshwar B.

data-driven, and ecosystem-based. Integration of artificial intelligence, digital epidemiology, genomic surveillance, climate forecasting, environmental monitoring, and precision aquaculture will enable earlier identification of disease risks and more targeted interventions.

At the policy level, stronger international collaboration, harmonized surveillance systems, improved access to veterinary diagnostics, expanded farmer training, and investment in sustainable disease-prevention technologies will be essential for reducing antimicrobial dependence worldwide.

Continued interdisciplinary research integrating microbiology, veterinary medicine, environmental science, public health, economics, and social sciences will further strengthen One Health stewardship strategies capable of addressing the complex ecological dimensions of antimicrobial resistance.

Critical Synthesis: The evolution of antimicrobial stewardship reflects a fundamental shift in aquaculture from reactive disease treatment toward integrated disease prevention and ecosystem health management. Contemporary stewardship recognizes that antimicrobial resistance cannot be mitigated through prudent prescribing alone but requires coordinated improvements in farm management, diagnostics, vaccination, biosecurity, surveillance, governance, and technological innovation.

From a One Health perspective, responsible antimicrobial use represents a shared responsibility across the human, animal, and environmental sectors. Sustainable aquaculture therefore depends on multidisciplinary stewardship programmes that simultaneously preserve antimicrobial efficacy, protect aquatic ecosystems, ensure food safety, maintain animal welfare, and safeguard human health. Strengthening these interconnected strategies will be pivotal for achieving resilient food systems and mitigating the global burden of antimicrobial resistance in the coming decades.

Antimicrobial Resistance in Aquaculture: Mechanisms, Dissemination, and Emerging Trends

The rapid expansion of aquaculture has transformed aquatic food production into a cornerstone of global food security. However, the extensive use of antimicrobials for disease prevention and treatment has unintentionally accelerated the emergence and spread of antimicrobial resistance (AMR), creating one of the most pressing challenges confronting sustainable aquaculture and public health. Unlike terrestrial livestock production, aquaculture is conducted within highly interconnected aquatic environments where antimicrobial residues, resistant microorganisms, and antimicrobial resistance genes (ARGs) can move freely through water, sediments, biofilms, aquatic organisms, and wastewater systems. Consequently, aquaculture has become an important ecological interface linking environmental, animal, and human health within the One Health framework [11,14,19].

The development of AMR in aquatic ecosystems is a dynamic evolutionary process driven by microbial adaptation under continuous antimicrobial selection pressure. Modern molecular investigations demonstrate that resistance is not confined to pathogenic bacteria alone but is widely distributed among environmental microorganisms that collectively constitute the aquatic resistome. Through extensive genetic exchange mediated by mobile genetic elements, these environmental reservoirs serve as sources of resistance determinants that may ultimately reach clinically important pathogens affecting both animals and humans [13,15].

Understanding the molecular basis of resistance evolution and dissemination is therefore essential for designing effective antimicrobial stewardship programmes capable of protecting aquatic animal health while simultaneously preserving the therapeutic effectiveness of critically important antimicrobials for human medicine.

Emergence and Evolution of Antimicrobial Resistance in Aquatic Ecosystems

Antimicrobial resistance has emerged as one of the most significant unintended consequences of antimicrobial use in aquaculture. Aquatic ecosystems provide favourable conditions for the selection, persistence, and dissemination of antimicrobial-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) because cultured animals, environmental microorganisms, sediments, biofilms, plankton, and surrounding water continuously interact within a shared ecological network [11,14]. Unlike terrestrial farming systems, where antimicrobial dissemination may be relatively localized, aquaculture generally operates in open or semi-open environments that facilitate the widespread distribution of antimicrobial residues and resistant microorganisms throughout connected aquatic ecosystems.

The routine administration of medicated feeds, together with antimicrobial residues originating from uneaten feed, faecal material, fish excretions, and aquaculture effluents, results in prolonged exposure of aquatic microbial communities to sub-inhibitory antimicrobial concentrations. Although these concentrations are often insufficient to eliminate bacterial populations, they create sustained selective pressure that favours the survival and proliferation

Copyright© Bireshwar B.

of resistant organisms while simultaneously accelerating the acquisition and maintenance of resistance determinants [13]. Increasing evidence indicates that even trace concentrations of antimicrobial residues can alter microbial community composition and promote adaptive responses that enhance bacterial survival under antimicrobial stress.

Resistance evolution within aquatic environments is not limited to clinically important pathogens. Commensal bacteria, sediment-associated microorganisms, aquatic biofilms, and environmental microbial communities collectively function as reservoirs of ARGs that may subsequently be transferred to opportunistic and pathogenic bacteria through horizontal gene transfer. Consequently, aquaculture ecosystems are increasingly recognised as major contributors to the global environmental resistome, linking environmental microbiology with veterinary medicine, food safety, and public health.

Climate change further amplifies these evolutionary processes. Rising water temperatures, altered hydrological cycles, increasing nutrient enrichment, extreme weather events, and deteriorating water quality modify microbial community structure, pathogen ecology, and host susceptibility. These environmental disturbances may increase disease frequency, leading to greater antimicrobial use and further intensifying selective pressure for resistance development. Climate-related changes therefore reinforce the interconnected nature of antimicrobial resistance across environmental, animal, and human health sectors, highlighting the importance of integrated One Health surveillance and climate-resilient aquaculture management.

Molecular Mechanisms of Antimicrobial Resistance

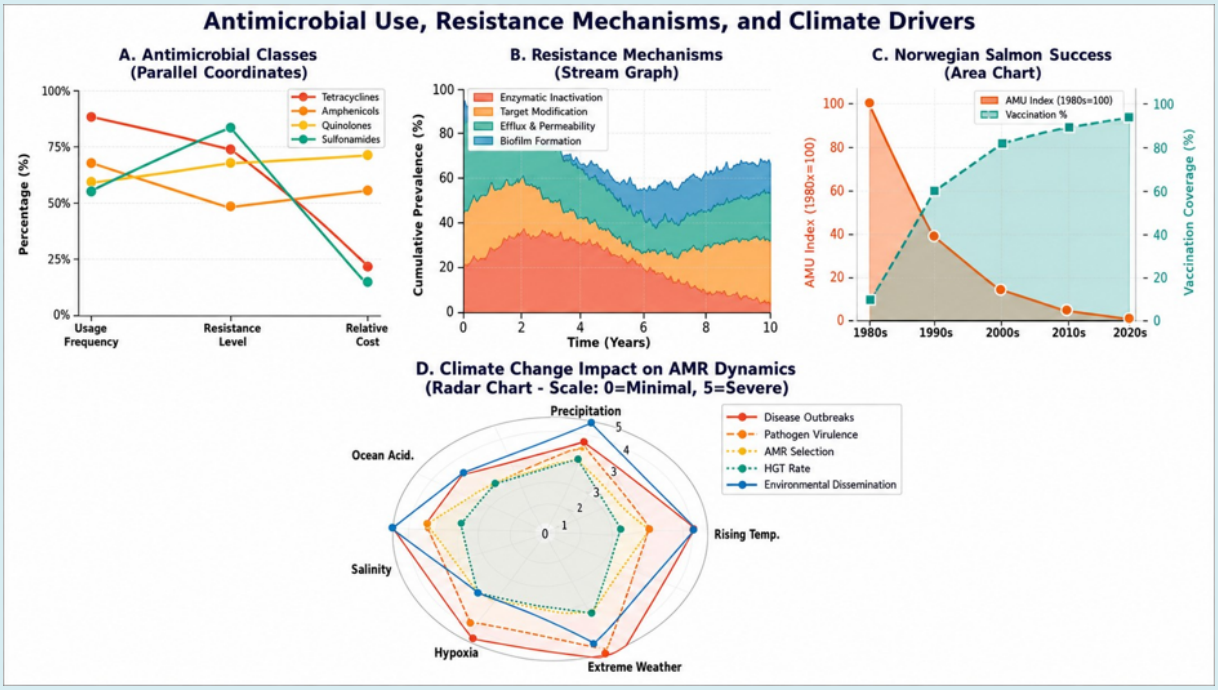


Figure 3: Antimicrobial Use, Resistance Mechanisms & Climate Drivers.

Panels:

Antimicrobial classes: usage frequency vs. resistance levels, with WHO critically important annotation for quinolones; B. Resistance mechanisms in aquatic pathogens — prevalence and MDR contribution (Enzymatic inactivation 70%, Efflux pumps 80%, etc.); C. Norwegian salmon success story — AMU reduction timeline vs. vaccination coverage (1980s→2020s, >99% reduction); D. Climate change impact heatmap on AMR dynamics (6 climate factors × 5 impact dimensions, scored 0–5).

Bacteria associated with aquaculture employ a diverse array of molecular strategies to survive antimicrobial exposure. Resistance may be intrinsic, reflecting naturally occurring structural or physiological characteristics, or acquired, resulting from chromosomal mutations or the acquisition of foreign genetic material through horizontal gene transfer. In many aquatic bacterial pathogens, several resistance mechanisms coexist simultaneously, producing multidrug-resistant (MDR) phenotypes that considerably reduce therapeutic options [6,11].

Copyright© Bireshwar B.

Enzymatic Inactivation of Antimicrobials: Enzymatic degradation or chemical modification of antimicrobial compounds represents one of the most efficient bacterial defence mechanisms. Gram-negative bacteria commonly isolated from aquaculture—including Aeromonas, Vibrio, Edwardsiella, and members of the family Enterobacteriaceae—produce enzymes capable of inactivating antimicrobial agents before they reach their intracellular targets.

Among these enzymes, β-lactamases are particularly important because they hydrolyse the β-lactam ring of penicillins, cephalosporins, and related antibiotics. The global emergence of extended-spectrum β-lactamases (ESBLs) and carbapenemases has become a major public health concern, as these enzymes compromise the effectiveness of critically important antimicrobials widely used in human medicine [29]. Likewise, aminoglycoside-modifying enzymes—including acetyltransferases, phosphotransferases, and nucleotidyltransferases—chemically modify aminoglycoside antibiotics, substantially reducing their antibacterial activity.

Modification of Antimicrobial Targets: Another widespread mechanism of resistance involves structural modification of bacterial targets, thereby reducing antimicrobial binding and therapeutic efficacy. Point mutations within the gyrA and parC genes alter DNA gyrase and topoisomerase IV, producing resistance to quinolones and fluoroquinolones. Similarly, methylation of 23S ribosomal RNA mediated by erm genes reduces susceptibility to macrolides, while alterations in ribosomal proteins and penicillin-binding proteins further contribute to multidrug resistance. These adaptive modifications have been documented in several bacterial pathogens commonly associated with aquaculture, including Vibrio, Aeromonas, Edwardsiella, and Flavobacterium species [18]. The accumulation of multiple target-site mutations frequently results in progressively higher resistance levels and reduced clinical treatment success.

Reduced Membrane Permeability and Active Efflux: Many aquatic bacteria restrict intracellular antimicrobial accumulation through coordinated changes in membrane permeability and active efflux systems. Alterations in outer membrane porins decrease antimicrobial uptake, while multidrug efflux pumps actively expel antimicrobial molecules from bacterial cells before toxic concentrations can be reached. Several highly conserved transporter families—including the Resistance–Nodulation– Division (RND), Major Facilitator Superfamily (MFS), ATP-Binding Cassette (ABC), and Multidrug and Toxic Compound Extrusion (MATE) systems—have been identified in numerous aquatic bacterial pathogens [30]. These transport systems frequently confer resistance to multiple antimicrobial classes simultaneously and therefore represent one of the principal molecular mechanisms underlying multidrug resistance in aquaculture-associated bacteria.

Biofilm-Associated Resistance: Biofilm formation provides bacteria with a highly effective ecological strategy for surviving antimicrobial exposure under aquatic conditions. Within biofilms, microbial cells become embedded in a complex extracellular polymeric matrix that restricts antimicrobial penetration, alters nutrient availability, and creates physiologically diverse bacterial subpopulations exhibiting reduced metabolic activity.

These characteristics substantially increase bacterial tolerance to antimicrobial treatment while facilitating horizontal gene transfer among neighbouring microorganisms. Biofilms developing on pond sediments, tank surfaces, water distribution systems, aquaculture equipment, aquatic vegetation, and fish mucus therefore function as persistent environmental reservoirs of antimicrobial-resistant bacteria and ARGs [31,32].

Beyond protecting resident bacteria, biofilms also promote long-term persistence of resistance genes within aquatic ecosystems by creating stable ecological niches where diverse microbial populations remain in close physical proximity. Consequently, biofilms are increasingly recognised as critical hotspots for the evolution and dissemination of antimicrobial resistance across environmental, veterinary, and human health sectors.

Critical Perspective

The molecular mechanisms responsible for antimicrobial resistance rarely operate in isolation. Instead, aquatic bacterial populations frequently combine enzymatic inactivation, target modification, reduced permeability, active efflux, and biofilm formation within the same organism, producing highly adaptable multidrug-resistant phenotypes capable of surviving under diverse environmental conditions. The coexistence of these mechanisms, together with extensive horizontal gene transfer and environmental selection pressure, accelerates resistance evolution and complicates therapeutic management.

From a One Health perspective, understanding these molecular adaptations is fundamental for developing precision antimicrobial stewardship programmes, strengthening molecular surveillance, and identifying innovative alternatives that minimise resistance selection while preserving antimicrobial efficacy for both veterinary and human medicine.

Copyright© Bireshwar B.

Horizontal Gene Transfer and the Aquatic Resistome

The rapid dissemination of antimicrobial resistance within aquatic ecosystems is driven predominantly by horizontal gene transfer (HGT), a process that enables bacteria to acquire resistance determinants independently of vertical inheritance. Unlike mutation-based resistance, which develops gradually through successive generations, HGT allows genetically unrelated bacterial species to exchange antimicrobial resistance genes (ARGs) within relatively short evolutionary timescales. This remarkable genetic plasticity has transformed aquatic environments into dynamic reservoirs where resistance can emerge, persist, and spread across diverse microbial communities [12].

In aquaculture, HGT occurs primarily through three complementary mechanisms: conjugation, transformation, and bacteriophage-mediated transduction. Among these, conjugation is considered the most efficient pathway for disseminating resistance because self-transmissible plasmids readily move between bacterial cells, often carrying multiple ARGs simultaneously. Transformation enables competent bacteria to incorporate extracellular DNA released from lysed microorganisms, whereas transduction facilitates the transfer of resistance genes through bacteriophages that infect bacterial hosts. Collectively, these processes promote the rapid acquisition of multidrug resistance among both pathogenic and environmental bacteria inhabiting aquatic ecosystems.

The movement of ARGs is further facilitated by mobile genetic elements (MGEs), including plasmids, transposons, insertion sequences, integrons, and integrative conjugative elements (ICEs). These mobile DNA elements function as genetic vehicles that capture, rearrange, and disseminate resistance determinants across phylogenetically diverse bacterial populations. Among them, Class 1 integrons have attracted particular attention because of their exceptional capacity to acquire and express multiple resistance gene cassettes. Their widespread occurrence in aquaculture-associated bacteria has been strongly linked to the emergence of multidrug-resistant (MDR) phenotypes, making them valuable molecular indicators of anthropogenic antimicrobial selection pressure [33]. Increasing evidence indicates that certain components of aquaculture production systems serve as ecological “hotspots” for horizontal gene transfer. Pond sediments, biofilms, sludge, hatchery tanks, recirculating aquaculture systems, and wastewater discharge points typically harbour dense and metabolically active microbial communities exposed to persistent, sub- inhibitory concentrations of antimicrobial residues. These conditions promote close microbial interactions, enhance genetic exchange, and facilitate long-term maintenance of ARGs within environmental bacterial populations [13,33]. Biofilms deserve particular attention because they provide highly structured microbial habitats where bacterial cells remain in close physical proximity within extracellular polymeric matrices. This organisation not only protects microorganisms from environmental stressors and antimicrobial exposure but also substantially increases opportunities for plasmid transfer and other HGT events. Consequently, biofilms have emerged as important reservoirs for resistance evolution and persistence in aquaculture environments.

From a broader ecological perspective, the aquatic resistome extends beyond clinically relevant pathogens. It encompasses the entire collection of resistance genes present in environmental bacteria, commensal microorganisms, aquatic animal microbiota, sediments, biofilms, and wastewater-associated microbial communities. These environmental reservoirs function as long-term genetic repositories from which resistance determinants may be transferred to opportunistic and clinically important pathogens. Consequently, aquaculture ecosystems represent critical interfaces linking environmental microbiology, veterinary medicine, food production, and human health within the One Health continuum.

Major Antimicrobial Resistance Genes of One Health Importance

Advances in metagenomic sequencing, whole-genome sequencing, and resistome analysis have revealed an extraordinary diversity of antimicrobial resistance genes (ARGs) within aquaculture environments. These resistance determinants are widely distributed among aquatic pathogens, commensal bacteria, environmental microorganisms, and mobile genetic elements, reflecting the extensive genetic exchange that occurs within aquatic ecosystems [21].

The diversity and abundance of ARGs identified in aquaculture mirror the antimicrobial classes most frequently used for disease management. Resistance genes conferring reduced susceptibility to tetracyclines, sulfonamides, β-lactams, quinolones, aminoglycosides, macrolides, phenicols, and polymyxins have been reported from freshwater, brackish, and marine production systems across multiple geographic regions. Their widespread distribution demonstrates that antimicrobial resistance in aquaculture is not confined to individual bacterial species but instead reflects a complex ecological network involving pathogens, environmental microorganisms, and mobile genetic elements.

Among the most frequently detected resistance determinants are members of the tet gene family (tetA, tetM,

Copyright© Bireshwar B.

tetO, and tetX), which mediate resistance to tetracyclines through active efflux mechanisms or ribosomal protection. Similarly, sul1, sul2, and sul3 genes confer resistance to sulfonamides by encoding alternative dihydropteroate synthases that are no longer inhibited by these antimicrobial agents. Because tetracyclines and sulfonamides have historically been among the most extensively used antimicrobial classes in aquaculture, these genes are now widely recognised as molecular indicators of antimicrobial selection pressure. Resistance to β-lactam antibiotics has become an increasing concern owing to the global dissemination of β-lactamase genes, including blaTEM, blaCTX-M, blaNDM, and blaOXA. These genes encode enzymes capable of hydrolysing penicillins, cephalosporins, and, in some cases, carbapenems. The emergence of extended-spectrum β-lactamases (ESBLs) and carbapenemases in aquaculture-associated bacteria is particularly alarming because carbapenems represent critically important antimicrobials reserved for the treatment of severe multidrug-resistant infections in human medicine [19].

Quinolone resistance is increasingly associated with plasmid-mediated qnr genes, including qnrA, qnrB, and qnrS, which protect bacterial DNA gyrase and topoisomerase IV from quinolone inhibition. These genes frequently coexist with chromosomal mutations affecting target enzymes, producing higher levels of resistance and reducing the clinical effectiveness of fluoroquinolone therapy.

Macrolide resistance is primarily mediated by erm genes, notably ermB and ermF, which encode ribosomal methyltransferases that reduce antimicrobial binding to the bacterial ribosome. Aminoglycoside resistance, in contrast, commonly results from drug-modifying enzymes encoded by aac, aph, and aadA genes, which chemically modify aminoglycosides before they reach their intracellular targets.

Particularly concerning is the increasing detection of plasmid-mediated colistin resistance genes (mcr-1 to mcr-10) within aquaculture-associated bacterial populations. These genes modify the lipid A component of bacterial lipopolysaccharide, reducing susceptibility to colistin—one of the last-resort antimicrobials used for treating multidrug-resistant Gram- negative infections in humans. Likewise, the occurrence of carbapenemase genes such as blaNDM, blaKPC, and blaOXA-48 in environmental and aquaculture-associated bacteria highlights the growing overlap between environmental reservoirs and clinically significant antimicrobial resistance [19].

The distribution of ARGs also varies among bacterial taxa. Species of Aeromonas, Vibrio, and Edwardsiella frequently harbour tet, sul, qnr, floR, and bla genes, whereas members of the Enterobacteriaceae increasingly carry clinically important carbapenemase and colistin resistance determinants. Pseudomonas species often possess multiple resistance mechanisms, including multidrug efflux systems, β-lactamases, and biofilm-associated resistance, allowing them to function as persistent environmental reservoirs of antimicrobial resistance. Taken together, current evidence indicates that aquaculture environments harbour a highly diverse and continuously evolving pool of resistance genes that extends far beyond cultured pathogens alone. Continuous exchange of these genes among aquatic microorganisms reinforces the need for integrated genomic surveillance capable of monitoring both known and emerging resistance determinants across the entire aquaculture production continuum.

Bacterial group	Frequently reported resistance genes	Major resistance mechanism	Public health significance
Aeromonas spp.	tet, sul, qnr, bla	Efflux pumps, target modification	Opportunistic human pathogen
Vibrio spp.	tet, qnr, blaCTX-M	Target alteration, β-lactamases	Seafood-associated infections
Edwardsiella spp.	tet, floR	Efflux pumps	Fish pathogen
Enterobacteriaceae	blaNDM, blaKPC, mcr	Carbapenemases, colistin resistance	Critical human health concern
Pseudomonas spp.	Multiple MDR genes	Efflux systems, biofilm formation	Environmental reservoir

Table 2: Major antimicrobial-resistant bacterial groups, representative resistance genes, and their One Health significance in aquaculture.

