

## Probiotics, Prebiotics, and Synbiotics as Sustainable Alternatives to Antibiotics in Aquaculture: A Review

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### Abstract

Aquaculture has emerged as the world's fastest-growing food production sector, accounting for more than half of total fish consumption and playing an important role in food security, nutrition, and economic development, particularly in developing nations. However, illness outbreaks associated with intensive production systems have always resulted in widespread antibiotic use. Although antibiotics are successful in controlling bacterial infections in the short term, their widespread and prolonged use has resulted in antimicrobial resistance (AMR), environmental contamination, antibiotic residue accumulation in fish tissues, and increased regulatory restrictions. These issues have fuelled the search for sustainable, biologically based solutions. Probiotics, prebiotics, and synbiotics have emerged as intriguing functional feed additives that can improve gut microbial balance, stimulate immunological responses, increase nutritional utilisation, and improve water quality. Probiotics function by competitive exclusion, antibacterial chemical synthesis, enzyme secretion, and immunological regulation. Prebiotics specifically boost the beneficial gut microbiota, improving intestinal morphology and immunological competence. Synbiotics combine the two techniques to increase microbial survival and host advantages. Experimental research shows that numerous aquaculture species benefit from improved growth performance, feed conversion ratio, survival rates, and disease resistance. Despite its benefits, difficulties such as strain specificity, environmental variability, formulation stability, cost, and regulatory monitoring persist. Overall, probiotics, prebiotics, and synbiotics are sustainable, environmentally friendly alternatives to antibiotics that have considerable potential for increasing aquaculture productivity while protecting the environment and public health.

**Keywords:** Aquaculture sustainability, Antimicrobial resistance (AMR), Probiotics, Prebiotics, Synbiotics and Functional feed additives

### Introduction

Aquaculture has emerged as the world's fastest-growing food production sector, with significant implications for global food security, poverty reduction, job creation, and rural economic

development. As capture fisheries approach or exceed maximum sustainable yields, aquaculture meets growing worldwide demand for fish and shellfish. According to the Food and Agriculture Organization (Gul *et al.*, 2024), aquaculture now accounts for more than half of all fish consumed globally, and production is expected to rise further due to population growth, urbanisation, and rising earnings.

Fish contains high-quality animal protein and critical micronutrients such as long-chain omega-3 fatty acids (EPA and DHA), fat-soluble vitamins (A and D), B-complex vitamins, and minerals like iodine, selenium, iron, and zinc (Singh *et al.*, 2025). Aquaculture has a substantial impact on food security, livelihood enhancement, and poverty reduction in developing nations like Nigeria. The aquaculture value chain, which includes hatchery management, feed production, grow-out operations, processing, storage, distribution, and marketing, employs millions of people both directly and indirectly (Srikulnath *et al.*, 2025). Despite these benefits, aquaculture faces biological and environmental difficulties that jeopardise its long-term viability. Disease outbreaks continue to be a severe limitation, often resulting in significant economic losses. High stocking numbers, poor water quality, environmental variations, and nutritional imbalances all cause to disease occurrence (Kumar *et al.*, 2025). *Aeromonas hydrophila*, *Vibrio spp.*, *Edwardsiella tarda*, and *Streptococcus spp.* are among the most common bacterial pathogens.

Historically, antibiotics have been used extensively to treat illnesses, prevent outbreaks, and stimulate growth. Excessive use of antibiotics has led to AMR, environmental damage, and public health hazards from antibiotic residues in fish tissues (Ljubojević Pelić *et al.*, 2024). As a result, research has shifted toward long-term solutions that improve host health via biological mechanisms. Probiotics, prebiotics, and synbiotics have shown promise as functional feed additives that increase gut microbial balance, immunological responses, nutritional utilisation, and water quality (Mugwanya *et al.*, 2022).

This review critically evaluates the significance of probiotics, prebiotics, and synbiotics as long-term alternatives to antibiotics in aquaculture, highlighting their methods of action, effects on growth

performance and disease resistance, obstacles, and future research possibilities.

**Antibiotic Use in Aquaculture and Emerging Concerns**

Antibiotics such as oxytetracycline, sulfonamides, florfenicol, and quinolones are commonly used in aquaculture to treat bacterial infections and disease outbreaks (Trif et al., 2023). While they may be useful in the short term, their long-term effects are becoming increasingly worrying. Prolonged exposure to subtherapeutic levels promotes the selection of

resistant bacterial strains, which can spread resistance genes to other bacteria, including potential human infections (Mutuku et al., 2022). Unmetabolized antibiotics also contaminate the environment, altering microbial populations and nutrient cycle mechanisms (Singh et al., 2024). In addition, antibiotic residues in fish tissues may exceed acceptable levels, resulting in trade restrictions, rejection of export consignments, and public health concerns. Increased regulatory scrutiny emphasises the importance of decreasing antimicrobial reliance in aquaculture systems.

