Sustainable management of antibiotic resistance in aquaculture environments

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Abstract

Balanced approaches to controlling antibiotic resistance in aquaculture settings are paramount to protecting ecosystems, health, and food supply. Antibiotic usage, often prevalent and uncontrolled, presents a significant risk to the Reserve Banks of Bacteria and Antibiotic Resistance Genes (BARGS) in aquaculture. These resistant strains threaten global health because they can be disseminated via water bodies, aquaculture species, and human activities. The focus of this paper is to investigate comprehensive approaches to reducing the resistant strains, including the betterment of regulatory policies, employing alternative methods such as probiotics or vaccines, and Best Management Practices (BMPs) that incorporate biosecurity measures, water quality enhancement, and judicious use of antibiotics spent in aquaculture. Policy frameworks are also strengthened with the importance of persistent monitoring and surveillance systems tracking resistance trends. Farmers, along with scientists, regulators, and consumers, need to encourage collaboration in aquaculture systems (farm-level) to foster sustainability and responsibility integrated into fisheries science, which in return will aid in establishing a control framework on the growing concerns surrounding the usage of antibiotics in aquaculture while preserving its ecosystem. This enables a move towards more ecologically-friendly strategies in aquaculture alongside strengthening its prospects as the primary food supplier in the future shown in Figure 1.

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Keywords: Antibiotic resistance, Aquaculture, Sustainable management, Probiotics, biosecurity, Environmental monitoring

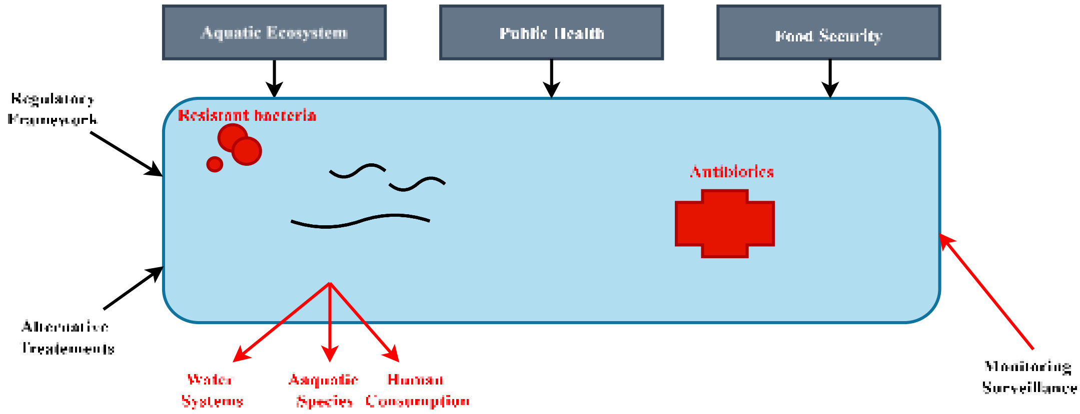

Figure 1: Graphical abstract.

Introduction

Preamble: The increasing prevalence of antibiotic resistance is one of the most serious concerns facing modern aquaculture practices today (Ahmad *et al.*, 2022). As the global appetite for seafood increases, aquaculture is essential for augmenting global food resources (Chatterjee and Sanyal, 2024). Contradicting this, fisheries have always used antibiotics indiscriminately, posing public health and environmental threats (Watts *et al.*, 2017). Antibiotic-resistant bacteria (ARGs) are now a factor in everyday life (Smihunova *et al.*, 2024). These defense mechanisms can rapidly propagate through waters, endangering ecosystems, wildlife, and humans (Santos and Ramos, 2018). The risk is further elevated by recreational and professional interactions with contaminated marine organisms (Rao and Chatterjee, 2024). The complete lack of antibiotic stewardship internationally (Preena *et al.*, 2020; Ziwei and Han, 2023).

Without prompt intervention, the efficacy of these critical medicines could sharply decline (Moreau and Sinclair, 2024). Restoring this trend relies on implementing sustainable management approaches. Integrated strategies should focus on preliminary concerns of drafting and creating legal safeguards (Pepi and Focardi, 2021). It is also crucial to focus on alternative non-conventional treatment methods such as probiotics and vaccine treatments (Nihlani *et al.*, 2024; Lieke *et al.* 2020). Essential are Best Management Practices (BMPs) covering biosecurity, water quality, and sensible antibiotic use (Hemamalini *et al.*, 2022). Strong monitoring and surveillance systems are needed to spot early, direct, data-driven policy decision trends of opposition (Krishnan and Patel, 2023; Brunton *et al.*, 2019). Success depends on all the players involved: scientists, customers, authorities, and farmers cooperating (Reverter *et al.*, 2020; Chinnasamy, 2024). Ensuring aquaculture is a sustainable and safe component of the food supply for the planet calls for everyone to participate and think creatively (Hamed *et al.*, 2023; Ferri, Lauteri and Vergara, 2022).