Copyright© Bireshwar B.

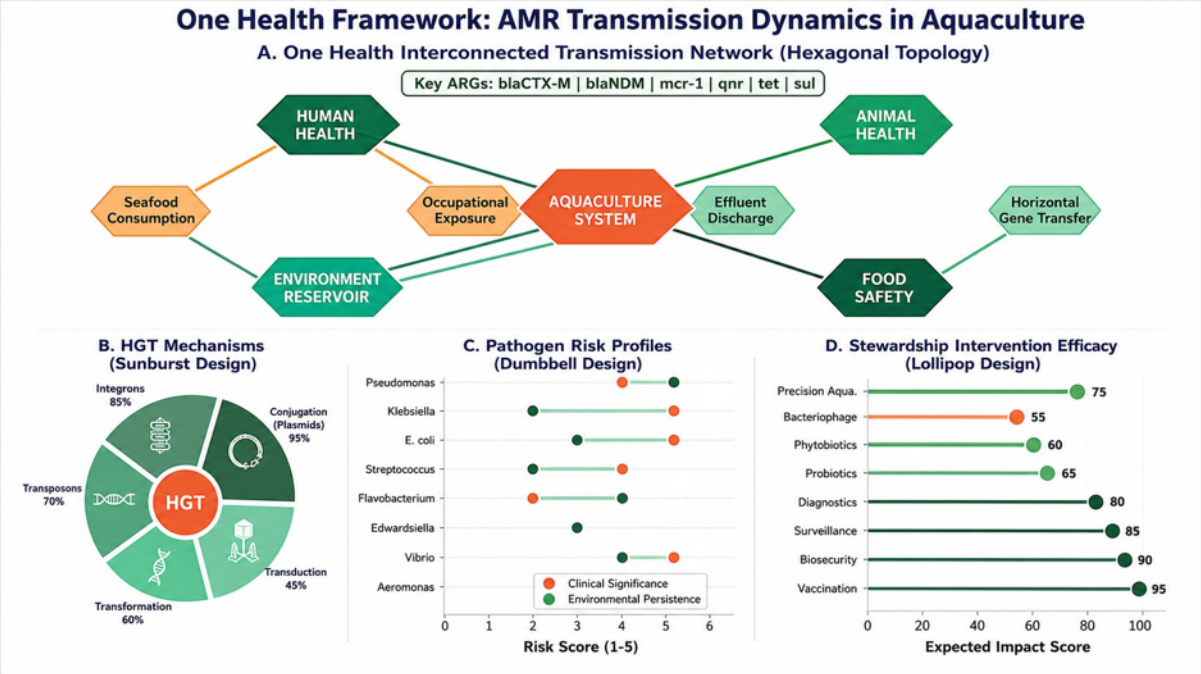


Figure 4: One Health Framework — AMR Transmission Dynamics

Panels:

A. Conceptual One Health Venn diagram showing interconnected Human-Animal-Environment sectors with aquaculture at the center and four key transmission pathways (Seafood Consumption, Occupational Exposure, Environmental Dissemination, Horizontal Gene Transfer)

B. HGT mechanisms ranked by relative importance in aquatic environments (Conjugation 95%, Integrons 85%, etc.)

C. Pathogen risk profiles comparing clinical significance vs. environmental persistence for major aquaculture pathogens (Aeromonas, Vibrio, E. coli, Klebsiella, etc.)

D. Stewardship intervention efficacy scores with priority classification (Vaccination 95, Biosecurity 90, Surveillance 85, etc.)

Antimicrobial class	Representative resistance genes	Primary mechanism
Tetracyclines	*tetA, tetM, tetO, tetX*	Efflux pumps and ribosomal protection
Sulfonamides	*sul1, sul2, sul3*	Target replacement
β-Lactams	*blaTEM, blaCTX-M, blaNDM, blaOXA*	Enzymatic hydrolysis
Quinolones	*qnrA, qnrB, qnrS*	Target protection
Macrolides	*ermB, ermF*	Ribosomal methylation
Aminoglycosides	*aac, aph, aadA*	Drug modification
Colistin	*mcr-1 to mcr-10*	Lipid A modification

Table 3: Representative antimicrobial resistance genes reported in aquaculture and their principal molecular mechanisms.

Major Antimicrobial-Resistant Bacterial Pathogens in Aquaculture

The occurrence of antimicrobial resistance among bacterial pathogens affecting aquaculture has become an important challenge for aquatic animal health, sustainable food production, and public health. Resistance has now been documented in numerous bacterial species associated with freshwater, brackish, and marine production systems, reflecting the diverse microbial communities that inhabit aquatic environments. Beyond compromising therapeutic efficacy in cultured fish and shellfish, these resistant bacteria contribute to the wider environmental dissemination of antimicrobial resistance genes (ARGs), reinforcing the interconnected nature of animal, environmental, and human health within the One Health framework.

Copyright© Bireshwar B.

The principal antimicrobial-resistant bacterial pathogens reported in aquaculture, together with their associated diseases, representative resistance genes, predominant resistance mechanisms, and public health relevance, are summarized in Table 4. Collectively, these organisms demonstrate that aquaculture ecosystems harbour both host-specific pathogens and clinically important environmental bacteria capable of acting as reservoirs and disseminators of antimicrobial resistance.

Bacterial pathogen	Major diseases in aquaculture	Common antimicrobial resistance genes	Predominant resistance mechanisms	One Health significance	WHO Priority Status / Clinical Relevance	Represent ative references
Aeromonas hydrophila	Motile aeromonad septicaemia	*tetA, tetE, sul1, qnrS, floR*	Efflux pumps, target protection, plasmid-mediated resistance	Opportunistic human pathogen and important environmental reservoir of ARGs	High clinical relevance; emerging zoonotic pathogen and reservoir of transferable resistance genes	[14,18]
Aeromonas veronii	Haemorrhagic septicaemia, ulcerative disease	*tet, sul, qnr, bla genes*	Horizontal gene transfer, multidrug efflux	Causes fish disease and occasional human infections	Moderate–High clinical relevance; emerging zoonotic concern	[14]
Vibrio parahaemolyticus	Acute hepatopancreatic necrosis disease (AHPND), vibriosis	*qnrVC, tet, blaCTX-M*	Target-site mutations, plasmid-mediated quinolone resistance	Major seafood-borne pathogen	High clinical relevance; WHO-recognized foodborne pathogen	[7,34]
Vibrio alginolyticus	Vibriosis	*tet, sul, qnr*	Efflux pumps, integron-associated resistance	Marine environmental reservoir with zoonotic potential	Moderate clinical relevance; opportunistic human pathogen	[18]
Vibrio harveyi	Luminous vibriosis	*tet, floR, sul*	Mobile genetic elements, biofilm formation	Major shrimp pathogen with environmental persistence	Moderate clinical relevance; economically important aquaculture pathogen	[14]
Edwardsiella tarda	Edwardsiellosis	*tet, cat, floR*	Plasmid-mediated resistance	Fish pathogen with zoonotic potential	High clinical relevance; recognized foodborne and opportunistic pathogen	[1]
Edwardsiella piscicida	Edwardsiellosis	*tet, sul, floR*	Efflux systems, horizontal gene transfer	Emerging aquaculture pathogen	Emerging clinical relevance; increasing importance in fish health	[18]

Copyright© Bireshwar B.

Flavobacterium columnare	Columnaris disease	*tet, erm*	Ribosomal target modification, efflux	Major freshwater fish pathogen	Low direct human relevance; significant for aquaculture sustainability	[1]
Streptococcus iniae	Streptococcosis	*ermB, tetM*	Ribosomal methylation and target modification	Zoonotic pathogen affecting fish handlers	High clinical relevance; recognized zoonotic pathogen	[7]
Piscirickettsia salmonis	Piscirickettsiosis	*Reduced susceptibility to florfenicol and oxytetracycline*	Adaptive resistance, intracellular persistence	Causes major economic losses in salmon aquaculture	Low human clinical relevance; very high veterinary importance	[25]
Escherichia coli	Environmental contamination indicator	*blaCTX-M, blaNDM, mcr-1*	ESBL production, carbapenemase production	Indicator organism for environmental contamination and AMR dissemination	Critical priority; major WHO priority pathogen group because of ESBL- and carbapenem-resistant strains	[13]
Klebsiella pneumoniae	Environmental opportunist	*blaKPC, blaNDM, blaOXA-48*	Carbapenemase production	Clinically important multidrug-resistant pathogen	Critical priority; WHO critical-priority pathogen	[15]
Acinetobacter baumannii	Environmental opportunist	*blaOXA, blaNDM*	Biofilm formation, multidrug efflux	Environmental reservoir with increasing aquatic detection	Critical priority; WHO critical-priority pathogen	[19]
Pseudomonas aeruginosa	Opportunistic infections	*mex efflux genes, blaVIM*	Multidrug efflux pumps, biofilm formation	Environmental reservoir of multidrug resistance	High priority; clinically important opportunistic pathogen with global AMR concern	[14]

Table 4: Major antimicrobial-resistant bacterial pathogens reported in aquaculture, associated resistance mechanisms, One Health significance, and WHO priority status.

Footnote

WHO Priority Status / Clinical Relevance reflects the public health importance of each organism based on the WHO Bacterial Priority Pathogens List (2024), foodborne disease significance, zoonotic potential, and its role as a reservoir or disseminator of antimicrobial resistance genes within the One Health framework. For aquatic pathogens not formally included in the WHO priority list (e.g., Flavobacterium columnare and Piscirickettsia salmonis), the designation reflects their veterinary and aquaculture relevance rather than human clinical priority.

Among aquatic pathogens, members of the genera Aeromonas, Vibrio, Edwardsiella, Flavobacterium, Streptococcus, and Piscirickettsia account for a substantial proportion of bacterial diseases affecting commercially important fish and shellfish. Increasing resistance to tetracyclines, sulfonamides, quinolones, β-lactams, florfenicol, and macrolides has been reported in these

Copyright© Bireshwar B.

organisms, reducing treatment efficacy and increasing production losses in intensive aquaculture systems [14,18]. Species belonging to the genus Aeromonas deserve particular attention because of their broad host range, widespread environmental distribution, and remarkable capacity to acquire multidrug resistance. Both Aeromonas hydrophila and Aeromonas veronii frequently harbour resistance determinants such as tet, sul, qnr, floR, and bla genes, many of which are located on mobile genetic elements that facilitate horizontal transfer between aquatic microorganisms. In addition to causing severe diseases in fish, these bacteria are recognised as opportunistic human pathogens, highlighting their dual significance within the One Health continuum.

Similarly, Vibrio species—including Vibrio parahaemolyticus, V. harveyi, and V. alginolyticus—represent major bacterial pathogens of marine aquaculture. These organisms increasingly exhibit multidrug-resistant phenotypes associated with plasmid-mediated quinolone resistance, β-lactamase production, biofilm formation, and integron-mediated acquisition of resistance genes. Because several Vibrio species are also responsible for seafood-borne infections in humans, their increasing resistance has important implications for both aquaculture biosecurity and food safety.

Other important fish pathogens, including Edwardsiella tarda, Edwardsiella piscicida, Flavobacterium columnare, Streptococcus iniae, and Piscirickettsia salmonis, have also demonstrated increasing resistance to multiple antimicrobial classes. Although these pathogens differ in host specificity and disease epidemiology, they share common adaptive mechanisms, including horizontal gene transfer, multidrug efflux systems, intracellular persistence, ribosomal target modification, and plasmid-mediated resistance. Their continued emergence complicates disease management and underscores the importance of preventive health strategies, including vaccination, biosecurity, and rapid molecular diagnostics. Aquaculture environments also contain numerous environmental and opportunistic bacteria with considerable clinical relevance. Multidrug-resistant Escherichia coli, Klebsiella pneumoniae, Acinetobacter baumannii, and Pseudomonas aeruginosa have increasingly been detected in aquaculture water, sediments, biofilms, and cultured organisms. The presence of clinically significant resistance determinants—including blaCTX-M, blaNDM, blaKPC, blaOXA-48, mcr, and metallo-β-lactamase genes—indicates that aquatic environments are not merely passive recipients of antimicrobial resistance but active reservoirs where resistance genes can circulate between environmental bacteria and human-associated pathogens [14,15,34].

Importantly, the public health significance of these microorganisms extends beyond their pathogenicity. Many function as environmental reservoirs capable of maintaining and disseminating ARGs through complex microbial networks involving sediments, wastewater, wildlife, biofilms, and aquatic microbiota. Consequently, surveillance strategies that focus exclusively on individual pathogens may underestimate the broader ecological processes driving resistance evolution within aquatic ecosystems.

Critical Perspective

Current evidence suggests that the importance of antimicrobial-resistant bacteria in aquaculture lies not only in their ability to cause disease but also in their ecological role as reservoirs and vectors of resistance determinants. The continuous movement of ARGs among pathogenic, commensal, and environmental bacteria through horizontal gene transfer creates highly interconnected resistance networks that extend far beyond individual farms. Accordingly, surveillance programmes should increasingly prioritise ecosystem-level monitoring of resistance genes, mobile genetic elements, and multidrug-resistant bacterial communities alongside conventional pathogen surveillance. Such an integrated approach will provide a more comprehensive understanding of resistance ecology and strengthen antimicrobial stewardship within the One Health framework.

Emerging Technologies for Antimicrobial Resistance Surveillance

Effective surveillance forms the foundation of antimicrobial stewardship because it enables early detection of emerging resistance, supports evidence-based therapeutic decisions, and informs public health policy. Over the past decade, antimicrobial resistance surveillance in aquaculture has undergone a profound transformation, evolving from conventional culture- based microbiology towards integrated genomic, molecular, and computational approaches capable of characterising resistance across entire microbial communities.

Traditional bacterial isolation and antimicrobial susceptibility testing remain indispensable for clinical diagnosis and routine surveillance. However, these methods are inherently limited because they primarily detect cultivable microorganisms and often require several days before results become available. In contrast, contemporary molecular technologies provide rapid, culture-independent approaches for identifying antimicrobial resistance genes (ARGs), mobile genetic elements, and microbial community dynamics with considerably greater sensitivity and taxonomic resolution [13,21].

Copyright© Bireshwar B.

Technology	Primary application	Major advantages	Technology Readiness Level	Current limitations
Whole-genome sequencing (WGS)	Characterization of antimicrobial-resistant pathogens, outbreak investigation, genomic epidemiology	High genomic resolution; identifies resistance genes, virulence factors, and transmission pathways	Routine (Reference laboratories)	High cost; requires bioinformatics expertise and standardized analytical pipelines
Shotgun metagenomics	Environmental resistome profiling and microbiome characterization	Detects both culturable and non-culturable microorganisms; comprehensive ARG detection	Emerging	Expensive; computationally intensive; challenges in quantitative interpretation
Long-read sequencing (Nanopore/PacBio)	Characterization of plasmids, integrons, and mobile genetic elements	Resolves complex genomic structures; improves assembly of resistance determinants	Emerging	Higher sequencing error rates than short-read platforms; relatively high cost
qPCR / Digital PCR (dPCR)	Quantification of specific antimicrobial resistance genes (ARGs)	Rapid, highly sensitive, quantitative, and suitable for routine surveillance	Routine	Limited to predefined targets; cannot detect novel resistance genes
Environmental DNA (eDNA)	Non-invasive monitoring of aquatic environments for pathogens and ARGs	Early detection; ecosystem-wide surveillance without sampling animals	Emerging	Does not distinguish viable from non-viable microorganisms; requires validation for AMR surveillance
CRISPR-based diagnostics	Rapid detection of pathogens and antimicrobial resistance genes	Highly sensitive, rapid, portable, and suitable for field applications	Research	Validation, standardization, and regulatory approval remain limited for aquaculture applications
AI-assisted genomic surveillance	Integration of genomic, environmental, and epidemiological datasets for resistance prediction	Supports real-time decision-making, predictive analytics, and outbreak forecasting	Emerging	Requires large, high-quality datasets, digital infrastructure, and advanced computational expertise

Table 5: Emerging molecular technologies for antimicrobial resistance surveillance in aquaculture.

Technology Readiness Level (TRL):

Routine: Validated technologies already implemented in diagnostic or surveillance laboratories and suitable for routine antimicrobial stewardship.

Emerging: Technologies with demonstrated practical potential that are being adopted in pilot studies or specialized surveillance programmes but are not yet widely implemented.

Research: Technologies currently undergoing validation or early-stage development before routine field application.

Among these technologies, whole-genome sequencing (WGS) has become a cornerstone of genomic epidemiology. WGS enables comprehensive characterisation of bacterial genomes, facilitating identification of resistance determinants, tracking of multidrug-resistant clones, investigation of outbreak transmission pathways, and detection of evolutionary changes occurring during disease emergence. The increasing affordability of sequencing platforms has accelerated their adoption in aquatic animal health research and surveillance. Complementary high-throughput approaches, including shotgun metagenomics and long- read sequencing, extend surveillance beyond individual pathogens by characterising the entire environmental resistome. These technologies permit direct analysis of water, sediments, biofilms, and aquaculture-associated microbiomes without the need for bacterial cultivation, providing valuable insights into the diversity,

Copyright© Bireshwar B.

abundance, organisation, and mobility of antimicrobial resistance genes within complex microbial ecosystems [11].

Targeted molecular methods remain indispensable components of surveillance programmes. Quantitative polymerase chain reaction (qPCR) and digital PCR (dPCR) provide rapid and highly sensitive quantification of selected resistance genes, while environmental DNA (eDNA) monitoring enables non-invasive surveillance of aquatic ecosystems through analysis of DNA released by microorganisms into the surrounding environment. Together, these approaches facilitate continuous environmental monitoring and allow early detection of emerging resistance before widespread dissemination occurs.

Recent advances in biotechnology and computational biology are further expanding surveillance capabilities. CRISPR-based molecular diagnostics provide rapid and highly specific detection of bacterial pathogens and selected ARGs under field conditions, whereas artificial intelligence (AI) and machine-learning algorithms increasingly support interpretation of complex genomic datasets, prediction of resistance phenotypes, identification of transmission pathways, and real-time epidemiological surveillance [22]. The integration of AI with genomic epidemiology has considerable potential to strengthen early-warning systems and improve evidence-based antimicrobial stewardship. Collectively, these technological advances are shifting antimicrobial resistance surveillance from pathogen-centred diagnostics towards ecosystem-level monitoring of resistance evolution. By integrating genomics, environmental microbiology, bioinformatics, and computational analytics, modern surveillance systems provide a far more comprehensive understanding of how antimicrobial resistance emerges, persists, and disseminates within aquaculture and surrounding ecosystems.

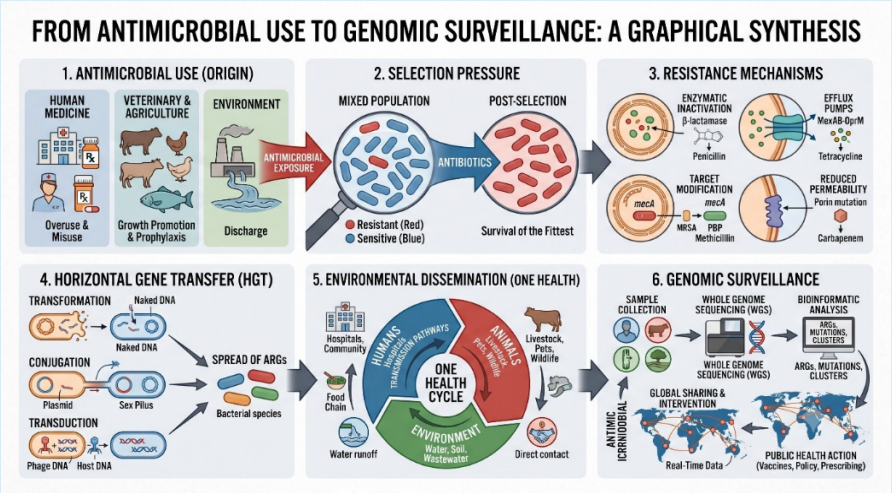


Figure 5: Graphical synthesis illustrating the progression from antimicrobial use: → selection pressure → resistance mechanisms → horizontal gene transfer → environmental dissemination → genomic surveillance.

Critical Synthesis

Current evidence indicates that antimicrobial resistance in aquaculture is driven by complex ecological interactions that extend well beyond antimicrobial consumption alone. Environmental reservoirs, microbial community dynamics, horizontal gene transfer, mobile genetic elements, and anthropogenic pressures collectively shape the evolution and dissemination of antimicrobial resistance within aquatic ecosystems. Because aquaculture systems exchange water, sediments, microorganisms, and wildlife with surrounding environments, resistant bacteria and ARGs can circulate across environmental, animal, and human populations, reinforcing the need for integrated surveillance within the One Health framework [11,13].