**Table 1. Major Concerns Associated with Antibiotic Use in Aquaculture.**

Issue	Description	Implications
<b>Antimicrobial resistance</b>	Selection of resistant bacteria through prolonged exposure (Mutuku <i>et al.</i> , 2022)	Transfer of resistance genes to human pathogens
<b>Environmental contamination</b>	Accumulation of unmetabolized antibiotics in sediments (Singh <i>et al.</i> , 2024)	Disruption of microbial communities and nutrient cycling
<b>Residue accumulation</b>	Antibiotic residues in fish tissues (Trif <i>et al.</i> , 2023)	Trade restrictions and food safety concerns
<b>Regulatory challenges</b>	Increasing global restrictions (Trif <i>et al.</i> , 2023)	Economic losses from rejected exports

These concerns necessitate sustainable alternatives capable of maintaining fish health while safeguarding environmental and public health integrity.

**Probiotics in Aquaculture**

Probiotics are live bacteria that provide health advantages when given in sufficient quantities (Reddy and MS, 2021). In aquaculture, they can be given via feed augmentation, direct water application, or live feed enrichment. *Bacillus*, *Lactobacillus*,

*Enterococcus*, *Pseudomonas*, *Shewanella*, and yeasts such *Saccharomyces cerevisiae* are examples of common probiotic genera (Cho and Chung, 2020). Effective probiotic strains must be non-pathogenic, able to survive gastrointestinal transit, attach to the intestinal mucosa, and produce antibacterial chemicals or digestive enzymes (Mallott and Amato, 2021).

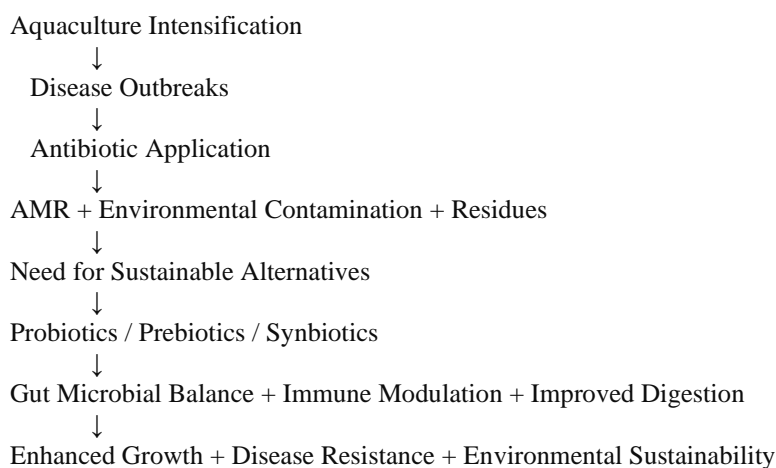
**Table 2. Common Probiotic Microorganisms in Aquaculture**

Genus	Key Characteristics	Functional Role
<b>Bacillus</b>	Spore-forming, heat-stable (Cho and Chung, 2020)	Enzyme production, pathogen inhibition
<b>Lactobacillus</b>	Lactic acid producer (Reddy and MS, 2021)	Gut acidification, immune stimulation
<b>Enterococcus</b>	Gut colonizer (Mallott and Amato, 2021)	Competitive exclusion
<b>Saccharomyces</b>	Yeast (Cho and Chung, 2020)	Immune modulation, nutrient enhancement

**Mechanisms of Action of Probiotics**

Probiotics provide benefits through a variety of biological processes. Melo-Bolívar *et al.* (2022) report that they compete with pathogens for adhesion sites in the gastrointestinal system, reducing pathogen colonisation. They generate antimicrobial chemicals such bacteriocins, organic acids, hydrogen peroxide, and peptides that directly inhibit harmful bacteria. Probiotics also influence immunological responses,

increasing lysozyme activity, complement activation, respiratory burst activity, phagocytosis, and cytokine secretion (Shija *et al.*, 2023). Furthermore, they boost digestive efficiency by producing extracellular enzymes such as proteases, amylases, lipases, and cellulases, resulting in higher feed conversion ratios (FCR) and specific growth rates (SGR) (Rahman & Arifuzzaman, 2021). Some strains contribute to better water quality by lowering ammonia and nitrite levels.

