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Enhancing Ornamental Fish Health and Aquaculture Sustainability: A Review on the Role of Probiotics in Disease Resistance, Gut Health, and Growth Performance

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ABSTRACT

Ornamental fish farming, a burgeoning industry, faces challenges related to fish health, disease management, and environmental impacts. This review explores the potential of probiotics, particularly strains of *Lactobacillus* and *Bacillus*, to address these challenges by enhancing fish health, growth performance, and disease resistance. Probiotics offer an environmentally sustainable alternative to traditional antibiotics, facilitating improved nutrient absorption, optimizing gut health, and reducing pathogenic infections. Despite their benefits, variability in effectiveness across fish species and environmental conditions suggests the need for tailored probiotic formulations. This review emphasizes the mechanisms through which probiotics improve aquaculture outcomes, including enzymatic activity, immune modulation, and competitive exclusion. Additionally, the paper discusses the challenges and future directions for optimizing probiotic use in aquaculture, aiming to promote sustainability while minimizing ecological impact. These insights support the integration of probiotics as a viable strategy for advancing ornamental fish farming and achieving more sustainable aquaculture practices.

INTRODUCTION

The ornamental fish farming industry faces significant challenges related to disease outbreaks, poor water quality, and the need to reduce reliance on antibiotics. These issues hinder the productivity and profitability of small farms, particularly in regions like Tamil Nadu, India [1,2]. Probiotics, particularly strains of *Lactobacillus* and *Bacillus*, have shown promise in improving fish health, enhancing gut microbiota, and boosting disease resistance. However, the effectiveness of probiotics can vary significantly across different fish species and environmental conditions This sector holds significant economic potential, contributing to both domestic employment and international trade [3]. However, a major hurdle for sustainable development in ornamental fish aquaculture is disease management. Poor water quality and microbial imbalances frequently lead to health issues in fish, impacting productivity and profitability [4]. Historically, antibiotics have been a primary solution to control infections, but their widespread use has raised concerns regarding the emergence of antibiotic-resistant strains and environmental degradation. In response to these challenges, probiotics have gained attention as a sustainable alternative [5]. Probiotics are defined as live microorganisms that, when consumed in appropriate quantities, provide health advantages to the host organism. In the context of aquaculture, these beneficial microbes are utilized to boost fish health, stimulate growth, and maintain the aquatic environment's stability. They accomplish this through multiple pathways, such as outcompeting harmful pathogens, enhancing the fish's immune system, and producing enzymes that aid in the breakdown and absorption of nutrients [6,7]. Research indicates that specific probiotic strains, particularly from the genera *Lactobacillus* and *Bacillus*, play a pivotal role in optimizing the gut microbiota of ornamental fish. These beneficial bacteria help establish a balanced microbial community, which not only promotes better growth rates and feed conversion efficiency but also reduces the likelihood of disease outbreaks [8]. This shift away from antibiotics to probiotics supports environmentally friendly and economically sustainable aquaculture practices. However, the efficiency of probiotics can vary widely depending on the fish species, environmental conditions, and probiotic strain, indicating that a tailored approach is crucial for success [9]. This review aims to provide a comprehensive analysis of the current research on probiotics in ornamental fish aquaculture. It will explore the mechanisms through which probiotics exert their beneficial effects, evaluate their impact on fish health and water quality, and identify the challenges associated with their use. The insights gathered from this review could guide more sustainable practices in ornamental fish farming, ultimately benefiting both the industry and the environment.

Challenges and Opportunities in India's Ornamental Fish Farming

Ornamental fish farming in India is a rapidly growing industry, driven by the country's rich biodiversity and economic potential. With approximately 374 indigenous freshwater species, India is well-positioned to cater to both domestic and international markets. The domestic market for ornamental fish is valued at INR 300 crores, providing employment to around 50,000 people across 5,000 retail outlets. However, India's share in the global ornamental fish trade is limited, contributing only USD 1.7 million, despite the global market being worth an estimated USD 8 billion

[10]. Biodiversity plays a crucial role in India's ornamental fish farming industry, with 90% of the fish exported being wild-caught species. The north-eastern region of India is a major contributor, accounting for 33.13% of the total freshwater ornamental fish trade. Tamil Nadu, an important economic activity in India, has become an important economic activity due to its favorable climate and rich biodiversity [11,12]. However, the state's contribution to the global ornamental fish trade remains relatively minimal, indicating the need for targeted strategies to unlock the full potential of the sector. One major constraint in the sector is the occurrence of disease outbreaks, particularly those linked to poor water quality, which significantly affects the productivity and profitability of small farms. Poor water management creates issues related to fish health and production costs, which need intervention [13]. Farmers in Tamil Nadu also face challenges in production and marketing, such as poor infrastructure, lack of international market access, and awareness of sustainable farming practices [14]. To realize the economy of ornamental fish farming, these challenges must be resolved through proper water management, good fish farming practices, and improved marketing strategies.