The transition from conventional microbiology to genomics-based surveillance represents a major milestone in antimicrobial stewardship. Technologies such as whole-genome sequencing, metagenomics, environmental DNA monitoring, CRISPR diagnostics, and AI- assisted data analysis enable earlier detection of emerging resistance, more accurate outbreak investigations, and comprehensive characterisation of environmental resistomes. Nevertheless, widespread implementation remains constrained by financial limitations, laboratory infrastructure, bioinformatics capacity, and the absence of harmonised surveillance protocols, particularly in low- and middle-income countries. Addressing these challenges through sustained investment, international collaboration, standardised methodologies, and open data sharing will be essential to ensure that

Copyright© Bireshwar B.

emerging technologies contribute effectively to global antimicrobial stewardship, sustainable aquaculture, and One Health governance.

Human Health Risks and One Health Implications of Antimicrobial Resistance in Aquaculture

Aquaculture Within the One Health Framework

Antimicrobial resistance (AMR) has emerged as one of the most pressing global health challenges of the twenty-first century, transcending the traditional boundaries of human medicine, veterinary science, agriculture, and environmental management. Increasing evidence demonstrates that antimicrobial-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) circulate continuously among humans, animals, food systems, and natural ecosystems, reinforcing the concept that AMR is fundamentally a One Health issue requiring coordinated, multidisciplinary action [7,16,35]. Within this interconnected framework, aquaculture occupies a particularly important position because it links aquatic ecosystems directly with food production, environmental microbiomes, and human populations.

The unprecedented expansion of aquaculture has substantially increased interactions between cultured aquatic animals and surrounding ecosystems. Modern production systems frequently operate within rivers, estuaries, reservoirs, coastal waters, and recirculating aquaculture systems that receive agricultural runoff, municipal wastewater, industrial discharges, and wildlife inputs. Consequently, aquaculture is exposed not only to antimicrobial agents used within farms but also to resistant microorganisms and ARGs originating from multiple environmental sources [14,17]. Rather than functioning solely as a source of resistance, aquaculture represents a dynamic ecological interface where resistance determinants are continuously exchanged among environmental microorganisms, aquatic animals, wildlife, and human-associated bacteria.

Unlike most terrestrial livestock systems, aquaculture generally operates in open or semi-open aquatic environments where water exchange is intrinsic to production. Antimicrobial residues, resistant bacteria, and mobile genetic elements released through uneaten medicated feed, fish excreta, pond sediments, and wastewater effluents can therefore disperse beyond farm boundaries and persist within surrounding aquatic ecosystems [11,13]. Sediments, biofilms, wetlands, and wastewater treatment systems subsequently function as long-term environmental reservoirs that facilitate horizontal gene transfer and maintain resistance even in the absence of continued antimicrobial exposure.

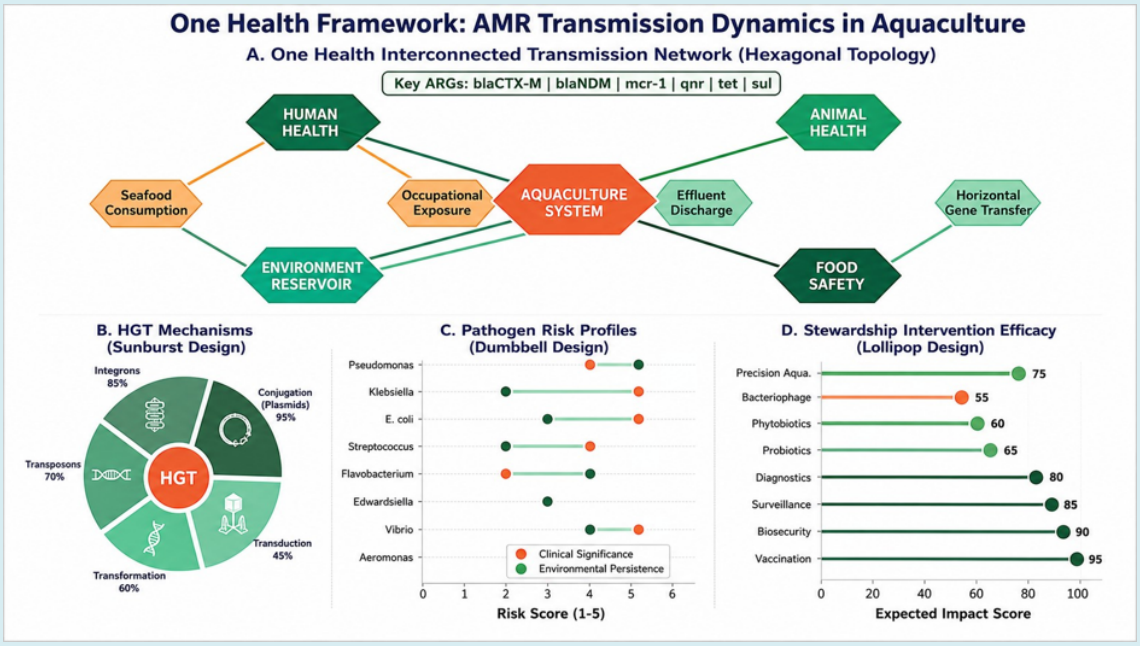


Figure 6: One Health framework illustrating antimicrobial resistance transmission dynamics associated with aquaculture. **Panels:** (A) Integrated One Health framework showing interactions among humans, animals, and the environment with aquaculture at the centre; (B) relative contribution of horizontal gene transfer mechanisms in aquatic environments; (C) comparative pathogen risk profiles based on clinical significance and environmental persistence; and (D) relative effectiveness of major antimicrobial stewardship interventions.

Copyright© Bireshwar B.

These ecological interactions illustrate that the consequences of antimicrobial use in aquaculture extend well beyond disease management. Resistant microorganisms and ARGs may circulate through aquatic food webs, migratory wildlife, recreational waters, seafood supply chains, and wastewater networks before ultimately reaching human populations. Climate change further complicates these interactions by altering water temperature, salinity, rainfall patterns, flooding frequency, and pathogen ecology, thereby influencing both antimicrobial consumption and resistance dissemination [1,28]. Consequently, effective antimicrobial stewardship in aquaculture must integrate environmental monitoring, food safety, animal health, and public health surveillance within a unified One Health governance framework.

Foodborne Transmission through Aquatic Products

Seafood constitutes one of the principal interfaces through which antimicrobial-resistant bacteria and antimicrobial resistance genes originating from aquaculture may enter human populations. Fish, crustaceans, molluscs, and other aquatic food products can become contaminated at multiple stages of production, including farming, harvesting, processing, transportation, retail distribution, and household preparation. Although the magnitude of exposure varies considerably among production systems and geographic regions, contamination at any point along the supply chain provides opportunities for resistant microorganisms to move from aquatic environments into human food systems [7,34].

A wide range of bacterial pathogens associated with seafood have demonstrated increasing antimicrobial resistance. Species such as Vibrio parahaemolyticus, Vibrio vulnificus, Aeromonas hydrophila, Salmonella enterica, Escherichia coli, and Listeria monocytogenes are frequently isolated from cultured aquatic products and processing environments, with many strains exhibiting multidrug-resistant phenotypes [14,18,34]. Of particular concern is the growing detection of extended-spectrum β- lactamase (ESBL)-producing Enterobacteriaceae, plasmid-mediated quinolone resistance genes, carbapenemases, and colistin resistance determinants within seafood-associated bacterial populations, reflecting increasing convergence between environmental and clinical antimicrobial resistance.

The risk of foodborne transmission is influenced not only by pathogen prevalence but also by production practices throughout the seafood value chain. Poor farm hygiene, contaminated harvesting waters, inadequate sanitation during processing, interruptions in cold-chain management, and cross-contamination during retail distribution or domestic food preparation all contribute to microbial persistence and dissemination. Processing facilities may also serve as ecological reservoirs where resistant microorganisms survive within biofilms on equipment and food-contact surfaces despite routine cleaning and disinfection procedures [36].

Although thorough cooking effectively eliminates most viable bacterial pathogens, it does not completely eliminate the broader public health concerns associated with antimicrobial resistance. Cross-contamination during handling of raw seafood, environmental persistence of resistance genes, and horizontal gene transfer among bacteria within food-processing environments remain important pathways through which resistance may continue to circulate. Consequently, food safety interventions should extend beyond thermal processing to encompass the entire production continuum from farm to consumer.

Reducing foodborne transmission requires integrated implementation of Good Aquaculture Practices (GAqP), Hazard Analysis and Critical Control Point (HACCP) systems, strict sanitation protocols, effective cold-chain management, routine microbiological surveillance, and systematic monitoring of antimicrobial-resistant bacteria and ARGs throughout seafood production and distribution. Increasing application of whole-genome sequencing, metagenomic surveillance, environmental DNA (eDNA) monitoring, and digital traceability systems is further strengthening risk assessment by enabling earlier detection of emerging resistant pathogens and improved tracking of contamination events [19,34].

Critical Synthesis

Current evidence indicates that foodborne transmission of antimicrobial resistance from aquaculture is best understood as an ecological process rather than a simple consequence of seafood consumption. Resistant microorganisms may enter the food chain through contaminated aquatic environments, persist during processing, and spread through inadequate hygiene, cross-contamination, or environmental reservoirs before reaching consumers. At the same time, resistance genes continue to circulate independently within aquatic microbial communities through horizontal gene transfer, even when viable pathogens are effectively controlled. These findings highlight the need for integrated risk management strategies that combine prudent antimicrobial use, enhanced farm biosecurity, comprehensive food safety systems, environmental monitoring, genomic surveillance, and coordinated One Health governance. Such an ecosystem-based approach offers the greatest opportunity to reduce antimicrobial resistance while simultaneously protecting aquatic animal health, environmental sustainability, food security, and human health.

Copyright© Bireshwar B.

Bacterial species	Common aquatic products	Major public health concern	Representative antimicrobial resistance	Major resistance genes (examples)	WHO priority status*	One Health surveillance significance
Vibrio parahaemolyticus	Marine fish, shrimp, shellfish	Gastroenteritis	Tetracycline and quinolone resistance	*tet(A), tet(B), qnrVC, gyrA mutations*	High	Important seafood-borne pathogen requiring integrated surveillance across aquaculture, seafood, and coastal environments.
Vibrio vulnificus	Oysters and shellfish	Septicaemia, wound infections	Multidrug resistance	*tet, qnr, blaCARB, efflux pump genes*	High	Critical zoonotic pathogen linked to seafood consumption and occupational exposure in marine environments.
Aeromonas hydrophila	Freshwater fish	Gastrointestinal illness and opportunistic infections	Tetracycline and sulfonamide resistance	*tet(E), sul1, sul2, qnrS, blaTEM*	High	Major aquatic reservoir of antimicrobial resistance genes (ARGs) with high potential for horizontal gene transfer.
Salmonella enterica	Fish and seafood products	Foodborne salmonellosis	ESBL production and multidrug resistance	*blaCTX-M, blaTEM, blaSHV, qnr, aac(6')-Ib-cr*	Critical	Priority foodborne pathogen requiring coordinated surveillance from farm to consumer under the One Health framework.
Escherichia coli	Processed seafood and aquaculture water	Indicator of faecal contamination; opportunistic infections	ESBL and carbapenem resistance	*blaCTX-M, blaNDM, blaKPC, blaOXA-48, mcr-1*	Critical	Sentinel organism for monitoring antimicrobial resistance, environmental contamination, and wastewater impacts.
Listeria monocytogenes	Ready-to-eat seafood	Listeriosis	Emerging multidrug resistance	*tet(M), erm(B), fosX, lnu genes*	High	Important food-processing and ready-to-eat seafood pathogen requiring integrated food safety and environmental surveillance.

Table 6: Foodborne antimicrobial-resistant bacteria associated with aquaculture products, their public health significance, major resistance determinants, WHO priority status, and One Health surveillance implications.

Occupational Exposure to Antimicrobial-Resistant Microorganisms

Occupational exposure represents an important yet frequently overlooked pathway through which antimicrobial-resistant bacteria (ARB) and antimicrobial resistance genes (ARGs) may be transmitted from aquaculture systems to humans. Workers involved throughout the aquaculture value chain—including fish and shrimp farmers, hatchery personnel, veterinarians, aquatic animal health professionals, laboratory technicians, seafood processors, transport workers, and retail handlers—are routinely exposed to aquatic microorganisms during daily operations. Repeated contact with cultured animals, production water, sediments, biofilms, processing equipment, and wastewater increases opportunities for colonization by resistant microorganisms and, under certain circumstances, the development of occupational infections [1,19].

Exposure occurs through several complementary pathways. Direct skin contact with contaminated water, fish mucus, and sediments is the most common route, particularly

Copyright© Bireshwar B.

when workers perform harvesting, grading, vaccination, or disease management activities. Cuts, abrasions, puncture wounds caused by fish spines or handling equipment, and compromised skin integrity facilitate bacterial entry into underlying tissues, increasing susceptibility to opportunistic infections. Additional exposure may occur through accidental ingestion of contaminated water, inhalation of aerosols generated during pond aeration, high-pressure cleaning, or recirculating aquaculture operations, as well as contact with diseased or dead aquatic animals during necropsy and routine health inspections [14,17].

Although severe occupational infections remain relatively uncommon, repeated exposure may promote transient colonization of the skin, respiratory tract, or gastrointestinal microbiota by antimicrobial-resistant bacteria. Such colonization provides opportunities for resistance determinants to circulate between environmental microorganisms and the human microbiome through horizontal gene transfer, potentially contributing to the wider dissemination of ARGs within households, healthcare facilities, and surrounding communities. This risk is particularly relevant for workers involved in intensive aquaculture systems where bacterial density, antimicrobial use, and environmental microbial diversity are greatest.

The occupational risks associated with aquaculture extend beyond direct pathogen exposure. Seafood processing facilities, hatcheries, and live-fish markets frequently harbour complex microbial biofilms on equipment and food-contact surfaces that may persist despite routine cleaning procedures. These environments provide favourable conditions for the survival of multidrug-resistant organisms and facilitate repeated occupational exposure. Consequently, occupational health should be recognised as an integral component of antimicrobial stewardship rather than being considered solely a workplace safety issue.

Reducing occupational exposure requires a comprehensive biosecurity strategy incorporating engineering controls, administrative measures, and individual protective practices. Consistent use of appropriate personal protective equipment (PPE), strict hand hygiene, prompt management of skin injuries, safe handling and disposal of diseased aquatic animals, routine disinfection of equipment, occupational health surveillance, and continuous worker education are all essential elements of effective infection prevention programmes. These measures not only reduce the risk of occupational disease but also minimise opportunities for resistant microorganisms to move between aquaculture environments and human populations [16,19].

Critical Synthesis

Current evidence indicates that occupational exposure represents a critical interface linking aquaculture environments with human health within the One Health continuum. Although documented occupational infections remain relatively infrequent, chronic low-level exposure may facilitate transient carriage of antimicrobial-resistant bacteria and ARGs, thereby contributing to their wider environmental dissemination. Protecting workers therefore requires more than conventional workplace safety measures; it demands integration of occupational health surveillance, antimicrobial stewardship, farm biosecurity, and continuous education into national One Health action plans. Strengthening these components will improve worker safety while reducing opportunities for resistance transmission across the aquaculture production chain.

Occupational group	Major exposure routes	Potential health risks	Recommended preventive measures	One Health relevance
Aquaculture farmers	Contact with pond water, fish mucus, sediments, biofilms, and contaminated equipment	Colonization by antimicrobial-resistant bacteria; skin and soft-tissue infections; wound infections	Personal protective equipment (PPE), hand hygiene, prompt wound care, safe handling practices, routine health surveillance	High – Primary interface between aquatic animals, the farm environment, and humans; critical for limiting occupational exposure and environmental dissemination of AMR.
Hatchery personnel	Handling eggs, larvae, live feed, culture water, and hatchery equipment	Exposure to antimicrobial-resistant aquatic microorganisms and opportunistic pathogens	Protective clothing, routine sanitation, biosecurity protocols, regular disinfection, health monitoring	High – Prevents early dissemination of resistant microorganisms throughout the production cycle and reduces disease transmission.

Copyright© Bireshwar B.

Veterinarians and aquatic animal health professionals	Clinical examination, sampling, antimicrobial administration, surgery, necropsy, laboratory diagnostics	Exposure to multidrug-resistant pathogens, accidental inoculation, zoonotic infections	PPE, biosafety protocols, vaccination where appropriate, antimicrobial stewardship, laboratory biosafety practices	Very High – Central to antimicrobial stewardship, surveillance, responsible prescribing, and prevention of cross-sector transmission between animals, humans, and the environment.
Seafood processors	Handling raw fish and shellfish, contaminated surfaces, wastewater, and processing equipment	Cross-contamination, foodborne infections, occupational exposure to resistant bacteria	HACCP implementation, gloves, protective clothing, sanitation and hygiene programmes, worker training	High – Protects food safety, reduces contamination of seafood products, and minimizes transmission of AMR through the food chain.
Market workers and retailers	Handling fresh seafood, contaminated equipment, storage containers, and market surfaces	Transient carriage of resistant bacteria, cross-contamination to consumers	Hygiene training, routine cleaning and disinfection, proper cold-chain management, PPE	Moderate–High – Reduces dissemination of resistant microorganisms at the human–food interface and supports public health protection.

Table 7: Occupational exposure pathways to antimicrobial-resistant microorganisms in aquaculture and recommended preventive measures, and One Health relevance.

Environmental Dissemination of Antimicrobial Resistance

Environmental dissemination is widely recognised as one of the defining characteristics of antimicrobial resistance in aquaculture because aquatic production systems are intrinsically connected to surrounding ecosystems through continuous water exchange and ecological interactions. Unlike many terrestrial livestock systems, where waste can be partially contained, aquaculture commonly operates in open or semi-open freshwater, estuarine, and marine environments that permit unrestricted movement of microorganisms, antimicrobial residues, and resistance determinants between production facilities and adjacent ecosystems [11,13]. Consequently, antimicrobial resistance generated within aquaculture can extend well beyond farm boundaries and become integrated into the broader environmental resistome.

Multiple interconnected pathways contribute to this environmental dissemination. Aquaculture effluents, uneaten medicated feed, fish excreta, sludge disposal, sediment disturbance, pond drainage, runoff from production facilities, and wastewater discharge collectively introduce antimicrobial residues, resistant bacteria, and ARGs into rivers, lakes, estuaries, and coastal waters. Once released, these contaminants interact with indigenous microbial communities, altering microbial diversity, increasing selective pressure, and promoting the persistence of resistance determinants within water columns, sediments, suspended particulate matter, and biofilms [14].

Aquatic sediments and biofilms play particularly important ecological roles because they provide stable habitats that support dense microbial communities and facilitate horizontal gene transfer. Within these microenvironments, plasmids, integrons, transposons, bacteriophages, and other mobile genetic elements promote continuous exchange of ARGs among environmental bacteria, aquatic pathogens, and opportunistic human pathogens. Consequently, these environmental reservoirs function not only as repositories of resistance but also as active centres for resistance evolution and dissemination [13,33].

Increasing evidence also indicates that wastewater treatment systems, wetlands, migratory birds, aquatic invertebrates, wild fish populations, and recreational waters contribute to the regional and global movement of antimicrobial resistance. These interconnected pathways demonstrate that resistance originating from aquaculture cannot be viewed in isolation but must instead be understood within a broader environmental network encompassing agriculture, urban wastewater, wildlife, and natural ecosystems. Such ecological connectivity reinforces the central principles of the One Health framework.

Climate change is expected to further intensify these processes. Rising water temperatures, altered salinity,

Copyright© Bireshwar B.

changing precipitation patterns, prolonged droughts, flooding, and more frequent extreme weather events influence bacterial growth, disease outbreaks, antimicrobial usage, and environmental transport of resistant microorganisms. Flood events may redistribute contaminated sediments over large geographic areas, while warmer temperatures enhance bacterial proliferation and increase opportunities for horizontal gene transfer. These climate-driven changes are therefore likely to amplify environmental dissemination of antimicrobial resistance and complicate future disease management in aquaculture [1,28,35].

Effective mitigation requires an ecosystem-based approach that extends beyond prudent antimicrobial use. Improved wastewater treatment, environmentally responsible effluent management, optimisation of feeding practices, sediment management, restoration of riparian buffer zones, environmental genomic surveillance, and climate-resilient aquaculture infrastructure are increasingly recognised as essential components of sustainable antimicrobial stewardship. Integration of these measures within national One Health policies will help reduce environmental selection pressure while protecting aquatic biodiversity and public health.

Critical Synthesis

Current evidence demonstrates that environmental dissemination is a central ecological driver of antimicrobial resistance in aquaculture rather than simply a downstream consequence of antimicrobial use. The persistence of antimicrobial residues, resistant bacteria, and ARGs within water, sediments, biofilms, and wildlife creates interconnected environmental reservoirs that sustain resistance over extended periods and facilitate its movement across environmental, veterinary, and human microbial communities. Climate change is expected to magnify these processes through altered hydrological regimes, increasing disease pressure, and greater environmental disturbance. Consequently, effective antimicrobial stewardship must combine prudent antimicrobial use with environmental surveillance, wastewater management, ecosystem restoration, and climate-adaptive aquaculture practices within a coordinated One Health governance framework.