**Figure 1. Conceptual Flow of Antibiotic Replacement Strategy in Aquaculture****Prebiotics in Aquaculture**

Prebiotics are nondigestible food components that specifically promote the growth and activity of beneficial gut microbes (Chavan *et al.*, 2023). Examples include mannan-oligosaccharides (MOS), fructo-oligosaccharides (FOS), inulin, galacto-oligosaccharides, and beta-glucans. These chemicals are resistant to digestion in the upper gastrointestinal tract and are fermented by beneficial bacteria in the

intestine, resulting in short-chain fatty acids that lower gut pH and inhibit harmful microorganisms. Beta-glucans also operate as immunostimulants, increasing macrophage activity and nonspecific immunological responses (Khanjani *et al.*, 2022). Prebiotics improve gut shape by increasing villi height and absorptive surface area, which boosts nutrition absorption and growth performance.

**Table 3. Common Prebiotics and Their Functions**

Prebiotic	Source	Functional Benefits
MOS	Yeast cell walls	Pathogen binding and immune stimulation (Khanjani <i>et al.</i> , 2022)
FOS	Plant-derived	Short-chain fatty acid production (Chavan <i>et al.</i> , 202)
Inulin	Chicory root	Improved gut microbiota balance (Chavan <i>et al.</i> , 2023)
Beta-glucans	Fungi/yeast	Immunostimulation (Khanjani <i>et al.</i> , 2022)

**Synbiotics as a Combined Strategy**

Synbiotics combine probiotics and prebiotics to improve microbial survival, colonisation, and metabolic activity in the gastrointestinal tract (Srirenegaraj *et al.*, 2023). The prebiotic component specifically supports probiotic bacteria, resulting in prolonged activity and better host contact (Elshaghabe and Rokana, 2021). Experimental investigations have shown benefits in weight gain, FCR, SGR, survival rates, and immunological indices (Rahman and Arifuzzaman, 2021). For example, *Oreochromis niloticus* fed with *Bacillus subtilis* and MOS shown increased resistance to *Aeromonas hydrophila* (Al-Ghamdi *et al.*, 2023). Similarly, *Litopenaeus vannamei* fed *Lactobacillus* spp. with inulin showed increased immunity to *Vibrio* infection (Li *et al.*, 2021). Synbiotics help to promote environmental sustainability by lowering feed waste and increasing water quality.

**Effects on Growth Performance and Disease Resistance**

Functional feed additives have a considerable impact on feed conversion ratio (FCR), specific growth rate (SGR), weight gain, survival rates, immunological markers, and gut architecture. Increased villi height

and mucosal surface area aid in food absorption, while stronger immune responses boost resistance to bacterial and viral infections. Collectively, these enhancements increase production while decreasing use on antibiotics (Fachri *et al.*, 2024).

**Challenges and Future Perspectives**

Despite their benefits, probiotics, prebiotics, and synbiotics have several drawbacks. Their efficacy varies with species, environmental conditions, and management approaches (Hossain *et al.*, 2024). Heat sensitivity during feed processing can impair probiotic viability (Warner, 2024). High product costs and little regulatory monitoring further impede wider use, especially in underdeveloped countries (Hassen *et al.*, 2024). Future research should focus on isolating locally adapted strains, metagenomic characterisation of gut microbiota (Botta *et al.*, 2025), optimising dosage and formulation stability, conducting long-term field validation trials, and strengthening regulatory frameworks in conjunction with farmer education programs.

**Conclusion and Recommendations**

The rising intensification of aquaculture production has increased disease risks, traditionally leading to

high antibiotic reliance. However, the advent of antimicrobial resistance, environmental contamination, and food safety issues have made antibiotic-based disease management untenable. The evidence presented in this review shows that probiotics, prebiotics, and synbiotics are biologically driven alternatives that can improve growth performance, feed efficiency, immunological competence, gut architecture, and disease resistance while minimising environmental impact. Their multifunctional methods, which include competitive pathogen exclusion, antimicrobial metabolite synthesis, immunological modulation, improved enzymatic digestion, and gut microbiota stabilisation, aid in their integration into sustainable aquaculture systems.

However, their efficacy is still determined by species specificity, environmental factors, strain selection, formulation stability, and management approaches. To maximise their potential, future efforts should focus on isolating and characterising locally adapted strains, using metagenomic tools for gut microbiota profiling, optimising dosage and delivery systems, and developing heat-stable formulations suitable for commercial feed processing. Long-term field validation experiments in various manufacturing systems are required to ensure consistency and economic viability. Strengthening regulatory frameworks, quality control standards, and farmer education initiatives can help to increase adoption, particularly in developing countries.

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