Addressing Health and Environmental Challenges in Ornamental Fish Production

Aquaculture plays a crucial role in maintaining ornamental fish populations, yet the industry faces significant hurdles related to health management and environmental impact. It has been estimated that by the year 2000, aquaculture would contribute to over 25% of the global seafood supply. This sector is essential for the large-scale production of popular fish species, helping to decrease the dependence on wild-caught populations. The ornamental fish market is substantial, with Florida's freshwater species alone generating an annual revenue of $70 million [15]. Back in 1992, the global trade for ornamental fish was valued at around $247 million, with a considerable share sourced from farm-bred fish. Cultivating ornamental species such as *C. rubrofuscus* plays a key role in reducing the negative environmental effects associated with wild capture, which can lead to habitat destruction. To maintain biodiversity and ecosystem health, sustainable aquaculture practices, including ethical breeding and careful collection techniques, are critical [16]. Despite the benefits, there are ongoing challenges in ensuring the sustainability of aquaculture operations and mitigating the ecological impacts of both farmed and wild-caught fish.

Health and Environmental Challenges in Ornamental Fish Aquaculture

Aquaculture is pivotal in meeting the increasing demand for ornamental fish, including species like *Cyprnius rubrofuscus*. It also plays a key role in supporting biodiversity while addressing health and disease management issues. However, many ornamental fish species are vulnerable to parasitic infections, with research showing that around 34% are affected by parasites. Additionally, zoonotic bacteria such as Aeromonas species pose risks to both fish and humans, emphasizing the importance of effective antimicrobial strategies [17,18]. Probiotics have been investigated as a means to boost fish health, enhance growth, and increase disease resistance. However, the effectiveness of probiotics varies, with some studies indicating minimal impact on growth rates for species like *Carassius auratus* and *Xiphophorus helleri*. Maintaining water quality is another crucial aspect, as aquaculture environments are often prone to high levels of pathogenic bacteria, necessitating rigorous monitoring and management [19]. Despite the essential role of aquaculture in maintaining ornamental fish populations, it still faces challenges related to disease control and environmental impact. These challenges highlight the ongoing need for research and innovation to develop more effective and sustainable practices.

Microbial Diversity and Dietary Habits in Ornamental Fish

Ornamental fish in Tamil Nadu exhibit a wide range of microbial communities within their gut, shaped by unique feeding behaviors that are vital to their health and aquaculture practices. These fish predominantly feed on pelagic organisms and plant-based materials, both of which are crucial to their nutritional needs and ecological functions [20]. Studying the gut content of these species reveals valuable information about their dietary preferences, which is key to refining feeding strategies and enhancing the efficiency of aquaculture operations. The gastrointestinal tracts of these fish host a rich microbial diversity, with certain bacteria playing an important role in digestion and boosting immune defenses, directly impacting fish health and growth [21]. However, these fish are also vulnerable to parasitic infections, particularly from parasites like Argulus and Lernaea, which can adversely affect their well-being and reproductive success. Seasonal variations significantly influence the prevalence of these parasites, making it necessary to consider seasonal factors in aquaculture management [22]. To ensure sustainable ornamental fish farming in Tamil Nadu, it is essential to maintain a balance between supporting beneficial microbes and managing parasite threats. This balance is crucial for promoting healthy fish populations and achieving long-term aquaculture success.

Balancing Beneficial and Pathogenic Bacteria for Optimal Fish Health A Microbial Communities in *C. rubrofuscus*

The microbial community found in the foregut, hindgut, and skin of *C. rubrofuscus* plays a critical role in the fish's health and nutritional well-being. Research highlights that these regions host a variety of bacterial species, each contributing to different aspects of digestion and overall fish vitality [23]. In the foregut, *Bacillus licheniformis* and other *Bacillus* species have been identified as efficient producers of phytase, aiding in nutrient breakdown and absorption. The hindgut shares similar beneficial bacteria, with strains like *Bacillus subtilis* and *Bacillus cereus* recognized for their enzyme production, which supports the digestive processes [24]. The skin of freshwater species, including *C. rubrofuscus*, is home to both helpful and harmful bacteria. Beneficial strains such as *Bacillus* improve digestion and nutrient intake, whereas pathogenic bacteria like *Aeromonas* and *Vibrio* are often linked to skin diseases [25]. The presence of these pathogens underscores the importance of effective microbial management to prevent health problems and ensure a stable aquaculture environment. A balanced microbial ecosystem is essential for promoting the well-being of ornamental fish in aquaculture, highlighting the need for careful monitoring and management of both beneficial and harmful bacteria to maintain optimal fish health.