Driver	Mechanism contributing to AMR	Evidence/Examples	Potential mitigation strategy	Priority for One Health intervention
Inappropriate antimicrobial use	Selective pressure promotes emergence and proliferation of resistant bacteria	Empirical treatment, prophylactic use, incorrect dosage, prolonged exposure	Antimicrobial stewardship, prescription-based therapy, antimicrobial susceptibility testing (AST), treatment guidelines	High
Poor farm biosecurity	Increased disease incidence leads to frequent antimicrobial treatment	High stocking density, poor hygiene, inadequate quarantine	Enhanced biosecurity, routine sanitation, health monitoring, vaccination	High
Environmental contamination	Dissemination of antimicrobial residues, resistant bacteria, and ARGs into surrounding ecosystems	Wastewater discharge, sediment accumulation, aquaculture effluents	Wastewater treatment, environmental monitoring, responsible waste management	High
Horizontal gene transfer (HGT)	Transfer of antimicrobial resistance genes among bacterial populations through plasmids, integrons, and transposons	ARG dissemination in aquatic microbiomes and biofilms	Genomic surveillance, environmental monitoring, reduction of antimicrobial selective pressure	High
Climate change	Environmental stress enhances pathogen proliferation and increases disease outbreaks	Rising temperature, salinity changes, hypoxia, extreme weather events	Climate-adaptive management, predictive surveillance, resilient production systems	Moderate–High

Copyright© Bireshwar B.

Global trade and animal movement	International dissemination of resistant pathogens and antimicrobial resistance genes	Movement of live aquatic animals, broodstock, seafood products	Import risk assessment, certification, quarantine, international surveillance	Moderate
Limited diagnostic capacity	Empirical antimicrobial treatment due to lack of pathogen identification	Delayed laboratory confirmation, inadequate AST	Rapid molecular diagnostics, regional diagnostic laboratories, point-of-care testing	High
Weak surveillance systems	Delayed detection of emerging AMR trends and ineffective policy responses	Fragmented AMU and AMR reporting, inconsistent monitoring	Integrated One Health surveillance, harmonized reporting systems, digital databases	High
Regulatory limitations	Poor enforcement allows inappropriate antimicrobial access and misuse	Over-the-counter sales, weak veterinary oversight	Strengthened legislation, prescription-only policies, residue monitoring, regulatory enforcement	High
Knowledge and training gaps	Limited awareness encourages inappropriate antimicrobial use	Insufficient farmer education and extension services	Capacity building, continuing education, stewardship training programmes	Moderate
Socioeconomic constraints	Financial limitations reduce adoption of preventive health measures	Small-scale producers unable to invest in vaccination, diagnostics, or biosecurity	Financial incentives, extension services, certification programmes, technical support	Moderate
Emerging pathogens and evolving resistance	Novel pathogens and resistant strains complicate disease management	Expansion of multidrug-resistant Aeromonas, Vibrio, and other opportunistic bacteria	Continuous surveillance, vaccine development, rapid diagnostics, adaptive stewardship	Emerging

Table 8: Major drivers of antimicrobial resistance (AMR) in aquaculture and priorities for One Health intervention.

Mobile Genetic Elements and Cross-Sector Transmission of Antimicrobial Resistance

One of the most significant public health concerns associated with antimicrobial resistance (AMR) is not merely the emergence of resistant bacterial strains but the capacity of antimicrobial resistance genes (ARGs) to move across bacterial populations, host species, and ecological boundaries. In aquatic environments, this dissemination is primarily mediated by mobile genetic elements (MGEs), including plasmids, integrons, transposons, insertion sequences, integrative and conjugative elements (ICEs), and bacteriophages. These genetic vehicles enable the rapid horizontal transfer of resistance determinants among environmental microorganisms, aquatic pathogens, commensal bacteria, and clinically important human pathogens, thereby accelerating the evolution and spread of multidrug resistance [11,33].

Aquaculture environments provide favourable ecological conditions for horizontal gene transfer because of their high microbial diversity, dense bacterial populations, continuous exposure to antimicrobial residues, and close interactions among aquatic animals, sediments, biofilms, wastewater, and natural water bodies. These interconnected microbial communities facilitate frequent genetic exchange, allowing resistance genes selected within aquaculture systems to persist and spread beyond farm boundaries. Consequently, aquatic ecosystems are increasingly recognised as important reservoirs and exchange hubs within the global resistome [13].

Several clinically important ARGs have now been reported in aquaculture-associated bacteria and environmental samples. These include extended-spectrum β-lactamase genes (bla_{CTX-M}), carbapenemase genes (bla_{NDM},bla_{KPC}, bla_{OXA-48}), plasmid-mediated colistin

Copyright© Bireshwar B.

resistance genes (mcr-1 to mcr-10), quinolone resistance genes (qnr), tetracycline resistance genes (tet), and sulfonamide resistance genes (sul). Many of these genes are located on conjugative plasmids and integrons, facilitating their movement across taxonomically diverse bacterial populations [6,19].

The detection of carbapenemase-and colistin-resistance genes in aquaculture environments is particularly concerning because carbapenems and polymyxins remain among the few effective therapeutic options for treating severe multidrug-resistant infections in humans. Their occurrence in environmental bacteria raises the possibility that these critical resistance determinants may be transferred into clinically significant pathogens through environmental and foodborne pathways, thereby reducing the effectiveness of last-resort antimicrobial therapies. This highlights the need for surveillance systems that monitor not only resistant organisms but also the mobile genetic elements responsible for ARG dissemination [19,35].

Critical Synthesis

Current evidence demonstrates that mobile genetic elements constitute the principal drivers of resistance dissemination across the human–animal–environment interface. Rather than remaining confined to individual bacterial species or production systems, ARGs circulate through interconnected microbial networks linking aquaculture, wastewater, wildlife, agriculture, and healthcare settings. Consequently, effective One Health surveillance should extend beyond pathogen detection to include systematic monitoring of plasmids, integrons, bacteriophages, and other mobile genetic elements that underpin resistance evolution. Such an ecosystem-level approach will provide earlier warning of emerging threats and improve the effectiveness of antimicrobial stewardship programmes.

Human Gut Colonization and the Human Resistome

Increasing evidence indicates that the public health consequences of aquaculture-associated antimicrobial resistance extend beyond foodborne infections. Following the consumption of contaminated seafood, antimicrobial-resistant bacteria may survive passage through the gastrointestinal tract and transiently or persistently colonize the human intestinal microbiota. Although colonization does not necessarily result in clinical disease, it creates opportunities for antimicrobial resistance genes (ARGs) to become incorporated into the complex microbial ecosystem of the human gut, thereby expanding the intestinal resistome [15].

The human gastrointestinal tract contains one of the most diverse microbial communities in the body and functions as a dynamic reservoir of antimicrobial resistance. Within this ecosystem, horizontal gene transfer occurs continuously through conjugation, transformation, and bacteriophage-mediated transduction, enabling ARGs introduced by foodborne or environmental bacteria to be exchanged with commensal microorganisms and opportunistic pathogens. Mobile genetic elements—including plasmids, integrons, transposons, and bacteriophages—facilitate these genetic exchanges, allowing clinically important resistance determinants to persist even in the absence of active infection or antimicrobial treatment [11,13].

Colonized individuals may therefore serve as asymptomatic reservoirs of antimicrobial- resistant bacteria and ARGs. These organisms can subsequently spread within households, healthcare facilities, and communities through direct or indirect transmission, while antimicrobial exposure from medical therapy or environmental sources may further enrich resistant bacterial populations already established within the gut microbiome. Consequently, seafood-associated exposure should be regarded not only as a source of infection but also as a mechanism contributing to the long-term enrichment and persistence of the human resistome. Recent advances in metagenomics, whole-genome sequencing (WGS), long-read sequencing, and resistome profiling have transformed our understanding of these processes. These approaches enable comprehensive characterization of microbial communities, resistance genes, and mobile genetic elements without reliance on conventional culture techniques, thereby improving understanding of ARG movement between aquatic environments, food products, animals, and humans. Incorporating resistome analysis into national food safety and One Health surveillance programmes will strengthen risk assessment and facilitate evidence- based antimicrobial stewardship.

Critical Synthesis

The available evidence suggests that one of the greatest public health risks associated with aquaculture-derived AMR is the silent enrichment of the human intestinal resistome rather than the occurrence of overt foodborne disease. The gut microbiome functions as an ecological interface where resistance determinants acquired through diet, environmental exposure, and antimicrobial therapy may accumulate, persist, and subsequently disseminate to pathogenic bacteria. Future surveillance programmes should therefore integrate resistome profiling alongside conventional pathogen detection to better characterize human exposure pathways and guide preventive interventions within the One Health framework.

Copyright© Bireshwar B.

Socioeconomic and Public Health Consequences

The consequences of antimicrobial resistance associated with aquaculture extend far beyond individual disease outbreaks, affecting healthcare systems, food security, international trade, environmental sustainability, and the long-term resilience of aquatic food production. As aquaculture continues to supply an increasing proportion of the world's animal protein, maintaining antimicrobial effectiveness has become both a public health priority and an economic necessity [1,9].

From a clinical perspective, antimicrobial-resistant infections are associated with increased morbidity, mortality, prolonged hospitalization, and substantially higher healthcare costs. The emergence of resistance to critically important antimicrobials limit therapeutic options and complicates treatment of severe bacterial infections. Although aquaculture represents only one component of the global AMR landscape, the movement of resistant bacteria and ARGs through food systems and aquatic environments reinforces the need for coordinated surveillance and stewardship across environmental, veterinary, and public health sectors [19].

Economic consequences are equally significant. Disease outbreaks caused by resistant pathogens increase mortality, reduce production efficiency, and elevate treatment costs, thereby decreasing farm profitability. International seafood trade may also be affected through import restrictions, shipment rejections, product recalls, and increased compliance costs associated with antimicrobial residue monitoring and food safety regulations. These impacts are often greatest for small-scale producers operating in low- and middle-income countries, where access to diagnostics, veterinary support, and disease prevention technologies remains limited [1,37].

Consumer expectations are also changing. Growing awareness of antimicrobial resistance, environmental sustainability, and food safety has increased demand for seafood produced under responsible antimicrobial stewardship programmes. Certification schemes, traceability systems, responsible farming practices, and transparent supply chains are therefore becoming increasingly important determinants of market competitiveness and international trade.

Critical Synthesis

Current evidence demonstrates that AMR imposes interconnected health, economic, environmental, and social costs that cannot be addressed through isolated interventions. Sustainable aquaculture will depend upon integrated investments in disease prevention, surveillance, farmer education, biosecurity, regulatory oversight, and technological innovation. Strengthening antimicrobial stewardship within a coordinated One Health framework will improve public health protection while supporting resilient food systems and sustainable economic development.

Exposure pathway	Potential consequence	Evidence level	Relative risk	Priority surveillance tool	Mitigation strategy
Seafood consumption	Foodborne exposure to antimicrobial-resistant bacteria	High	High	Culture + AST, WGS, residue monitoring	Food safety monitoring, withdrawal period compliance, HACCP
Occupational exposure	Colonization or infection among farm workers	Moderate	Moderate	Culture, WGS (outbreak investigation)	PPE, hygiene, occupational surveillance, education
Aquaculture effluents	Environmental dissemination of ARGs and resistant bacteria	High	High	Metagenomics, eDNA, WGS	Wastewater treatment, environmental monitoring
Wildlife and aquatic ecosystems	Dissemination of resistant microorganisms across aquatic ecosystems	Moderate	Moderate	eDNA, metagenomics, integrated environmental surveillance	Environmental monitoring, ecosystem protection

Copyright© Bireshwar B.

Horizontal gene transfer (HGT)	Transfer of ARGs to clinically important bacteria	High	High	WGS, metagenomics, resistome analysis	Integrated AMR surveillance, source control, stewardship
Aquatic sediments (recommended addition)	Long-term environmental reservoir of ARGs	Moderate	Moderate	Metagenomics, eDNA	Sediment monitoring and improved waste management
Live aquatic animal trade (recommended addition)	Cross-border dissemination of resistant pathogens	Moderate	Moderate–High	Integrated surveillance, WGS	Import screening, quarantine, traceability

Table 9: Human health risks associated with antimicrobial resistance in aquaculture under the One Health framework.

Integrating One Health into Aquaculture Stewardship

The emergence and dissemination of antimicrobial resistance in aquaculture exemplify the interconnected nature of human, animal, and environmental health, making the One Health approach indispensable for sustainable antimicrobial stewardship. Aquaculture systems interact continuously with natural water bodies, wildlife, agricultural landscapes, food supply chains, and human populations, creating multiple opportunities for resistant microorganisms and antimicrobial resistance genes (ARGs) to circulate across ecological boundaries. Consequently, reducing antimicrobial use alone is unlikely to achieve lasting reductions in AMR unless supported by coordinated interventions across environmental, veterinary, agricultural, and public health sectors [16,19].

A comprehensive One Health stewardship framework integrates surveillance of antimicrobial use, resistant bacteria, ARGs, antimicrobial residues, and environmental risk factors across aquaculture production systems. Such integrated surveillance enables early identification of emerging resistance, clarifies transmission pathways, and supports evidence-based disease prevention strategies. Equally important are investments in veterinary oversight, vaccination programmes, rapid molecular diagnostics, farm biosecurity, wastewater treatment, environmental monitoring, farmer education, and responsible management practices that collectively reduce disease incidence and dependence on antimicrobials [1,8].

International collaboration remains central to effective governance. The Quadripartite One Health Joint Plan of Action (2022-2026) developed by FAO, WHO, WOAH, and UNEP provides a coordinated framework for addressing AMR across agriculture, aquaculture, environmental management, and public health. Harmonized surveillance protocols, standardized reporting systems, international data sharing, and collaborative policy development are essential for managing the transboundary nature of antimicrobial resistance. Emerging technologies further strengthen One Health implementation. Whole-genome sequencing, metagenomics, environmental DNA (eDNA), digital PCR, artificial intelligence, and predictive analytics now enable real-time detection of resistance determinants, source attribution, and early warning of emerging threats. Integration of these tools into national surveillance programmes will improve risk assessment, support precision antimicrobial stewardship, and facilitate adaptive management of aquaculture systems under changing environmental conditions [22,38].

Critical Synthesis

The evidence reviewed throughout this section demonstrates that antimicrobial resistance associated with aquaculture is fundamentally an ecosystem-level challenge rather than a problem confined to aquatic animal production. Resistant bacteria and ARGs circulate continuously among aquatic environments, wildlife, food systems, and human populations through multiple interconnected pathways, including seafood consumption, occupational exposure, environmental dissemination, and horizontal gene transfer. Consequently, successful stewardship requires a transition from reactive antimicrobial treatment towards preventive, ecosystem-based health management.

Future priorities should focus on strengthening biosecurity, vaccination, environmental management, wastewater treatment, rapid diagnostics, farmer education, harmonized regulations, and integrated genomic surveillance. Continued investment in multidisciplinary research, international collaboration, and emerging molecular technologies will be essential for preserving antimicrobial effectiveness while ensuring resilient, productive, and environmentally sustainable aquaculture systems. This integrated One Health approach provides the foundation for safeguarding aquatic animal health, environmental integrity, food security, and human health in an increasingly interconnected world.

Having established the public health implications and One Health dimensions of antimicrobial resistance in

Copyright© Bireshwar B.

aquaculture, the following section examines antimicrobial stewardship programmes in greater detail, focusing on governance frameworks, implementation strategies, practical interventions, and future directions for reducing antimicrobial dependence while sustaining aquaculture productivity.

Antimicrobial Stewardship Strategies in Aquaculture

Concept and Principles of Antimicrobial Stewardship

Antimicrobial stewardship (AMS) has emerged as one of the most important strategies for combating antimicrobial resistance (AMR) while ensuring the sustainable production of aquatic foods. Defined as a coordinated, multidisciplinary approach to optimize antimicrobial use, AMS seeks to achieve effective disease treatment while minimizing unnecessary antimicrobial exposure and slowing the emergence and dissemination of resistant microorganisms. Although stewardship was initially developed within human healthcare to improve antimicrobial prescribing, its scope has expanded considerably to include veterinary medicine, livestock production, and aquaculture, where disease control, environmental sustainability, food safety, and public health are intrinsically interconnected [16,19,39].

Aquaculture presents unique stewardship challenges compared with terrestrial animal production systems. Most cultured fish and shellfish are reared in open or semi-open aquatic environments where microorganisms, antimicrobial residues, sediments, and water are continuously exchanged with surrounding ecosystems. Consequently, antimicrobial administration may influence not only treated animals but also environmental microbial communities, aquatic wildlife, food products, and ultimately human populations through multiple ecological pathways. This continuous connectivity makes aquaculture an ideal example of the One Health concept, in which animal, environmental, and human health are closely linked [6,11].

The overarching goal of antimicrobial stewardship in aquaculture is to maintain effective disease control while minimizing dependence on antimicrobial therapy. Rather than focusing solely on reducing antimicrobial consumption, modern stewardship programmes emphasize disease prevention, early diagnosis, evidence-based therapeutic decisions, and continuous monitoring of antimicrobial use (AMU) and antimicrobial resistance (AMR). By preventing disease before treatment becomes necessary, stewardship simultaneously improves animal health, farm productivity, environmental sustainability, and food safety.

Successful stewardship programmes integrate several complementary components. Veterinary oversight remains fundamental, ensuring that antimicrobial therapy is prescribed only when clinically justified and supported by appropriate diagnostic evidence whenever feasible. Laboratory confirmation of bacterial infections, antimicrobial susceptibility testing, and adherence to approved treatment protocols help ensure that the most appropriate antimicrobial is selected, thereby reducing unnecessary exposure to broad-spectrum agents and minimizing selective pressure for resistance development. Compliance with recommended dosages, treatment duration, withdrawal periods, and accurate record keeping further improves treatment efficacy while reducing antimicrobial residues in aquatic products and surrounding environments [1,8].

Contemporary stewardship also recognizes that effective disease management depends primarily on preventive rather than therapeutic interventions. Improvements in farm biosecurity, water quality management, stocking density, nutrition, husbandry practices, vaccination programmes, selective breeding for disease resistance, and routine health monitoring substantially reduce disease incidence and consequently decrease the need for antimicrobial treatment. Complementary alternatives—including probiotics, prebiotics, synbiotics, phytotherapeutics, immunostimulants, bacteriophages, quorum-quenching compounds, and precision aquaculture technologies are increasingly incorporated into integrated disease management strategies that reduce antimicrobial dependence while maintaining production efficiency [38,40,41].

A defining feature of modern antimicrobial stewardship is the integration of surveillance across the entire aquaculture production system. Continuous monitoring of antimicrobial consumption, resistance patterns, antimicrobial residues, aquatic microbiomes, and environmental resistomes provides essential information for evaluating stewardship performance, identifying emerging resistance, and guiding evidence-based policy development. Advances in whole-genome sequencing, metagenomics, environmental DNA (eDNA), digital PCR, artificial intelligence (AI), and Internet of Things (IoT)-based precision aquaculture now enable earlier disease detection and real-time monitoring of resistance dynamics, supporting more targeted and judicious antimicrobial use [13,22].

The international framework for antimicrobial stewardship has also evolved considerably. The World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO), the World Organisation for Animal Health (WOAH), and the United Nations Environment Programme (UNEP), through the Quadripartite One Health

Copyright© Bireshwar B.

collaboration, advocate harmonized surveillance, responsible antimicrobial use, strengthened regulatory oversight, environmental monitoring, and coordinated multisectoral governance. These global recommendations provide the scientific and policy foundation for national stewardship programmes and reinforce the importance of integrating aquaculture into broader One Health action plans aimed at preserving antimicrobial effectiveness for future generations [8,16,19,35].

Critical Synthesis

Antimicrobial stewardship in aquaculture has evolved from a narrow emphasis on prudent antimicrobial prescribing to a comprehensive framework for sustainable aquatic animal health management. Current evidence indicates that meaningful reductions in antimicrobial resistance cannot be achieved simply by restricting antimicrobial use; rather, success depends on strengthening disease prevention, improving farm management, expanding surveillance systems, enhancing regulatory governance, and promoting collaboration among veterinarians, farmers, microbiologists, environmental scientists, policymakers, and public health professionals.

Future stewardship programmes are expected to become increasingly data-driven, integrating genomic surveillance, artificial intelligence, precision aquaculture, and predictive epidemiological modelling to support earlier disease detection and evidence-based interventions. At the same time, stewardship must remain adaptable to regional socioeconomic conditions, particularly in low- and middle-income countries where resource limitations, diagnostic capacity, and regulatory implementation continue to constrain progress. Consequently, antimicrobial stewardship should be viewed as a dynamic, ecosystem-based management strategy that simultaneously safeguards aquatic animal health, environmental integrity, food security, and human health within the broader One Health framework.