Related Works

Nanotechnology-Based Approaches for Sustainable Aquaculture Management

This paper examines how new toxins, including aquaculture antibiotics, damage the surroundings (Okeke *et al.*, 2022). Based on nanotechnology, it looks at greener solutions to antibiotic resistance, including nano-drug delivery, nanosensors, and nanoformulations (Farías *et al.*, 2024; Thornber *et al.*, 2022). Furthermore, the study includes public health concerns related to nanoparticles and provides ideas for sustainable aquaculture management (Hu and Sinniah, 2024).

Addressing Antimicrobial Resistance (AMR) through the DPSIR Framework in LMIC Aquaculture

Research on AMR in aquaculture used the DPSIR paradigm in rural Bangladesh (Buschmann *et al.*, 2012**)** Sociological, microbiological, and metagenomic data exposed the sources of antibiotic resistance and their connection to long-term sustainability (Sun and Kim, 2014; Hossain *et al.*, 2022). Results support worldwide projects aiming at lowering antimicrobial resistance in aquaculture environments with low- or medium-income levels (Zhao *et al.*, 2021; Alam and Subramanian, 2024).

Antibiotic Use and Resistance Management in Intensive Aquaculture Systems

The writers of this paper stress how the misuse of antibiotics in intensive aquaculture has advanced antibiotic resistance (Salin and Arome Ataguba, 2018). This draws attention to the present statistics on antibiotic resistance and residues in the most active countries of antibiotic production—the paper call for a global standardizing of antibiotic monitoring, control, and residue restrictions (Otieno and Wanjiru, 2024).

Discussion

The growth of antibiotic resistance in aquaculture compromises world health, food security, and water ecosystems. Unchecked use of antibiotics generates resistant genes and bacteria, which can then travel across food chains. For this reason, sustainable management solutions are much needed. Regulatory control and treatment alternatives are quite crucial. Coordinated efforts help to guarantee aquaculture's longevity.

The Threat of Antibiotic Resistance in Aquaculture

Antibiotic resistance in aquaculture has grown in importance because of its direct effects on public health and aquatic environments. The misuse and lack of control around antibiotics in fish farming, which is done to minimize disease outbreaks, is one typical cause of ARGs. Rather than being housed in aquaculture facilities, these resistant strains are passed via natural aquatic systems following release into nearby bodies of water. Quantitative analysis of antibiotic resistance in aquaculture shown in Table 1.

Table 1: Quantitative analysis of antibiotic resistance in aquaculture.

Aspect	Key Data / Statistics
Prevalence	- 90% of aquatic bacteria are resistant to ≥1 antibiotic- 20% show multi-drug resistance
Regional Resistance	- South China: 48.15% resistant to erythromycin- Africa (E. coli): 87.1% resistant to ampicillin, 66.4% to tetracycline
Environmental Leakage	- Up to 75% of antibiotics released into the water- Resistance in Acinetobacter spp. rose from 5% to 100% in 2 months (Thailand)
Seafood Contamination	- 69.45% of bacteria from seafood resistant to >4 antibiotics (Italy)
Global Trends	- Asia: 33% of surveyed antibiotics had >50% resistance from 2000–2018

One must first admit that there is a problem to identify long-term solutions. Dealing with this issue will help to safeguard the environment, guarantee food security, and reduce the hazards to world health from antibiotic resistance.