Stewardship component	Primary objective	Expected impact	Implement ation priority	Evidence strength	One Health benefit
Veterinary oversight	Rational antimicrobial prescribing	High	High	Strong	Human & Animal
Rapid diagnostics	Evidence-based treatment	High	High	Strong	Human & Animal
Vaccination	Disease prevention	Very high	High	Strong	Animal & Environment
Farm biosecurity	Prevent pathogen introduction	Very high	High	Strong	All sectors
Water quality management	Minimize environmental stress	High	High	Moderate–Strong	Environment
Probiotics & phytobiotics	Reduce antimicrobial dependence	Moderate–High	Medium	Moderate	Animal & Environment
Bacteriophage therapy	Control MDR pathogens	Emerging	Medium	Emerging	Human & Animal
Precision aquaculture (AI/IoT)	Early disease detection	High	Emerging	Emerging	All sectors
AMU & AMR surveillance	Stewardship evaluation	Very high	High	Strong	All sectors
Farmer education & training	Improve stewardship compliance	High	High	Strong	Human & Animal

Table 10: Integrated antimicrobial stewardship interventions for sustainable aquaculture.

Surveillance of Antimicrobial Use and Resistance

Surveillance of antimicrobial use (AMU), antimicrobial resistance (AMR), and antimicrobial residues is a fundamental pillar of antimicrobial stewardship in aquaculture. Reliable surveillance systems provide the evidence required to understand how antimicrobials are used, detect emerging resistance, evaluate the effectiveness of stewardship interventions, and support regulatory decision-making. Without continuous surveillance, inappropriate antimicrobial practices may remain unnoticed, allowing resistant microorganisms and antimicrobial resistance genes (ARGs) to accumulate within aquaculture systems and

Copyright© Bireshwar B.

disperse into surrounding aquatic environments, ultimately increasing risks to animal, environmental, and human health [7,8,16].

Unlike many terrestrial livestock systems, aquaculture presents unique surveillance challenges because production occurs in dynamic aquatic environments where water, sediments, microorganisms, wildlife, and cultured organisms are continuously interconnected. Consequently, surveillance programmes must extend beyond monitoring antimicrobial consumption at the farm level to include resistant bacteria, ARGs, antimicrobial residues, and environmental reservoirs. Such an integrated approach aligns closely with the One Health framework by recognising that antimicrobial resistance evolves through interactions among aquatic ecosystems, food production systems, and human activities rather than within farms alone [11,14].

A comprehensive surveillance programme therefore combines several complementary components. Farm treatment records, veterinary prescriptions, and antimicrobial sales data provide valuable information on antimicrobial consumption patterns, while routine bacterial isolation and antimicrobial susceptibility testing continue to serve as the foundation for phenotypic resistance monitoring. Increasingly, these conventional approaches are being complemented by molecular detection of ARGs, residue monitoring in aquatic products, and environmental assessment of water, sediments, and biofilms. Integrating these datasets enables investigators to identify temporal trends, evaluate stewardship performance, detect emerging resistance hotspots, and generate evidence for adaptive management and policy development [1,40].

The rapid development of genomic technologies has transformed surveillance from pathogen- centred diagnostics to ecosystem-level monitoring of antimicrobial resistance. Whole- genome sequencing (WGS) now enables detailed characterization of resistant pathogens, identification of outbreak clusters, and tracking of transmission pathways with unprecedented genomic resolution. Similarly, shotgun metagenomics allows direct characterization of microbial communities and environmental resistomes without the need for bacterial culture, revealing resistance determinants present in both culturable and previously undetected microorganisms. These approaches have substantially improved understanding of how ARGs circulate among aquatic animals, environmental microbiota, wildlife, wastewater, and food production systems [11,13].

Targeted molecular techniques further strengthen surveillance programmes by enabling rapid and quantitative detection of priority resistance genes. Quantitative PCR (qPCR) and digital PCR (dPCR) provide highly sensitive measurement of clinically important ARGs, whereas environmental DNA (eDNA)-based surveillance offers a non-invasive method for monitoring pathogen occurrence and resistance dynamics across aquaculture ecosystems. More recently, CRISPR-based molecular diagnostics have shown considerable promise for rapid, field- deployable detection of bacterial pathogens and resistance determinants, although broader validation is still required before routine implementation in commercial aquaculture settings [21,42].

Digital innovations are also reshaping antimicrobial surveillance. Artificial intelligence (AI), machine-learning algorithms, cloud-based reporting systems, and Internet of Things (IoT)- enabled precision aquaculture platforms can integrate microbiological, environmental, climatic, and production data into real-time decision-support systems. These technologies facilitate earlier detection of disease outbreaks, improve prediction of antimicrobial resistance trends, and support evidence-based interventions before large-scale disease transmission occurs. As digital infrastructure continues to improve, integrating genomic epidemiology with AI-assisted analytics is expected to substantially enhance both surveillance efficiency and antimicrobial stewardship [1,22].

At the global level, coordinated surveillance initiatives have improved harmonization of antimicrobial monitoring across sectors and countries. The WHO Global Antimicrobial Resistance and Use Surveillance System (GLASS), WOAH's annual reports on antimicrobial agents intended for use in animals, and FAO-supported surveillance programmes provide standardized methodologies for data collection, reporting, and international comparison. These collaborative initiatives promote transparency, facilitate global risk assessment, and strengthen implementation of the Quadripartite One Health Joint Plan of Action by encouraging coordinated surveillance across veterinary, environmental, and public health sectors [7,8,16].

Despite these advances, major disparities persist in surveillance capacity worldwide. Many low- and middle-income countries continue to experience limited laboratory infrastructure, inadequate diagnostic capability, insufficient bioinformatics expertise, fragmented reporting systems, and financial constraints that restrict routine surveillance. Furthermore, differences in sampling strategies, laboratory protocols, analytical pipelines, and reporting standards often reduce comparability among studies and complicate the generation of reliable global estimates of antimicrobial use and resistance. Addressing these limitations will require sustained investment in laboratory capacity, standardized methodologies, workforce training, digital reporting platforms, and international technical cooperation [1,7,8].

Copyright© Bireshwar B.

Critical Synthesis

Current evidence clearly demonstrates that surveillance forms the scientific foundation of antimicrobial stewardship in aquaculture. Restricting antimicrobial use alone cannot effectively mitigate antimicrobial resistance unless supported by continuous monitoring of antimicrobial consumption, resistant microorganisms, antimicrobial resistance genes, environmental reservoirs, and treatment outcomes. The integration of conventional microbiology with genomics, environmental surveillance, artificial intelligence, and digital reporting systems represents a major shift towards predictive, ecosystem-based surveillance capable of identifying resistance before it becomes firmly established. Nevertheless, technological innovation alone will not ensure effective stewardship. Long-term success will depend equally on strengthening laboratory infrastructure, harmonizing surveillance standards, promoting international data sharing, and expanding technical support for resource-limited countries. Building integrated surveillance systems that link aquatic animal health, environmental monitoring, food safety, and public health is therefore essential for preserving antimicrobial effectiveness while ensuring sustainable aquaculture within the One Health framework.

Surveillance component	Primary objective	Representative methods	Expected outcome
Antimicrobial use (AMU) monitoring	Quantify antimicrobial consumption	Veterinary prescriptions, sales records, farm treatment logs	Evidence-based antimicrobial use policies
Phenotypic AMR surveillance	Detect resistant bacterial isolates	Culture, antimicrobial susceptibility testing (AST)	Early identification of resistance trends
Genotypic AMR surveillance	Detect ARGs and mobile genetic elements	Whole-genome sequencing, metagenomics, qPCR, dPCR	Detection of emerging resistance and transmission pathways
Environmental surveillance	Monitor environmental reservoirs of AMR	Water, sediment, biofilm and eDNA analysis	Assessment of environmental dissemination
Residue surveillance	Ensure food safety and regulatory compliance	Residue analysis in fish and shellfish tissues	Protection of consumers and export markets
Digital surveillance and AI analytics (new)	Integrate multi-source surveillance data	AI-assisted analytics, cloud-based reporting, IoT-enabled monitoring	Early warning systems and predictive stewardship
National reporting and international data sharing	Harmonize surveillance and inform policy	WHO GLASS, WOAH reporting, FAO surveillance programmes	Coordinated One Health stewardship and global risk assessment

Table 11: Components of an integrated antimicrobial use and antimicrobial resistance surveillance system for aquaculture stewardship.

Diagnostic Stewardship

Diagnostic stewardship has become an increasingly important component of antimicrobial stewardship (AMS) because inappropriate antimicrobial use in aquaculture frequently results from empirical treatment in the absence of laboratory confirmation. In many production systems, disease outbreaks are managed based on clinical signs alone, despite the fact that similar symptoms may arise from bacterial, viral, parasitic, nutritional, or environmental causes. Such empirical therapy often leads to unnecessary antimicrobial exposure, increased production costs, treatment failure, and greater selective pressure for antimicrobial resistance (AMR). Diagnostic stewardship seeks to address these challenges by promoting timely, accurate, and evidence-based pathogen identification before antimicrobial therapy is initiated whenever feasible [1,21].

Traditional bacteriological culture, followed by antimicrobial susceptibility testing (AST), remains the reference standard for identifying bacterial pathogens and guiding antimicrobial selection. These methods provide essential information on pathogen identity and resistance profiles but require specialized laboratory facilities and several days to generate results, limiting their utility during rapidly progressing disease outbreaks. Consequently, conventional microbiology is increasingly complemented by rapid molecular diagnostics that improve the speed and precision of clinical decision-making [13]. Recent advances in molecular biology have transformed aquatic animal disease diagnostics. Polymerase chain reaction (PCR), quantitative PCR (qPCR), loop-mediated isothermal amplification (LAMP),

Copyright© Bireshwar B.

and multiplex PCR assays enable rapid detection of bacterial, viral, and parasitic pathogens with high sensitivity and specificity. These techniques shorten diagnostic turnaround times and facilitate earlier intervention, thereby reducing unnecessary antimicrobial administration and improving treatment outcomes. Their application is particularly valuable during outbreaks where rapid differentiation between bacterial and non- bacterial diseases is essential for appropriate clinical management [20]. Genomics-based diagnostics are providing even deeper insights into pathogen epidemiology and antimicrobial resistance. Whole-genome sequencing (WGS) enables simultaneous characterization of pathogens, virulence determinants, antimicrobial resistance genes (ARGs), and transmission pathways at high genomic resolution. Similarly, metagenomic sequencing permits comprehensive analysis of complex microbial communities directly from environmental or clinical samples without requiring bacterial isolation. These approaches have significantly improved understanding of disease ecology, outbreak investigations, and resistance evolution within aquaculture systems [11,13].

Proteomic and biosensor technologies are also expanding the diagnostic toolbox. Matrix- assisted laser desorption/ ionization time-of-flight mass spectrometry (MALDI-TOF MS) enables rapid microbial identification within minutes once isolates are obtained, whereas portable biosensors and lab-on-a-chip platforms are increasingly being developed for field- based pathogen detection. These technologies reduce dependence on centralized laboratories and support faster therapeutic decision-making, particularly in remote aquaculture production areas.

Environmental surveillance has emerged as another important dimension of diagnostic stewardship. Environmental DNA (eDNA)-based monitoring allows non-invasive detection of pathogens and antimicrobial resistance genes directly from water, sediments, and biofilms, often before clinical disease becomes evident. Such surveillance enables farmers to identify emerging disease risks early, implement preventive management measures, and reduce reliance on reactive antimicrobial treatment. Integrating environmental monitoring with routine farm diagnostics therefore strengthens both disease prevention and antimicrobial stewardship within the One Health framework [21].

Artificial intelligence (AI) is expected to further transform diagnostic stewardship. Machine- learning algorithms can analyse water quality parameters, behavioural changes, production records, imaging data, and genomic information to predict disease outbreaks before clinical signs become apparent. AI-assisted image recognition systems are already capable of identifying abnormal swimming behaviour, external lesions, and stress responses, while cloud-based decision-support platforms can integrate diagnostic, environmental, and epidemiological data to recommend targeted disease management strategies. As these technologies mature, precision diagnostics are likely to become an integral component of sustainable aquaculture management [22,26].

Critical Synthesis

Current evidence indicates that diagnostic stewardship represents a critical transition from empirical antimicrobial use towards precision disease management in aquaculture. Conventional microbiology continues to provide the foundation for pathogen identification and susceptibility testing, but the integration of molecular diagnostics, genomics, environmental DNA monitoring, biosensor technologies, and artificial intelligence is fundamentally changing how aquatic diseases are detected and managed. These innovations enable earlier diagnosis, improve therapeutic accuracy, reduce unnecessary antimicrobial exposure, and strengthen surveillance of antimicrobial resistance. Nevertheless, widespread implementation remains constrained by financial costs, technical expertise, laboratory infrastructure, and limited accessibility in many low- and middle-income countries. Expanding affordable point-of-care diagnostics, strengthening laboratory networks, and integrating digital technologies into routine disease surveillance should therefore be regarded as priorities for future antimicrobial stewardship programmes within the One Health framework.

Farm Biosecurity and Disease Prevention

Disease prevention remains the most effective and economically sustainable strategy for reducing antimicrobial use in aquaculture. Unlike antimicrobial therapy, which is implemented after disease outbreaks occur, biosecurity aims to prevent pathogen introduction, establishment, and transmission throughout the production cycle. By minimizing disease incidence before therapeutic intervention becomes necessary, comprehensive biosecurity programmes reduce antimicrobial consumption, preserve antimicrobial efficacy, improve animal welfare, and strengthen environmental sustainability [1,8].

Biosecurity is best viewed as a multilayered management system rather than a collection of isolated practices. Effective programmes begin with the introduction of certified disease-free broodstock, larvae, and seed, combined with quarantine procedures for newly introduced animals and rigorous health certification. Continuous monitoring of water quality, maintenance of optimal stocking densities, balanced nutrition, and reduction of environmental stressors collectively enhance host immunity and reduce susceptibility

Copyright© Bireshwar B.

to infectious diseases. Together, these husbandry practices establish the foundation for sustainable disease prevention and improved production performance [40]. Operational biosecurity further limits pathogen transmission through strict sanitation and hygiene practices. Regular cleaning and disinfection of ponds, tanks, nets, pipelines, transport equipment, and production facilities reduce microbial persistence, while effective control of vectors, predators, and fomites minimizes opportunities for pathogen introduction. Equally important are the safe disposal of diseased animals, treatment of wastewater before discharge, and appropriate management of sludge and organic wastes, all of which help prevent the release of pathogens, antimicrobial residues, and antimicrobial resistance genes (ARGs) into surrounding aquatic environments. These measures reinforce the environmental dimension of antimicrobial stewardship within the One Health framework [14,40].

Technological innovation is further strengthening farm biosecurity. Recirculating aquaculture systems (RAS) provide greater control over water quality and pathogen exposure through advanced filtration, ultraviolet irradiation, ozone treatment, and controlled environmental conditions. At the same time, precision aquaculture technologies—including automated water-quality sensors, Internet of Things (IoT)-based monitoring systems, artificial intelligence-assisted health surveillance, and predictive disease models—enable continuous assessment of environmental conditions and early detection of disease risks before clinical outbreaks occur. These technologies facilitate proactive rather than reactive disease management and substantially reduce the need for antimicrobial intervention [26].

Biosecurity achieves its greatest impact when integrated with complementary disease prevention strategies such as vaccination, routine diagnostics, selective breeding for disease- resistant stocks, nutritional management, and continuous farmer education. Rather than functioning independently, these interventions operate synergistically to reduce pathogen pressure, strengthen host resilience, improve production efficiency, and support long-term antimicrobial stewardship [38,40].

Critical Synthesis

Evidence from commercial aquaculture consistently demonstrates that farms implementing comprehensive biosecurity programmes experience lower disease incidence, reduced antimicrobial consumption, improved productivity, and diminished environmental dissemination of resistant microorganisms. However, maintaining effective biosecurity requires continuous investment in infrastructure, routine monitoring, workforce training, and regulatory oversight. Future antimicrobial stewardship programmes should therefore prioritize preventive health management supported by precision aquaculture technologies, digital surveillance, and integrated One Health governance. Such an approach offers the greatest opportunity to reduce antimicrobial dependence while ensuring environmentally sustainable and economically resilient aquaculture.

Biosecurity component	Primary objective	Examples of implementation	Contribution to antimicrobial stewardship
Healthy stock introduction	Prevent pathogen entry	Certified disease-free broodstock and seed; quarantine	Reduces introduction of infectious agents and need for antimicrobial treatment
Farm management	Enhance host health and resilience	Water quality management, optimal stocking density, balanced nutrition	Lowers disease susceptibility and antimicrobial demand
Health surveillance	Early disease detection	Routine clinical monitoring, laboratory diagnostics	Enables timely intervention and targeted treatment
Sanitation and hygiene	Reduce pathogen persistence	Cleaning and disinfection of equipment, ponds, and facilities	Interrupts pathogen transmission and limits environmental contamination
Environmental management	Prevent dissemination of pathogens and ARGs	Wastewater treatment, safe disposal of mortalities and sludge	Reduces release of antimicrobial residues and resistant microorganisms
Precision biosecurity	Improve real-time disease prevention	RAS, automated water quality monitoring, AI-assisted health surveillance	Supports predictive disease management and minimizes unnecessary antimicrobial use

Table 12: Core biosecurity measures for disease prevention and antimicrobial stewardship in aquaculture.

Copyright© Bireshwar B.

Vaccination

Vaccination is widely recognised as one of the most effective interventions for reducing antimicrobial use in aquaculture and is now regarded as a cornerstone of antimicrobial stewardship (AMS). By preventing infectious diseases before clinical outbreaks occur, vaccines reduce the need for therapeutic antimicrobial treatment, improve animal survival and productivity, enhance food safety, and decrease the selective pressure that drives antimicrobial resistance (AMR). Within the One Health framework, vaccination contributes simultaneously to animal health, environmental protection, and the preservation of critically important antimicrobials used in human medicine [16,38]. Perhaps the most compelling demonstration of vaccine effectiveness comes from the Norwegian Atlantic salmon industry. Since the widespread introduction of comprehensive vaccination programmes during the late 1980s, antimicrobial consumption has declined by more than 99% while production has continued to expand substantially. This remarkable achievement illustrates that effective disease prevention can largely replace routine antimicrobial therapy when vaccination is integrated with strong biosecurity, improved husbandry, and continuous health surveillance [25,38].

Commercial vaccines are currently available against several economically important bacterial pathogens, including Aeromonas salmonicida, Vibrio anguillarum, Yersinia ruckeri, Lactococcus garvieae, and Streptococcus iniae. Advances in biotechnology are further expanding vaccination opportunities through recombinant protein vaccines, DNA and messenger RNA (mRNA)-based platforms, nanoparticle delivery systems, oral vaccines, immersion vaccines, and multivalent formulations capable of targeting multiple pathogens simultaneously. These innovations offer improved immunogenicity, simplified administration, and broader protection across diverse aquaculture species, thereby strengthening long-term disease prevention strategies [38,43].

Despite these advances, several challenges continue to limit widespread vaccine adoption. Antigenic diversity among aquatic pathogens, incomplete protection against intracellular bacteria, species-specific variation in immune responses, logistical difficulties associated with vaccine administration, and the relatively high cost of vaccine development remain important barriers, particularly for low-value species and small-scale aquaculture enterprises. Additional research is therefore needed to improve antigen discovery, develop broadly protective vaccine platforms, optimise delivery methods, and reduce production costs to enable wider implementation across both freshwater and marine aquaculture systems [43].

Vaccination should not be considered an isolated intervention but rather one component of an integrated disease prevention strategy. When combined with farm biosecurity, rapid diagnostics, surveillance, selective breeding, nutritional management, and environmental monitoring, vaccines substantially reduce disease incidence and antimicrobial dependence while improving production efficiency and animal welfare. This integrated approach provides a robust foundation for sustainable aquaculture and long-term antimicrobial stewardship.

Critical Synthesis

Current evidence consistently identifies vaccination as one of the most successful strategies for reducing antimicrobial consumption in aquaculture by preventing disease rather than treating infection. Experiences from commercial salmon aquaculture clearly demonstrate that sustained reductions in antimicrobial use are achievable when vaccination is integrated with comprehensive biosecurity, surveillance, and good husbandry practices. Future stewardship programmes should therefore prioritise the development of affordable, broadly protective, and species-specific vaccines alongside innovative delivery technologies capable of improving vaccine accessibility across diverse aquaculture systems. Continued investment in vaccinology will remain central to preserving antimicrobial efficacy while advancing sustainable aquaculture within the One Health framework.

Alternatives to Conventional Antimicrobials

The long-term sustainability of aquaculture increasingly depends on reducing reliance on conventional antimicrobials through preventive and biologically based disease-management strategies. Rather than functioning as direct substitutes for antibiotics, many of these alternatives enhance host resilience, modulate microbial communities, or target pathogens through mechanisms that impose lower selective pressure for antimicrobial resistance (AMR). Integrating these approaches with vaccination, biosecurity, and improved husbandry forms the basis of modern antimicrobial stewardship and aligns with the One Health objective of preserving antimicrobial efficacy while maintaining aquatic animal health [1,8].