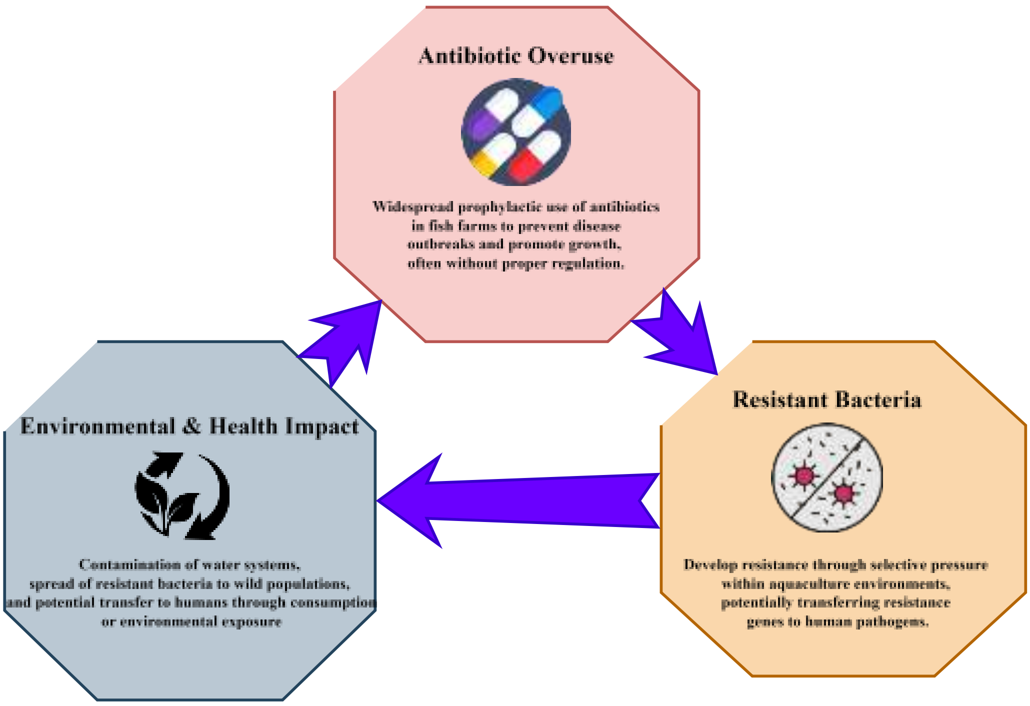

Figure 2: The threat of antibiotic resistance in aquaculture.

Since they can travel through sediments, aquatic life, and even humans who eat contaminated seafood, such resistant strains represent an even higher risk of incurable diseases from Figure 2. The accumulation and persistence of antibiotics and ARGs pose extra hazards to microbial balance, biodiversity, and the long-term survival of aquatic ecosystems.

Integrated Strategies for Sustainable Management

Management of aquaculture antibiotic resistance has to be multifaceted, including operational, technological, regulatory, and legislative elements.

Stronger regulatory systems will help to obtain precise guidelines on dosage, duration, and permitted substances; antibiotics should be given with care. Probiotics and vaccines are two complementary treatments showing potential in the fight against antibiotic resistance. While probiotics naturally improve fish health by regulating the microbiota, vaccines offer focused resistance against infectious diseases. Moreover, BMPs are essential in lowering environmental contamination and disease outbreak probability.