Probiotics, Prebiotics, and Synbiotics

Manipulation of the intestinal microbiome has emerged as one of the most extensively investigated alternatives to antimicrobial therapy. Probiotic microorganisms—including species of Bacillus, Lactobacillus, Pediococcus, Enterococcus, and Carnobacterium— improve gut microbial balance, enhance nutrient digestion, stimulate innate and

Copyright© Bireshwar B.

adaptive immune responses, and competitively exclude pathogenic bacteria through competitive colonization and production of antimicrobial metabolites. Prebiotics such as fructooligosaccharides, mannan oligosaccharides, and inulin selectively promote the growth of beneficial microorganisms, whereas synbiotics combine probiotics and prebiotics to maximize their synergistic effects. Numerous experimental and commercial studies have reported improvements in growth performance, disease resistance, feed efficiency, and survival following bacterial challenge, supporting their inclusion in sustainable aquaculture management programmes [41,44].

Phytobiotics

Plant-derived bioactive compounds represent another promising strategy for reducing antimicrobial use. Essential oils, polyphenols, flavonoids, alkaloids, terpenoids, tannins, and saponins possess antimicrobial, antioxidant, anti-inflammatory, and immunomodulatory properties that improve host resistance to bacterial infections. Extracts from garlic (Allium sativum), turmeric (Curcuma longa), oregano (Origanum vulgare), neem (Azadirachta indica), and numerous medicinal plants have demonstrated inhibitory activity against important aquaculture pathogens, including Aeromonas, Vibrio, Edwardsiella, and Streptococcus species. Despite encouraging experimental findings, greater standardization of formulations, dosing regimens, and efficacy under commercial farming conditions is still required before widespread implementation [44,45].

Bacteriophage Therapy

Lytic bacteriophages provide highly specific antibacterial activity by infecting and lysing susceptible bacterial pathogens while largely preserving beneficial microbial communities. Phage therapy has demonstrated considerable potential for controlling multidrug-resistant Aeromonas, Vibrio, Pseudomonas, and Flavobacterium species in laboratory and pilot-scale aquaculture systems. Advantages include host specificity, self-replication at infection sites, and minimal disruption of the resident microbiota. Nevertheless, practical application remains constrained by narrow host range, the emergence of phage-resistant bacterial variants, regulatory uncertainty, and challenges associated with large-scale formulation and environmental stability. Current research increasingly focuses on phage cocktails and combined phage–antibiotic therapies to improve treatment efficacy and reduce resistance development [42,46].

Immunostimulants

Dietary immunostimulants strengthen host defence mechanisms and reduce susceptibility to opportunistic infections, thereby lowering the need for antimicrobial intervention. Commonly investigated compounds include β-glucans, nucleotides, chitosan, yeast-derived polysaccharides, algal extracts, vitamins, and mineral supplements. These substances enhance phagocytic activity, complement activation, cytokine production, and antioxidant defence pathways, improving resistance to bacterial pathogens under intensive farming conditions. Although immunostimulants are not substitutes for vaccination or biosecurity, they provide valuable complementary tools for maintaining health during periods of environmental or physiological stress [44].

Quorum-Sensing Inhibitors and Antivirulence Strategies

Unlike conventional antimicrobials, quorum-sensing inhibitors target bacterial communication systems that regulate virulence factor production, motility, and biofilm formation rather than bacterial survival itself. By attenuating pathogenicity without imposing strong bactericidal selection pressure, these antivirulence approaches may reduce the likelihood of resistance evolution. Experimental studies have demonstrated promising effects against Vibrio, Aeromonas, and other aquatic pathogens using natural compounds, enzymes, and synthetic quorum-quenching molecules. Although most applications remain at the experimental stage, antivirulence therapies represent an innovative complement to integrated disease management and warrant further evaluation under commercial production conditions [47].

Critical Synthesis

Recent advances demonstrate that reducing antimicrobial dependence in aquaculture requires combining multiple preventive strategies rather than relying on any single intervention. Probiotics, phytobiotics, bacteriophages, immunostimulants, and quorum-sensing inhibitors each target different aspects of host–pathogen interactions and therefore complement established measures such as vaccination, biosecurity, and improved husbandry. However, their performance may vary among cultured species, production systems, and environmental conditions, highlighting the need for standardized efficacy trials, regulatory harmonization, and long-term field validation. Future stewardship programmes will likely adopt integrated health-management approaches that combine biological alternatives with precision monitoring and genomic surveillance, thereby reducing antimicrobial use while maintaining productivity and environmental sustainability within a One Health framework [1,8,45].

Copyright© Bireshwar B.

Precision Aquaculture and Digital Stewardship

Rapid advances in digital technologies are transforming aquaculture from reactive disease management towards predictive, data-driven health management. Precision aquaculture combines Internet of Things (IoT) sensors, artificial intelligence (AI), machine learning (ML), cloud-based analytics, robotics, and automated decision-support systems to monitor environmental conditions, animal behaviour, and farm performance in real time. By detecting subtle biological and environmental changes before clinical disease becomes evident, these technologies support earlier intervention, reduce unnecessary antimicrobial treatments, and strengthen antimicrobial stewardship [1,8].

Continuous measurement of water quality variables—including temperature, dissolved oxygen, pH, salinity, ammonia, nitrite, turbidity, and oxidation–reduction potential—provides high-resolution information on environmental conditions that influence pathogen proliferation and host susceptibility. When integrated with AI-based predictive models, these datasets can identify disease risk patterns, optimize feeding regimes, adjust stocking densities, and generate early-warning alerts for disease outbreaks. Computer vision technologies further complement environmental monitoring by detecting behavioural alterations, abnormal swimming patterns, reduced feed intake, external lesions, and stress-associated responses that may precede clinical infection by several days [20,26]. Digital stewardship extends beyond farm monitoring by integrating diagnostic results, antimicrobial use (AMU) records, antimicrobial resistance (AMR) surveillance data, laboratory reports, and production records into unified digital management platforms. These systems improve traceability, facilitate regulatory compliance, support evidence-based prescribing, and enable continuous evaluation of stewardship performance. Coupling digital farm management with whole-genome sequencing, metagenomics, environmental DNA (eDNA) surveillance, and resistome analyses further enhances understanding of resistance emergence and transmission pathways across aquaculture ecosystems within a One Health framework [1,7].

Despite substantial technological progress, implementation remains uneven globally. High installation and maintenance costs, limited internet connectivity, inadequate technical expertise, fragmented data standards, cybersecurity concerns, and restricted access to digital infrastructure continue to limit adoption, particularly among small-scale producers in low- and middle-income countries. Addressing these constraints will require investments in digital infrastructure, workforce training, interoperable data platforms, and policy frameworks that promote equitable access to precision technologies while protecting data integrity and privacy [1,37].

Critical Synthesis

Precision aquaculture is redefining antimicrobial stewardship by enabling continuous surveillance, predictive disease management, and evidence-based decision-making. Rather than replacing conventional diagnostics, veterinary oversight, vaccination, and farm biosecurity, digital technologies enhance these interventions by providing timely, high- resolution information that supports early intervention and reduces unnecessary antimicrobial use. Future stewardship programmes are expected to integrate AI-driven analytics, genomic surveillance, environmental monitoring, and digital traceability into comprehensive One Health management systems. Achieving this vision, however, will require greater investment in infrastructure, standardized data governance, and international collaboration to ensure that digital innovations are accessible across both industrial and small-scale aquaculture sectors.

Regulatory Frameworks and Policy Implementation

Effective antimicrobial stewardship (AMS) in aquaculture depends not only on sound farm management but also on regulatory systems that promote responsible antimicrobial use while safeguarding animal, environmental, and public health. Regulatory frameworks establish the legal, institutional, and operational mechanisms governing the authorization, manufacture, distribution, prescription, administration, and post-market surveillance of veterinary antimicrobial agents. Within the aquaculture sector, these frameworks provide the foundation for ensuring that antimicrobial use is evidence-based, medically justified, and consistent with the broader objectives of the One Health approach [7,8].

Modern regulatory programmes extend beyond controlling access to antimicrobial products. They incorporate integrated measures including veterinary prescription requirements, licensing and quality assurance of veterinary medicinal products, compliance with withdrawal periods, monitoring of antimicrobial residues in aquatic products, surveillance of antimicrobial use (AMU) and antimicrobial resistance (AMR), standardized farm record- keeping, and continuous education of producers and aquatic animal health professionals. Increasingly, national regulations also discourage or prohibit the routine prophylactic use of medically important antimicrobials and the use of antibiotics for growth promotion, emphasizing targeted treatment based on clinical diagnosis and, where feasible, antimicrobial

Copyright© Bireshwar B.

susceptibility testing. Collectively, these measures reduce unnecessary antimicrobial exposure and help preserve the efficacy of critically important drugs [1,7].

Experiences from several aquaculture-producing nations demonstrate that strong governance can substantially reduce antimicrobial consumption without compromising productivity. Norway's salmon industry, for example, has combined stringent veterinary oversight, extensive vaccination programmes, comprehensive disease surveillance, and mandatory reporting of antimicrobial use to achieve one of the lowest levels of antibiotic consumption in commercial aquaculture worldwide. Similar stewardship initiatives have been implemented across the European Union, Canada, Australia, Chile, and several Asian countries through coordinated legislation, residue monitoring, national action plans on AMR, and risk-based surveillance systems. These experiences illustrate that regulatory success depends on integrating legislation with preventive disease management, farmer engagement, surveillance, and scientific innovation rather than relying solely on antimicrobial restrictions [8,38].

Despite considerable progress, regulatory implementation remains uneven across regions. Many low- and middle-income countries continue to face limitations in veterinary infrastructure, laboratory capacity, diagnostic services, regulatory enforcement, and surveillance networks. Informal antimicrobial markets, inconsistent product quality, unrestricted access to veterinary medicines, and limited awareness among producers frequently undermine stewardship efforts. In addition, fragmented reporting systems and limited digital infrastructure reduce the ability of regulatory authorities to monitor antimicrobial consumption and detect emerging resistance trends. Addressing these challenges will require sustained investment in institutional capacity, laboratory networks, digital reporting platforms, veterinary workforce development, and regional collaboration to strengthen governance across the aquaculture value chain [1,35].

Critical Synthesis

Regulatory governance remains one of the most influential determinants of successful antimicrobial stewardship in aquaculture. Evidence from countries with mature regulatory systems consistently demonstrates that reductions in antimicrobial consumption are achieved most effectively when legislation is integrated with surveillance, veterinary oversight, vaccination, farm biosecurity, and producer education. Conversely, weak governance, inadequate enforcement, and fragmented surveillance continue to accelerate inappropriate antimicrobial use and the emergence of resistance in many regions. Future policy development should therefore emphasize harmonized international standards, interoperable digital surveillance systems, strengthened veterinary and laboratory infrastructure, transparent reporting of antimicrobial use, and coordinated One Health governance. Such integrated regulatory approaches are essential for protecting seafood safety, maintaining consumer confidence, and preserving antimicrobial effectiveness for future generations [1,7,8].

Challenges and Future Priorities

Although antimicrobial stewardship has become a central pillar of sustainable aquaculture, translating stewardship principles into routine practice remains a global challenge. Marked disparities persist among countries in regulatory capacity, surveillance infrastructure, laboratory facilities, veterinary services, and access to modern diagnostic technologies. These differences contribute to inconsistent reporting of antimicrobial use (AMU) and antimicrobial resistance (AMR), limiting the comparability of surveillance data and constraining evidence- based policy development. In many low- and middle-income countries, empirical antimicrobial use continues to predominate because of limited diagnostic capacity, insufficient technical expertise, fragmented monitoring systems, and inadequate regulatory enforcement [7,8].

Economic constraints represent another major barrier to stewardship implementation. Small- scale aquaculture producers frequently operate with limited financial resources, restricting their access to veterinary consultation, laboratory diagnostics, vaccination programmes, biosecure production systems, and digital monitoring technologies. In several regions, informal distribution networks and unrestricted access to antimicrobial products further encourage indiscriminate antimicrobial use. Overcoming these challenges will require affordable stewardship programmes, improved extension services, financial incentives for adopting preventive health measures, and continuous education to strengthen awareness of antimicrobial resistance and responsible antimicrobial use among farmers and other stakeholders [1].

Rapid technological advances are creating new opportunities to strengthen stewardship. High-throughput sequencing, metagenomics, environmental DNA (eDNA) surveillance, resistome analysis, artificial intelligence, precision aquaculture, and digital decision-support systems now enable earlier detection of disease outbreaks, improved characterization of antimicrobial resistance genes (ARGs), and more accurate assessment of transmission pathways across aquatic ecosystems. At the same time, continued development of vaccines, probiotics, bacteriophage therapy, phytobiotics, immunostimulants, selective breeding programmes, and genome-assisted disease-resistance strategies offers realistic alternatives that can substantially

Copyright© Bireshwar B.

reduce dependence on conventional antimicrobial therapy. Integrating these innovations into routine production systems has the potential to transform disease management from reactive treatment to proactive prevention [40,45].

Future progress will depend equally on stronger international cooperation. Antimicrobial resistance is inherently transboundary, with resistant microorganisms and resistance genes moving through aquatic environments, food trade, wildlife, and human activities. Consequently, harmonized surveillance methodologies, interoperable databases, standardized reporting frameworks, coordinated research initiatives, and open international data sharing are essential for effective global stewardship. Collaboration among governments, researchers, veterinarians, producers, public health authorities, environmental scientists, and international organizations will be critical for developing stewardship strategies that are scientifically robust, economically viable, socially acceptable, and environmentally sustainable [1,7,8].

Critical Synthesis

Antimicrobial stewardship in aquaculture has progressed from a narrow emphasis on prudent antimicrobial prescribing to a holistic framework that integrates disease prevention, surveillance, diagnostics, vaccination, biosecurity, environmental management, regulatory governance, and innovative biological and digital technologies. Experiences from countries with mature stewardship programmes demonstrate that substantial reductions in antimicrobial consumption can be achieved without compromising aquatic animal health, productivity, or economic performance when preventive interventions are prioritized over routine therapeutic use. These successes reinforce the principle that sustainable stewardship depends on coordinated implementation of complementary measures rather than isolated interventions [38,40].

Nevertheless, important challenges remain before similar outcomes can be achieved globally. Persistent inequalities in infrastructure, regulatory capacity, technical expertise, financing, and access to emerging technologies continue to limit stewardship implementation in many aquaculture-producing regions. Addressing these gaps will require sustained investment in integrated One Health surveillance, laboratory and veterinary services, digital infrastructure, precision aquaculture, and international regulatory harmonization. Looking ahead, the convergence of genomics, artificial intelligence, environmental monitoring, and ecosystem- based management offers unprecedented opportunities to strengthen antimicrobial stewardship while supporting resilient, climate-adaptive, and environmentally sustainable aquaculture. Preserving antimicrobial efficacy will therefore depend not only on scientific innovation but also on coordinated policy action, international cooperation, and long-term commitment across the human, animal, and environmental health sectors.

Policy, Governance, and Future Perspectives

Global Policy Landscape for Antimicrobial Stewardship in Aquaculture

As antimicrobial resistance (AMR) has emerged as one of the defining global public health challenges of the twenty-first century, international efforts to promote responsible antimicrobial use have expanded across the human, animal, and environmental health sectors. Within aquaculture, antimicrobial stewardship (AMS) is now widely recognized as a key element of sustainable aquatic food production and an integral component of the One Health framework. The World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO), the World Organisation for Animal Health (WOAH), and the United Nations Environment Programme (UNEP) have jointly emphasized coordinated action through the Quadripartite One Health Joint Plan of Action (2022–2026), which promotes integrated surveillance, prudent antimicrobial use, and cross-sectoral governance to curb the spread of AMR [7,16].

International policy initiatives provide a common framework for national stewardship programmes. The WHO Global Action Plan on Antimicrobial Resistance and the WOAH Strategy on Antimicrobial Resistance and the Prudent Use of Antimicrobial Agents encourage countries to strengthen surveillance systems, improve veterinary oversight, regulate antimicrobial distribution, and expand stewardship practices throughout food-animal production systems [8,48]. Complementing these initiatives, the Codex Alimentarius Commission has established internationally harmonized guidance on AMR risk analysis, responsible antimicrobial use, and food safety, thereby supporting evidence-based policymaking and facilitating safe international trade in aquatic products [36].

Experiences from several aquaculture-producing nations demonstrate that effective policy can substantially reduce antimicrobial dependence without compromising productivity. Norway represents one of the most successful examples, where widespread vaccination, mandatory veterinary prescriptions, and long-term surveillance have reduced antimicrobial use in salmon farming by more than 99% since the late 1980s [25]. Similar progress has been achieved in the European Union through Regulation (EU) 2019/6, alongside strengthened stewardship programmes in Canada, Australia, Chile, and Japan that combine regulatory

Copyright© Bireshwar B.

oversight with residue monitoring and surveillance [8,49]. Nevertheless, implementation remains uneven in many low- and middle- income countries, where inadequate veterinary infrastructure, informal antimicrobial markets, and weak regulatory enforcement continue to limit responsible antimicrobial use [1].

Socioeconomic Barriers to Stewardship Implementation

The effectiveness of antimicrobial stewardship depends not only on scientific advances but also on the economic, institutional, and behavioural context in which aquaculture is practiced. Although preventive measures such as vaccination, biosecurity, surveillance, and precision farming have demonstrated their ability to reduce antimicrobial use, adoption varies widely because producers differ in their access to financial resources, infrastructure, veterinary support, and technical expertise [1,18].

These disparities are particularly evident among small-scale producers, who contribute substantially to global aquaculture yet often operate under significant resource constraints. Limited access to veterinary services, diagnostic laboratories, and certified medicines frequently results in empirical treatment decisions based on previous experience or informal advice rather than laboratory-confirmed diagnoses. At the same time, the costs associated with vaccination, biosecurity improvements, and water-quality management may discourage investment in preventive health measures, especially where disease outbreaks threaten household income and food security [7].

Institutional factors further influence stewardship outcomes. Weak enforcement of antimicrobial regulations, informal supply chains, unrestricted over-the-counter sales of veterinary antimicrobials, and inconsistent compliance with withdrawal periods continue to undermine responsible antimicrobial use in many regions. In addition, fragmented surveillance systems and insufficient coordination among veterinary, environmental, and public health agencies reduce the effectiveness of monitoring programmes for antimicrobial use (AMU), antimicrobial resistance (AMR), and antimicrobial residues [8]. Human behaviour also plays a critical role. Levels of awareness regarding AMR, biosecurity, and prudent antimicrobial use vary considerably among producers, while opportunities for continuing education and technical support remain limited in many aquaculture-dependent communities. Expanding farmer training programmes, strengthening extension services, and promoting participatory knowledge exchange are therefore essential to encourage preventive disease management and reduce reliance on routine antimicrobial therapy [37].

Overcoming these barriers will require integrated policy approaches that combine scientific innovation with economic incentives, institutional reform, and stakeholder engagement. Expanding access to veterinary and diagnostic services, improving the affordability of preventive technologies, supporting small-scale producers through targeted financial assistance, strengthening regulatory enforcement, and encouraging collaboration among farmers, researchers, veterinarians, industry, and policymakers are all critical for achieving equitable stewardship. Such measures are fully consistent with the One Health concept, which recognizes the close interdependence of animal, environmental, and human health [16].

Critical Synthesis

Current evidence suggests that the greatest obstacles to antimicrobial stewardship are often socioeconomic rather than technological. Many of the tools needed to reduce antimicrobial dependence already exist, but their successful implementation depends on adequate financial investment, institutional capacity, regulatory support, and education. Future stewardship programmes should therefore place equal emphasis on strengthening governance, improving access to veterinary services, building technical capacity, and ensuring that preventive technologies remain affordable and accessible across diverse aquaculture systems, particularly in resource-limited settings [37-40].

Climate Change and Emerging Disease Risks

Climate change is increasingly shaping the epidemiology of infectious diseases in aquaculture and is now recognized as an important factor influencing antimicrobial resistance (AMR). Rising water temperatures, changing precipitation patterns, ocean acidification, salinity fluctuations, hypoxia, and more frequent extreme weather events are altering aquatic ecosystems in ways that affect interactions among cultured animals, pathogens, and environmental microbial communities. Collectively, these environmental changes can weaken host immunity, enhance pathogen survival and virulence, and create conditions that favour the emergence, persistence, and spread of infectious diseases [1,28].

Among the pathogens most strongly influenced by climatic variability are temperature- sensitive bacteria such as Vibrio, Aeromonas, and other opportunistic species. Warmer waters have been associated with expanded geographic ranges and increased disease incidence in both freshwater and marine aquaculture systems. At the same time, environmental stress caused by fluctuating water quality and extreme climatic conditions can compromise the physiological resilience of fish and shellfish, increasing their susceptibility to opportunistic infections. As disease

Copyright© Bireshwar B.

outbreaks become more frequent or severe, producers may rely more heavily on antimicrobial treatments, thereby increasing the selective pressure for resistant bacteria and antimicrobial resistance genes (ARGs) [18]. Extreme weather events further complicate this situation by facilitating the movement of pathogens, antimicrobial residues, resistant microorganisms, and ARGs across aquatic environments. Floods, storm surges, and changing hydrological patterns can transport contaminated water, sediments, and organic matter between farms, rivers, estuaries, and coastal ecosystems, creating new opportunities for horizontal gene transfer and the establishment of environmental reservoirs of AMR. These interconnected processes highlight the importance of viewing climate change and antimicrobial resistance through a One Health perspective, where ecosystem health, animal health, and public health are intrinsically linked [28,50].

Building climate resilience should therefore become an integral part of antimicrobial stewardship in aquaculture. Climate-informed disease surveillance, continuous environmental monitoring, predictive epidemiological models, resilient production systems, improved water-resource management, enhanced biosecurity, and selective breeding for climate- tolerant and disease-resistant stocks can all reduce disease pressure before antimicrobial intervention becomes necessary. The integration of precision aquaculture technologies— including real-time environmental sensors and AI-assisted health monitoring—further strengthens preparedness by enabling earlier detection of disease risks and more timely management responses [7,16].

Critical Synthesis

Climate change is likely to intensify many of the factors that drive antimicrobial resistance in aquaculture by increasing disease pressure, altering pathogen ecology, and facilitating the environmental spread of resistance genes. Consequently, antimicrobial stewardship should extend beyond prudent antimicrobial use to include climate adaptation, ecosystem-based disease prevention, and predictive surveillance. Developing integrated climate–disease forecasting systems, expanding long-term environmental monitoring, and strengthening multidisciplinary One Health collaborations will be essential for improving the resilience of aquaculture while safeguarding antimicrobial efficacy under future climate scenarios [4,50].

Emerging Technologies Transforming Stewardship

Rapid developments in molecular biology, genomics, and digital technologies are transforming antimicrobial stewardship by enabling earlier disease detection, more accurate pathogen identification, and increasingly data-driven management decisions. Advances in whole-genome sequencing (WGS), shotgun metagenomics, resistome profiling, CRISPR- based diagnostics, and portable nanopore sequencing now allow high-resolution characterization of antimicrobial-resistant pathogens and antimicrobial resistance genes (ARGs). These approaches provide valuable insights into resistance evolution, transmission pathways, and outbreak dynamics that were previously difficult to obtain using conventional microbiological techniques [13].

At the same time, digital technologies are reshaping routine farm management. Artificial intelligence (AI), machine learning, Internet of Things (IoT)-enabled sensor networks, digital twins, cloud-based analytics, and blockchain-supported traceability systems can continuously monitor water quality, animal behaviour, production performance, and antimicrobial use. By integrating these datasets into decision-support platforms, producers can identify disease risks earlier, optimize management practices, improve treatment traceability, and strengthen compliance with antimicrobial stewardship guidelines [20].

The greatest potential of these innovations lies in their integration rather than their individual application. Combining genomic surveillance with environmental monitoring, epidemiological modelling, and digital decision-support systems creates opportunities to move from reactive disease control towards predictive, precision-based health management. Such integrated systems can facilitate targeted interventions, reduce unnecessary antimicrobial use, improve outbreak preparedness, and strengthen national and international AMR surveillance programmes within a One Health framework [1,7]. Despite these advances, widespread implementation remains uneven. High infrastructure costs, limited laboratory capacity, shortages of trained personnel, data interoperability challenges, and unequal access to digital technologies continue to restrict adoption, particularly in low- and middle-income countries. Addressing these constraints will require sustained investment in research infrastructure, workforce development, standardized data-sharing platforms, and international collaboration to ensure that technological innovations are translated into practical stewardship solutions across diverse aquaculture systems.

Critical Synthesis

Emerging technologies are redefining antimicrobial stewardship by integrating genomics, environmental surveillance, and digital decision-support into routine aquaculture management. These innovations offer unprecedented opportunities to improve disease prevention, strengthen AMR surveillance, and optimize antimicrobial use. However, technological advances alone are unlikely to achieve their full potential without supportive governance,

Copyright© Bireshwar B.

investment in infrastructure, technical capacity building, and international collaboration. Future stewardship programmes should therefore combine scientific innovation with strong regulatory frameworks and One Health governance to achieve sustainable improvements in aquatic animal health, environmental protection, and public health [21,22].

Research Gaps and Future Priorities

Although considerable progress has been made in understanding antimicrobial resistance within aquaculture, important scientific, technical, and policy challenges remain. Addressing these knowledge gaps will be essential for developing stewardship programmes that are both effective and adaptable to the rapidly changing landscape of aquatic food production. One immediate priority is the harmonization of antimicrobial use (AMU) reporting across countries and production systems. Differences in surveillance methodologies, reporting metrics, and data quality continue to limit meaningful international comparisons and impede global assessments of stewardship performance. Standardized reporting frameworks would improve benchmarking, facilitate policy evaluation, and strengthen international collaboration.

Long-term surveillance of antimicrobial resistance genes (ARGs) using standardized genomic approaches is equally important. Expanding the application of whole-genome sequencing, metagenomics, and environmental DNA (eDNA) monitoring would provide greater insight into the temporal and spatial dynamics of resistance evolution, the movement of ARGs between environmental reservoirs and aquaculture systems, and the role of horizontal gene transfer in resistance dissemination.

Another major research priority is understanding the complex interactions among climate change, environmental microbiomes, host immunity, and pathogen evolution. Mechanistic studies that integrate ecological, microbiological, and epidemiological perspectives will improve predictions of disease emergence and help identify management strategies that reduce antimicrobial dependence under changing environmental conditions.

Further evaluation of non-antibiotic disease-control strategies is also required. Although probiotics, bacteriophages, vaccines, phytobiotics, immunostimulants, quorum-quenching compounds, antimicrobial peptides, and CRISPR-based therapeutics have shown considerable promise, many have been evaluated primarily under laboratory or experimental conditions. Large-scale commercial trials across different species and production systems are needed to establish their long-term efficacy, economic feasibility, and practical applicability. Equally important are socioeconomic and behavioural studies that examine how farmers make treatment decisions, adopt stewardship practices, and respond to policy interventions. A better understanding of these human dimensions will support the design of stewardship programmes that are both scientifically robust and socially acceptable.

Future research should also prioritize the development of integrated One Health surveillance systems that connect environmental, veterinary, food safety, and clinical AMR datasets through interoperable databases, genomic epidemiology, and digital reporting platforms. Such integrated surveillance networks would enable earlier detection of emerging resistance threats while improving regional and global risk assessment.

Finally, more comprehensive economic evaluations are needed to determine the long-term costs and benefits of stewardship interventions. Cost-effectiveness analyses can provide policymakers with robust evidence for prioritizing investments in surveillance, vaccination, biosecurity, diagnostics, and emerging technologies while ensuring that stewardship remains economically sustainable for producers.

Critical Synthesis

Future progress in antimicrobial stewardship will depend on moving beyond isolated disciplinary approaches toward integrated research that combines microbiology, veterinary medicine, environmental science, epidemiology, economics, and social science. Scientific advances must be accompanied by stronger surveillance systems, harmonized international reporting, affordable preventive technologies, and evidence-based policy development. Through sustained multidisciplinary collaboration among researchers, veterinarians, aquaculture producers, policymakers, environmental scientists, economists, and industry stakeholders, antimicrobial stewardship can continue to evolve into a comprehensive One Health strategy that safeguards aquatic animal health, protects public health, and supports the long-term sustainability of global aquaculture.

Current Challenges and Opportunities in Implementing Antimicrobial Stewardship

Challenges to Effective Stewardship

Although antimicrobial stewardship (AMS) is now widely acknowledged as a cornerstone of sustainable aquaculture, its implementation remains highly uneven across regions. Progress has been substantial in countries

Copyright© Bireshwar B.

with well-developed veterinary services, comprehensive surveillance programmes, and strong regulatory oversight. In contrast, many low- and middle-income countries continue to face scientific, economic, institutional, and governance challenges that limit the adoption of evidence-based stewardship practices [1,7]. Addressing these constraints is essential if stewardship is to achieve meaningful reductions in antimicrobial use while maintaining aquatic animal health and farm productivity.

Limited Diagnostic Capacity

Accurate diagnosis forms the basis of responsible antimicrobial use, yet access to reliable diagnostic services remains limited in many aquaculture-producing regions. Farmers often initiate treatment based solely on clinical signs or previous experience because laboratory facilities are unavailable, too costly, or unable to provide timely results. As a consequence, broad-spectrum antimicrobials are frequently administered without confirmation of the causative pathogen or its susceptibility profile, increasing selective pressure for antimicrobial resistance (AMR) [18].

Expanding regional diagnostic laboratories, improving access to rapid molecular assays, and promoting standardized antimicrobial susceptibility testing would enable more targeted therapeutic decisions and substantially reduce unnecessary antimicrobial exposure [21].

Weak Surveillance Systems

Reliable information on antimicrobial use (AMU), antimicrobial resistance (AMR), and antimicrobial residues remains incomplete in many parts of the world. Variations in sampling protocols, laboratory methodologies, reporting systems, and regulatory requirements make it difficult to compare data across countries or evaluate the effectiveness of stewardship interventions. These gaps reduce the ability of policymakers to identify emerging resistance trends and implement timely control measures [7].

Recent advances in genomic surveillance, environmental monitoring, and digital reporting platforms offer important opportunities to strengthen surveillance systems. Integrating these tools into national monitoring programmes would improve early detection of resistance, support evidence-based decision-making, and facilitate international data sharing [21,22].

Regulatory and Governance Limitations

The regulatory environment governing antimicrobial use varies considerably among countries. While several nations have introduced prescription-only access to veterinary antimicrobials, routine residue monitoring, and restrictions on critically important antimicrobial agents, implementation and enforcement remain inconsistent. Weak inspection systems, informal drug markets, and limited veterinary oversight continue to undermine stewardship efforts in many regions [8].

Greater harmonization of regulatory frameworks, combined with stronger compliance monitoring and closer international cooperation, would improve stewardship outcomes and promote more consistent implementation of responsible antimicrobial-use policies worldwide [8,16].

Economic Constraints

Financial considerations often influence disease-management decisions at the farm level. Small-scale aquaculture producers, in particular, may lack the resources needed to invest in vaccination programmes, diagnostic testing, biosecurity infrastructure, or improved husbandry practices. Because antimicrobial treatment is frequently perceived as less expensive than preventive health management, economic pressures may inadvertently encourage routine antimicrobial use [37].

Policies that combine financial incentives with technical support could help overcome these barriers. Subsidies for preventive technologies, insurance schemes, sustainability certification, and strengthened extension services would encourage producers to adopt stewardship practices while maintaining farm profitability and competitiveness [37,51].

Knowledge and Capacity Gaps

Successful stewardship ultimately depends on informed decision-making by farmers, veterinarians, extension personnel, and policymakers. However, knowledge of antimicrobial resistance, prudent antimicrobial use, withdrawal periods, and residue management remains uneven across production systems and geographical regions [16,19]. Expanding farmer training programmes, continuing professional education, and extension services is therefore essential. Capacity-building initiatives that translate scientific evidence into practical management recommendations can significantly improve stewardship compliance and promote long-term behavioural change.

Emerging Opportunities

Despite these challenges, recent scientific and technological advances are creating new opportunities to strengthen antimicrobial stewardship and reduce dependence on conventional antibiotics.

Copyright© Bireshwar B.

Precision Aquaculture

Precision aquaculture is transforming disease management by integrating artificial intelligence (AI), Internet of Things (IoT) sensors, machine learning, automated feeding systems, and digital farm-management platforms. Continuous monitoring of water quality, animal behaviour, feeding performance, and environmental conditions allows producers to detect health problems at an early stage, enabling timely intervention before disease outbreaks require antimicrobial treatment [20].

Genomic Surveillance

Modern genomic technologies have greatly enhanced the capacity to monitor antimicrobial resistance. Whole-genome sequencing (WGS), metagenomics, and resistome analyses provide detailed information on resistance genes, transmission pathways, and outbreak dynamics. These tools can complement conventional surveillance by identifying emerging resistance determinants before they become widely established, thereby strengthening national and international AMR monitoring programmes [13].

Innovative Disease-Control Strategies

The development of effective alternatives to conventional antimicrobials is progressing rapidly. Vaccines, probiotics, bacteriophage therapy, antimicrobial peptides, phytobiotics, immunostimulants, and quorum-sensing inhibitors have all demonstrated potential to reduce disease incidence while decreasing reliance on antimicrobial therapy. Although many of these technologies require further validation under commercial farming conditions, they represent promising components of future stewardship programmes [5,41,42].

Integrated One Health Governance

The growing collaboration among FAO, WHO, WOAH, and UNEP through the Quadripartite One Health initiative has strengthened recognition that antimicrobial resistance is a shared challenge across human, animal, and environmental health. Integrated surveillance systems linking veterinary medicine, food safety, environmental monitoring, and clinical healthcare provide a more comprehensive understanding of resistance dynamics and support coordinated interventions across sectors [16].

Sustainable Aquaculture Certification

Consumer demand for responsibly produced seafood continues to increase, encouraging the adoption of certification programmes that incorporate antimicrobial stewardship into broader sustainability standards. Certification schemes such as the Aquaculture Stewardship Council (ASC) and Best Aquaculture Practices (BAP) increasingly require evidence of prudent antimicrobial use, biosecurity, traceability, and environmental management. These market- driven incentives encourage producers to adopt stewardship practices while improving consumer confidence and access to international markets [51,52].

Strategic Recommendations

The evidence synthesized throughout this review highlights several priority actions that could substantially strengthen antimicrobial stewardship in global aquaculture.

Policy and Governance

- Harmonize international standards for antimicrobial-use reporting and AMR surveillance.
- Strengthen regulatory oversight through prescription-based antimicrobial access, residue monitoring, and improved enforcement.
- Promote One Health governance by integrating veterinary, environmental, agricultural, and public health sectors.
- Surveillance and Diagnostics
- Expand regional diagnostic laboratory networks and rapid molecular diagnostic capacity.
- Integrate genomic surveillance, metagenomics, environmental DNA (eDNA), and artificial intelligence into routine disease monitoring.
- Standardize surveillance methodologies to improve international data comparability.
- Disease Prevention
- Prioritize vaccination, biosecurity, and preventive health management over routine antimicrobial treatment.
- Accelerate commercial validation and adoption of probiotics, bacteriophages, phytobiotics, immunostimulants, and other evidence-based alternatives.
- Incorporate precision aquaculture technologies for early disease detection and risk prediction.
- Capacity Building
- Strengthen farmer education, veterinary training, and extension services.
- Provide financial incentives and technical assistance to facilitate stewardship adoption, particularly among small-scale producers.
- Promote interdisciplinary collaboration between researchers, industry, regulators, and policymakers.
- Research and Innovation
- Invest in long-term studies evaluating the ecological, economic, and public health impacts of stewardship interventions.
- Develop climate-resilient disease-management strategies that integrate predictive modelling, environmental surveillance, and emerging genomic technologies.

Copyright© Bireshwar B.

Critical Perspective

The future of antimicrobial stewardship in aquaculture will depend less on discovering new antimicrobial agents than on improving the way aquatic animal health is managed. Disease prevention, early diagnosis, robust surveillance, and evidence-based decision-making offer greater long-term benefits than reliance on therapeutic antimicrobial use alone. As precision aquaculture, genomic surveillance, and digital health technologies continue to mature, they have the potential to transform stewardship from a reactive response to disease into a proactive system based on prediction, prevention, and continuous monitoring. Achieving this transition, however, will require more than technological innovation. Effective stewardship depends equally on strong governance, supportive regulatory frameworks, sustained investment in infrastructure, and the active participation of farmers, veterinarians, researchers, industry stakeholders, and policymakers. Countries that successfully integrate these components within a One Health framework are likely to achieve more resilient aquaculture systems, safeguard antimicrobial efficacy, and maintain sustainable seafood production. Conversely, persistent inequalities in infrastructure, technical capacity, regulatory enforcement, and education will continue to hinder global efforts to contain antimicrobial resistance [16,22].

Discussion

Balancing Aquaculture Productivity and Antimicrobial Stewardship

Aquaculture has become one of the fastest-growing food-production sectors worldwide and plays an increasingly important role in ensuring global food and nutritional security. As production systems intensify to meet rising demand, however, disease outbreaks have become more frequent, often resulting in greater dependence on antimicrobial agents. This creates a complex challenge: how to sustain high levels of productivity while minimizing antimicrobial use and slowing the emergence and spread of antimicrobial resistance (AMR). Rather than being viewed as a limitation on production, antimicrobial stewardship (AMS) should be recognized as an essential component of sustainable aquaculture that safeguards animal health, environmental integrity, and long-term industry resilience [1,18].

Evidence from countries with well-established stewardship programmes demonstrates that reducing antimicrobial use does not necessarily compromise productivity. Norway provides perhaps the clearest example, where widespread vaccination, strict biosecurity, veterinary oversight, and comprehensive surveillance have reduced antimicrobial consumption by more than 99% while maintaining one of the world's most productive salmon industries [25]. These achievements illustrate that effective disease prevention can successfully replace routine antimicrobial therapy. By contrast, regions with limited diagnostic capacity, weak regulatory oversight, and unrestricted access to veterinary antimicrobials continue to report higher antimicrobial consumption and increasing levels of resistance. Collectively, these contrasting experiences suggest that stewardship success depends more on effective governance, disease prevention, and farm management than on production intensity itself.

Integrating Evidence Across the One Health Continuum

The findings synthesized throughout this review reinforce that AMR in aquaculture cannot be understood solely as an aquatic animal health issue. Resistant bacteria, antimicrobial residues, and antimicrobial resistance genes (ARGs) move continuously among aquatic environments, wildlife, food systems, and human populations, forming interconnected ecological networks. Consequently, aquaculture should be viewed as one component of a much broader environmental resistome operating within the One Health framework [15,16].

Importantly, the movement of resistance is not a one-way process originating exclusively from aquaculture. Wastewater from hospitals, municipal sewage, agricultural runoff, pharmaceutical manufacturing, and other anthropogenic activities introduces resistant microorganisms and antimicrobial residues into rivers, estuaries, and coastal waters that support aquaculture production. Aquaculture systems may subsequently amplify or redistribute these resistance determinants through water exchange, sediments, and harvested products. This multidirectional exchange highlights the complexity of AMR ecology and cautions against attributing resistance development to any single sector. Addressing AMR therefore requires coordinated surveillance and management strategies that simultaneously consider environmental, veterinary, food safety, and public health perspectives [13,17].

Critical Appraisal of Current Stewardship Strategies

Over the past decade, antimicrobial stewardship has gained increasing international attention, leading to significant improvements in surveillance, regulatory oversight, and disease prevention. Nevertheless, implementation remains uneven across countries. Differences in surveillance capacity, laboratory infrastructure, reporting systems, and regulatory enforcement continue to limit

Copyright© Bireshwar B.

meaningful comparisons of antimicrobial use and resistance patterns at the global level. Moreover, variability in sampling protocols, antimicrobial susceptibility testing methods, and data-reporting standards complicates evidence synthesis and weakens the comparability of published studies [7,8]. Current stewardship initiatives have primarily focused on promoting prudent antimicrobial use and monitoring antimicrobial residues. Although these remain fundamental components of stewardship, they alone are insufficient to address the complex drivers of AMR. Increasing evidence supports a broader preventive framework that integrates vaccination, farm biosecurity, rapid diagnostics, precision aquaculture, environmental monitoring, farmer education, and socioeconomic incentives. Emerging technologies—including genomic surveillance, environmental DNA (eDNA) analysis, artificial intelligence, and predictive disease modelling—offer additional opportunities to improve early disease detection and support more targeted antimicrobial prescribing. These complementary approaches move stewardship beyond simple antimicrobial restriction towards proactive health management and sustainable disease prevention [16,40].

Knowledge Gaps and Research Priorities

Despite considerable advances in understanding AMR in aquaculture, several important knowledge gaps remain. Much of the current evidence is derived from studies conducted in Asia and Europe, whereas data from Africa, Latin America, and many small island nations remain comparatively scarce. This uneven geographical distribution limits our understanding of regional differences in antimicrobial use, pathogen ecology, and stewardship implementation. Long-term studies examining the persistence, mobility, and environmental fate of ARGs under commercial farming conditions are also relatively limited, despite their importance for evaluating long-term ecological risks [18]. Similarly, although alternatives to conventional antimicrobials—including probiotics, bacteriophages, phytobiotics, immunostimulants, antimicrobial peptides, and quorum- quenching compounds—have demonstrated encouraging results in experimental studies, relatively few have undergone large-scale commercial evaluation. More research is needed to assess their long-term efficacy, economic viability, scalability, and environmental impacts under diverse production systems. Developing standardized methodologies for evaluating stewardship interventions would also facilitate comparisons across studies and strengthen future evidence syntheses [41,42].

Another emerging research priority concerns the interaction between climate change and antimicrobial resistance. Increasing water temperatures, altered precipitation regimes, and more frequent extreme weather events are likely to influence pathogen ecology, host immunity, and antimicrobial use patterns in ways that remain poorly understood. Integrating climate science with microbial ecology, epidemiology, and aquatic animal health research will therefore be essential for developing stewardship strategies capable of responding to future environmental change [28,50].