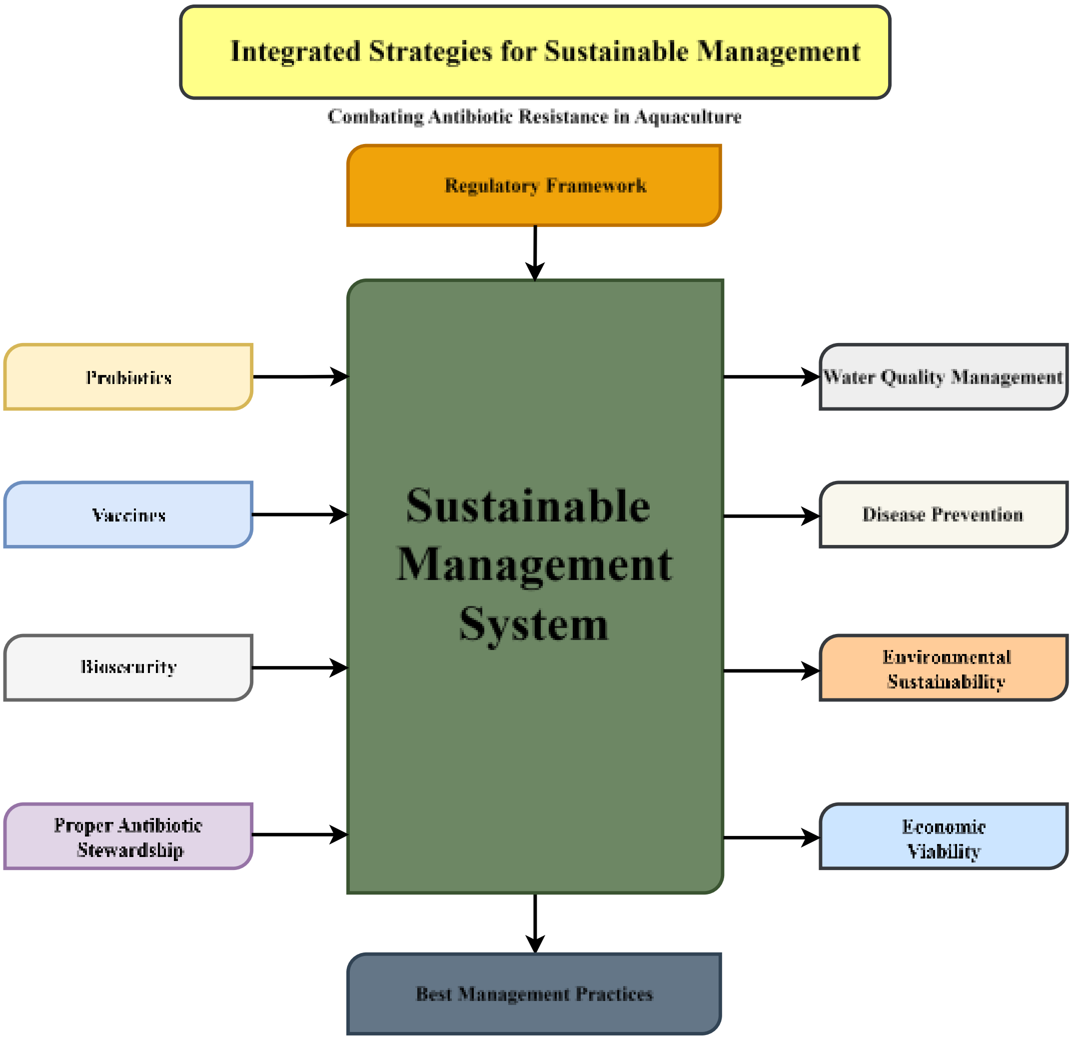

Figure 3: Integrated strategies for sustainable management.

Among these techniques are controlling water quality, enhancing biosecurity, and correctly processing waste and feed (Figure 3). During these operations, proper antibiotic stewardship should be practiced to help limit the transmission of microorganisms resistant to antibiotics. When used together, these strategies offer a complete strategy to stop the rise in resistance. Lowering dependency on medical interventions helps increase the aquaculture sector's environmental sustainability and financial stability.

Collaborative Efforts and Future Directions

Aquafarmers, scientists, legislators, and consumers must cooperate successfully to solve antibiotic resistance in aquaculture. Every one of these groups shapes sustainable policies and practices.

Scientists can develop fresh ideas and improve diagnostic methods to help identify disease outbreaks early on; legislators can then translate scientific results into laws people can obey. These goals can be reached if farmers are financially driven and informed to follow ethical antibiotic policies and biosecurity guidelines. Customers also impact the system when they ask for seafood that is caught ethically. Building strong monitoring and surveillance systems is an important part of this partnership. The data collected by these systems provides evidence-based policymaking and decision-making about antibiotic use, resistance trends, and environmental impacts. Future technology advancements that can improve real-time monitoring include digital tracking, artificial intelligence, and molecular diagnostics. Preserving antibiotic efficacy and sustainability of global aquaculture depend on cultivating a culture of shared responsibility.

Materials and Methods

The present work investigated long-term strategies for reducing antibiotic resistance in fish farming using a methodical approach. Policy papers, case studies, and scholarly literature were thoroughly analyzed in the research. Data was gathered from trustworthy databases and outside reports. This paper examined the significant events using a conceptual framework. This method helped us to understand the current methods and solutions completely.

Data Collection and Literature Review

A thorough literature study gathered data on antibiotic use, resistance trends, and sustainable practices in aquaculture. This was accomplished using academic sources like PubMed, Scopus, and Web of Science. Scholarly publications, government studies, and international guidelines were searched for modern trends, challenges, and innovations. Studies from countries with high aquaculture numbers were given particular thought. Terms including sustainable fish farming, biosecurity, antibacterial resistance in aquaculture, and alternative treatments were used throughout the search. Classifying and evaluating a few chosen sources allowed one to evaluate the effectiveness of regulatory strategies, technical solutions, and surveillance systems applied to control antibiotic resistance.

Methodological Framework and Analysis

The academics decided on a combined approach comprising qualitative analysis and framework development techniques. Synthesizing significant data from the literature helped to identify critical drivers, pressures, and reaction strategies related to antibiotic resistance in aquaculture. The interplay of social, regulatory, and environmental elements was categorized using a modified version of the Driver-Pressure-State-Impact-Response (DPSIR) model. This paradigm helped one better grasp the effectiveness of current approaches and expose flaws in policy implementation, stakeholder participation, and monitoring. This paper evaluated several choices, including immunizations and probiotics, to find the most beneficial. The method assured a complete understanding of long-term strategies to reduce antibiotic resistance in fish farming systems.

Conclusion

Stressing the tide of antimicrobial resistance in the aquaculture sector calls for a quick and coordinated worldwide response. Unchecked use of antibiotics compromises both aquatic ecosystems and human and animal health and raises the risk of gene transfer resistance to these medications. Long-term management plans that integrate regulatory monitoring, ethical antibiotic use, and emerging technologies, including probiotics, vaccines, and biosecurity protocols, all of which incorporate regulatory monitoring, are underlined in this paper.

Sophisticated surveillance technologies and continuous environmental monitoring are vital in finding opposition trends and guiding responsive policymaking. Effective application of these approaches calls for multi-stakeholder cooperation involving farmers, consumers, scientists, and legislators. Pooling our resources will help us to make aquaculture a more reliable, safe, and ecologically beneficial way of feeding the planet. By approaching antibiotic resistance holistically, we can preserve public health, biodiversity, and the future of aquaculture as an industry.

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