Practical Implications for Policy and Industry

The evidence reviewed has several important implications for both policymakers and the aquaculture industry. First, stewardship programmes should prioritize disease prevention through vaccination, biosecurity, improved husbandry, and routine health monitoring rather than relying primarily on antimicrobial treatment after disease outbreaks occur. Preventive health management not only reduces antimicrobial consumption but also improves animal welfare, production efficiency, and environmental sustainability.

Second, national surveillance systems should adopt integrated One Health approaches that combine monitoring of antimicrobial use, antimicrobial resistance, antimicrobial residues, and environmental contamination within a unified surveillance framework. Such integration would improve risk assessment, facilitate international comparisons, and support evidence- based policymaking.

Third, strengthening stewardship requires sustained investment in veterinary services, diagnostic laboratories, digital surveillance platforms, and farmer education. These investments are particularly important for small-scale producers, who often face financial and technical barriers to adopting preventive health measures. Expanding access to rapid diagnostics, extension services, and precision aquaculture technologies would improve decision-making while reducing unnecessary antimicrobial use [38,40].

Finally, international collaboration will remain central to future stewardship efforts. Harmonized surveillance protocols, coordinated regulatory frameworks, open data sharing, and collaborative research initiatives are essential for addressing AMR as a transboundary challenge. Strengthening partnerships among governments, researchers, industry stakeholders, international organizations, and farming communities will enhance the effectiveness of stewardship programmes while supporting sustainable aquaculture and global food security. Ultimately, preserving antimicrobial efficacy requires moving beyond sector- specific interventions toward an integrated One Health strategy that recognizes the interconnectedness of human, animal, and environmental health [16].

Copyright© Bireshwar B.

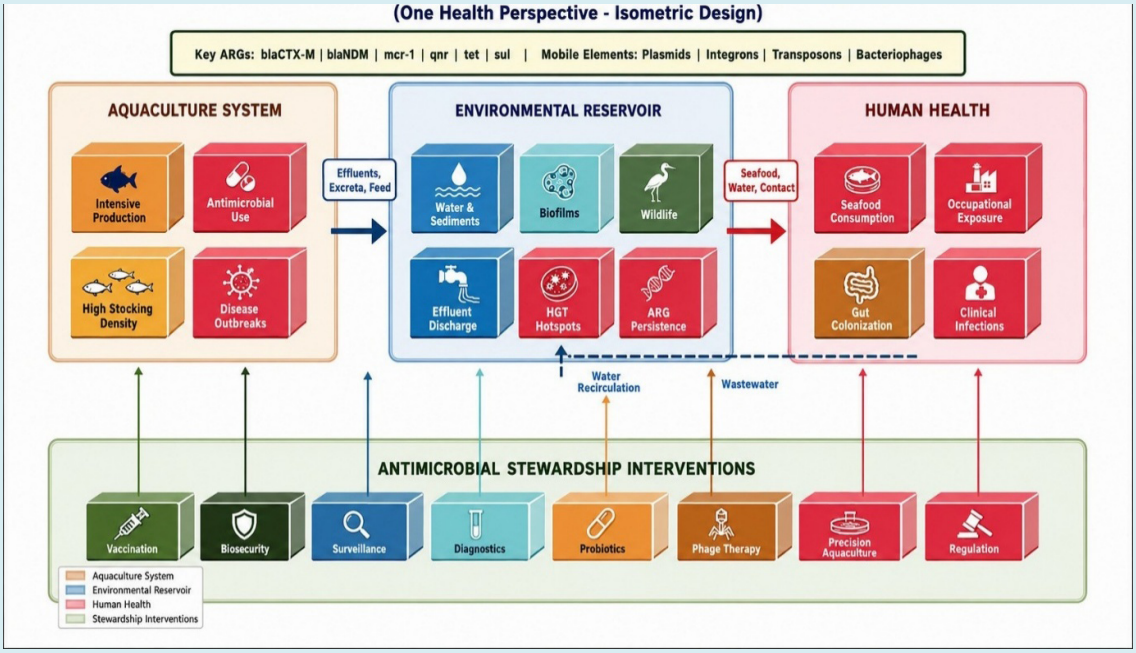


Figure 7: Conceptual Framework: Antimicrobial Resistance Transmission from Aquaculture to Human Health.

This conceptual framework illustrates the pathways through which antimicrobial resistance (AMR) may emerge and spread within aquaculture systems and ultimately affect human health under a One Health framework. Intensive aquaculture practices—including high stocking densities, disease outbreaks, and antimicrobial use—create selection pressure for resistant bacteria and antimicrobial resistance genes (ARGs). These resistance determinants persist and circulate within environmental reservoirs such as water, sediments, biofilms, and aquatic wildlife, where horizontal gene transfer facilitates their dissemination. Human exposure occurs through seafood consumption, occupational contact, environmental recreation, and contamination of interconnected water systems, potentially contributing to gut colonization and difficult-to-treat infections. The lower panel highlights key antimicrobial stewardship interventions—including vaccination, farm biosecurity, rapid diagnostics, surveillance, probiotics, bacteriophage therapy, precision aquaculture, and regulatory oversight—that interrupt resistance transmission at multiple stages. Together, the framework emphasizes that effective AMR mitigation requires integrated preventive strategies spanning aquaculture production, environmental management, food safety, and public health within a coordinated One Health approach.

Priority area	Current gap	Future direction
Surveillance	Fragmented AMU/AMR monitoring	Integrated One Health genomic surveillance
Diagnostics	Delayed pathogen identification	Rapid molecular and AI-assisted diagnostics
Vaccination	Limited species coverage	RNA, oral, and multivalent vaccines
Alternatives	Variable field efficacy	Large-scale commercial validation
Climate change	Limited predictive models	Climate-informed disease forecasting
Digital aquaculture	Uneven adoption	AI, IoT, blockchain, digital twins
Policy	Variable regulations	Global harmonization and stewardship indicators
Socioeconomics	Limited behavioural evidence	Farmer-centred implementation research

Table 13: Research priorities for antimicrobial stewardship in aquaculture.

Copyright© Bireshwar B.

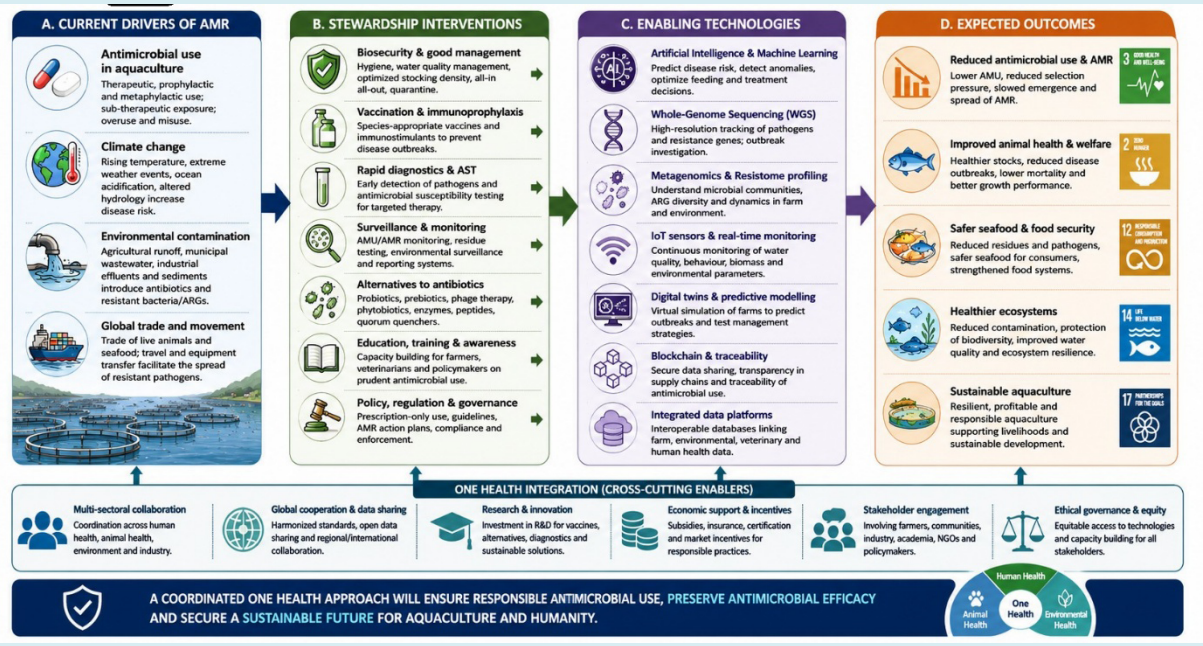


Figure 8: Future roadmap for antimicrobial stewardship in aquaculture under the One Health framework.

Conclusions

Aquaculture has become an essential pillar of global food production, contributing significantly to food security, nutrition, livelihoods, and economic development. As the sector continues to expand, ensuring sustainable production while minimizing the emergence and spread of antimicrobial resistance (AMR) has become one of its most pressing challenges. The evidence synthesized in this review demonstrates that inappropriate or excessive antimicrobial use not only selects for resistant microorganisms within aquaculture systems but also contributes to the dissemination of antimicrobial resistance genes (ARGs) through aquatic environments, food chains, and human–animal–environment interfaces. These interconnected pathways reinforce the need to address AMR within a comprehensive One Health framework rather than through sector-specific interventions alone [1,16].

A central finding of this review is that antimicrobial stewardship (AMS) should be viewed as a proactive health-management strategy rather than simply a means of reducing antimicrobial consumption. Successful stewardship relies on preventing disease before treatment becomes necessary. This requires the integration of prudent antimicrobial prescribing with robust surveillance, rapid diagnostics, vaccination, farm biosecurity, environmental management, farmer education, and evidence-based husbandry practices. Experiences from countries with well-established stewardship programmes clearly demonstrate that antimicrobial use can be dramatically reduced without compromising animal health or production efficiency when preventive health management is supported by effective governance, veterinary oversight, and continuous monitoring [40].

Rapid advances in genomics, metagenomics, environmental DNA (eDNA) surveillance, artificial intelligence, precision aquaculture, and digital decision-support systems are transforming the way aquatic animal health can be monitored and managed. These technologies provide opportunities for earlier disease detection, more accurate pathogen identification, real-time surveillance of antimicrobial resistance, and more targeted therapeutic interventions. However, their successful implementation remains uneven. Many low- and middle-income countries continue to face persistent challenges, including limited laboratory infrastructure, inadequate surveillance systems, shortages of trained personnel, restricted access to veterinary services, and insufficient regulatory capacity. Addressing these disparities will be critical for ensuring that advances in antimicrobial stewardship benefit aquaculture systems worldwide rather than only those with greater technical and financial resources [21,22].

Looking ahead, strengthening antimicrobial stewardship will require coordinated action across scientific, regulatory, and operational levels. Priorities should include harmonizing international surveillance and reporting systems, improving diagnostic and laboratory capacity, expanding vaccination and preventive health programmes, encouraging the adoption of validated alternatives to conventional antimicrobials, strengthening regulatory governance, and supporting

Copyright© Bireshwar B.

sustainable production practices through education, capacity building, and policy incentives. Continued investment in multidisciplinary research, international collaboration, and integrated One Health governance will also be essential for improving our understanding of AMR dynamics and translating scientific advances into practical disease-management strategies.

Ultimately, the long-term sustainability of aquaculture will depend not on increasing antimicrobial use but on strengthening prevention, surveillance, innovation, and responsible governance. By embedding antimicrobial stewardship into routine aquaculture management and aligning disease control with One Health principles, the industry can continue to expand while safeguarding antimicrobial efficacy, protecting aquatic ecosystems, ensuring seafood safety, and contributing to resilient and sustainable global food systems for future generations [16,37].

Declarations

Ethics approval and consent to participate: Not applicable
Consent for publication: Not applicable.
Availability of data and materials: Not applicable. No original datasets were generated or analysed for this review. The manuscript synthesizes information from published sources cited in the reference list.
Competing interests: The authors declare no competing interests
Funding: Not applicable, no specific funding supported this work.
Authors' contributions: BB conceived the review, designed the literature search strategy, and drafted the manuscript. BB critically revised the manuscript for important intellectual content and approved the final version.
Acknowledgements: Not applicable
Authors' information: Associate Professor in the Department of Zoology, St. Joseph's College, North Point, Darjeeling 734104, West Bengal, India

References

1. Food and Agriculture Organization of the United Nations (FAO) The state of world fisheries and aquaculture 2024 (SOFIA). Rome, Italy.

2. Naylor RL, Hardy RW, Buschmann AH, Bush SR, Cao L, et al. (2021) A 20-year retrospective review of global aquaculture. Nature. 591: 551-563.

3. Houston RD, Bean TP, Macqueen DJ, Gundappa MK, Jin YH, et al. (2020) Harnessing genomics to fast-track genetic improvement in aquaculture. Nat Rev Genet 21: 389-409.

4. Reverter M, Bontemps N, Lecchini D, Banaigs B, Sasal P (2020) Use of plant-derived products in aquaculture. Aquaculture 527: 735487.

5. Defoirdt T, Ruwandeepika HAD, Boon N, Bossier P (2022) Alternatives to antibiotics for sustainable aquaculture. Curr Opin Biotechnol 74: 96-102.

6. Cabello FC, Godfrey HP, Buschmann AH, Dölz H, Sommerset I, et al. (2024) Antimicrobial use and resistance in aquaculture. Aquaculture 580: 740012.

7. World Health Organization (WHO) (2023) Global antimicrobial resistance and use surveillance system (GLASS) report 2023. Geneva, USA.

8. World Organisation for Animal Health (WOAH) (2024) Annual report on antimicrobial agents intended for use in animals. Paris: WOAH, USA.

9. Murray CJL, Ikuta KS, Sharara F, Swetschinski L, Robles Aguilar G, et al. (2022) Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. Lancet 399(10325): 629-655.

10. Baquero F, Coque TM, Martínez JL (2021) Interactions between ecological and evolutionary processes in bacterial resistance. Nat Rev Microbiol 19: 728-742.

11. Larsson DGJ, Flach CF (2022) Antibiotic resistance in the environment. Nat Rev Microbiol 20: 257-269.

12. Lerminiaux NA, Cameron ADS (2019) Horizontal transfer of antibiotic resistance genes in clinical environments. Can J Microbiol 65(1): 34-44.

13. Bengtsson-Palme J, Larsson DGJ, Kristiansson E (2023) Environmental dimensions of antimicrobial resistance. Nat Rev Microbiol 21: 739-754.

14. Cabello FC, Godfrey HP, Buschmann AH, Dölz HJ (2023) Antimicrobial resistance in aquaculture: a One Health perspective. Rev Aquac 15: 1-28.

15. Hernando-Amado S, Coque TM, Baquero F, Martínez JL (2023) Defining and combating antibiotic resistance from a One Health perspective. Nat Microbiol 8: 1031-1045.

16. Food and Agriculture Organization of the United Nations (FAO) (2022) United Nations Environment Programme (UNEP), World Health Organization (WHO), World Organisation for Animal Health (WOAH). One Health joint plan of action (2022–2026). Geneva: FAO, USA.

Copyright© Bireshwar B.

17. Robinson TP, Bebay C, Barbuddhe SB, Christiaensen L, Guerne Bleich E, et al. (2023) One Health and antimicrobial resistance. Nat Rev Microbiol 21: 415-416.

18. Reverter M, Sarter S, Caruso D, Avarre JC, Combe M, et al. (2022) Aquaculture at the crossroads of global antimicrobial resistance. Nat Commun 13: 1870.

19. World Health Organization (WHO) (2022) Critically important antimicrobials for human medicine, 7th revision. Geneva, USA.

20. Kumar G, Engle C, Sharma R (2024) Artificial intelligence and precision aquaculture. Aquac Rep 35: 101923.

21. Nogueira T, Botelho A (2021) Metagenomics and other omics approaches to bacterial communities and antimicrobial resistance assessment in aquacultures. Antibiotics (Basel) 10(7): 787.

22. Ratan R, Ashwini M, Kamilya D, Nagarajan V (2026) Artificial intelligence and digital innovations in precision aquaculture: advancements, applications, and future directions. Franklin Open 15: 100567.

23. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, et al. (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372: n71.

24. Schar D, Sommanustweechai A, Laxminarayan R, Tangcharoensathien V (2020) Global trends in antimicrobial use in aquaculture. Sci Rep 10: 21878.

25. Sommerset I, Bang Jensen B, Bornø G, Haukaas A, Brun E (2022) The health situation in Norwegian aquaculture 2021. Oslo: Norwegian Veterinary Institute.

26. Martins CIM, Eding EH, Verdegem MCJ, Heinsbroek LTN, Schneider O, Blancheton JP, et al. (2020) Recirculating aquaculture systems and sustainable fish production. Rev Aquac 15: 1021-1046.

27. European Commission (2025) Rapid Alert System for Food and Feed (RASFF) annual report 2025. Luxembourg: Publications Office of the European Union, USA.

28. Intergovernmental Panel on Climate Change (IPCC) (2023) Climate change 2023: synthesis report. Geneva: IPCC.

29. Bush K, Bradford PA (2020) β-Lactams and β-lactamase inhibitors. Cold Spring Harb Perspect Med 10(8): a036665.

30. Li XZ, Plésiat P, Nikaido H (2023) Efflux-mediated antimicrobial resistance in Gram-negative bacteria. Clin Microbiol Rev 36(1): e00123-22.

31. Hall CW, Mah TF (2017) Molecular mechanisms of biofilm-based antibiotic resistance. FEMS Microbiol Rev 41(3): 2761301.

32. Flemming H-C, Wuertz S, Szewzyk (2023) Biofilms: an emergent form of bacterial life. Nat Rev Microbiol 21(11): 441-456.

33. Gillings MR (2023) Integrons and antimicrobial resistance. Microbiol Mol Biol 87(1): e00056-22.

34. European Food Safety Authority (EFSA) (2024) The European Union One Health 2023 zoonoses report. EFSA J 22(12): e08895.

35. United Nations Environment Programme (UNEP) (2023) Bracing for superbugs: strengthening environmental action in the One Health response to antimicrobial resistance. Nairobi.

36. Codex Alimentarius Commission (2021) Guidelines on integrated monitoring and surveillance of foodborne antimicrobial resistance (CXG 94-2021). Rome: Codex Alimentarius Commission.

37. World Bank (2024) Drug-resistant infections: a threat to economic development. Washington (DC): World Bank.

38. Brudeseth BE, Wiulsrød R, Fredriksen BN, Løvoll M, Evensen Ø (2023) Vaccines in fish health management. Fish Shellfish Immunol 136: 108734.

39. Dyar OJ, Huttner B, Schouten J, Pulcini C (2017) Strategies and challenges of antimicrobial stewardship in human healthcare. Clin Microbiol Infect 23(11): 793-798.

40. Afonso JS, El Tholth M, McIntyre KM, Carmo LP, Coyne L, et al. (2024) Strategies to reduce antimicrobials in livestock and aquaculture, and their impact under field conditions: a structured scoping literature review. J Antimicrob Chemother 79(1): 11-26.

41. Ringø E, Olsen RE, Vecino JLG, Wadsworth S, Romero J, et al. (2022) Probiotics in aquaculture. Rev Aquac 14: 1804-1835.

42. Kortright KE, Chan BK, Koff JL, Turner PE (2024) Phage therapy for bacterial infections. Nat Rev Microbiol 22: 61-78.

43. Farías DR, Ibarra R, Estévez R (2025) Insights and lessons from Chilean salmon aquaculture on antimicrobial use. Antibiotics 14(1): 1.

Copyright© Bireshwar B.

44. Dawood MAO, Metwally AES, El-Sharawy N, Abdel-Razek N, Abdel-Latif HMR, et al. (2022) Immunostimulants in sustainable aquaculture. Aquaculture 547: 737478.

45. Reverter M, Tapissier-Bontemps N, Sarter S, Saulnier D (2021) Plant-derived alternatives to antibiotics in aquaculture. Aquaculture 546: 737315.

46. Gordillo Altamirano FL, Barr JJ (2019) Phage therapy in the postantibiotic era. Clin Microbiol Rev 32(2): e00066-18.

47. Defoirdt T (2018) Quorum sensing inhibitors in aquaculture. Trends Biotechnol 36(5): 469-482.

48. World Health Organization (WHO) (2015) Global action plan on antimicrobial resistance. Geneva: WHO, USA.

49. European Commission (2019) Regulation (EU) 2019/6 of the European Parliament and of the Council of 11 December 2018 on veterinary medicinal products and repealing Directive 2001/82/EC. Off J Eur Union L4:43-167.

50. Woh PY, Chau MC, Wang W (2025) Antimicrobial resistance and climate change in the One Health food safety paradigm: a global perspective. Sci Total Environ 1001: 180499.

51. Aquaculture Stewardship Council (ASC)A (2025) SC certification programme: standards and guidance documents. Utrecht: Aquaculture Stewardship Council.

52. Global Aquaculture Alliance (GAA) (2024) Best Aquaculture Practices (BAP) certification standards. Portsmouth (NH): Global Aquaculture Alliance.

Copyright© Bireshwar B.