Probiotics A Sustainable Alternative for Enhanced Fish Health and Growth

The use of probiotics in aquaculture is on the rise, offering a sustainable and eco-friendly alternative to antibiotics for improving fish health, growth, and productivity. These beneficial microorganisms play a crucial role in disease prevention, strengthening the immune system, enhancing gut health, and boosting overall performance in aquatic species [9,26]. Probiotics contribute to a stronger immune response, better gut structure, and improved nutrient absorption, leading to faster growth and greater resistance to diseases. Certain probiotic strains, such as *Lactobacillus fermentum* and *Saccharomyces cerevisiae*, have demonstrated significant potential in enhancing growth rates and facilitating wound healing [27]. Additionally, innovative pigmented probiotic strains like *Exiguobacterium acetylicum* have exhibited potent antimicrobial activity, improving survival rates in aquatic environments by inhibiting harmful bacterial pathogens. *Bacillus* species, frequently found in fish digestive tracts, produce natural antimicrobial agents that limit the growth of harmful bacteria, thereby reducing the need for antibiotics in fish farming [28]. A balanced gut microbiome, supported by probiotics, is vital for efficient digestion and nutrient absorption, resulting in better feed utilization and growth in fish. Despite their advantages, the application of probiotics in aquaculture presents certain challenges. The effectiveness of probiotics can vary based on the strain, species, environmental conditions, and method of application, necessitating standardized guidelines [29]. More research is required to determine the ideal strains, dosages, and application techniques for different aquaculture systems while also evaluating potential environmental impacts. In summary, probiotics are a promising innovation in aquaculture, enhancing disease resistance, growth, and gut health while promoting environmental sustainability [30]. Although there are some limitations to their widespread use, ongoing research is crucial to optimize their application and fully understand their ecological implications [31]. With proper implementation, probiotics could revolutionize fish farming by fostering healthier populations, reducing antibiotic reliance, and advancing sustainable aquaculture practices.

The Role of Probiotics in Enhancing Fish Gut Health and Immunity

Probiotics contribute to the improvement of fish gut health by boosting immune function, alleviating stress, and promoting the growth of beneficial gut microorganisms. Certain probiotic strains, such as *Lactobacillus rhamnosus*, have demonstrated the ability to enhance innate immune responses in zebrafish, increase intestinal T cells and immunoglobulin cells in species like sea bass and gilthead sea bream, and reduce intestinal inflammation while improving the balance of gut microbiota [7,32]. In ornamental fish, including goldfish and swordtails, probiotic supplementation has been linked to a decline in antibiotic-resistant bacteria, fostering a healthier gut environment. Additionally, probiotics have been associated with enhanced growth rates and lower cortisol levels in fish larvae, suggesting improvements in both stress response and overall well-being [2,33]. Despite these benefits, the variability in effectiveness across different fish species highlights the need for further research to refine probiotic formulations for specific types of fish.

Evaluating Probiotic Strains for Gastrointestinal Survival A Key Factors for Acid and Bile Tolerance

Assessing probiotic strains involves examining their ability to survive harsh conditions in the gastrointestinal tract, particularly their tolerance to acidic environments and bile salts. Two critical methods used in this evaluation are the pH tolerance test and the bile tolerance test. Probiotic strains must withstand highly acidic conditions, typically around a pH of 2.5, to survive the stomach environment [34]. For instance, certain Lactobacillus strains have shown considerable viability after two hours of exposure to a pH of 2.5. The resistance levels can vary across strains, with *L. gasseri* and *L. fermentum* displaying strong resistance, suggesting their potential as effective probiotics. In addition to acid resistance, probiotics must endure the presence of bile salts, with successful strains showing survival rates above 50% in a 0.3% bile concentration [35]. Some *Lactobacillus* strains have been reported to survive in bile concentrations as high as 1.2%. Although pH and bile tolerance are critical for characterizing probiotics, variations in strain responses highlight the need for standardized testing protocols to ensure reliable comparisons [36]. Moreover, focusing solely on survival may overlook other important probiotic qualities, such as metabolic activity and interactions with the host microbiota.

Table 1. The Key Properties, Benefits, and Challenges of Probiotic Bacteria

Property	Description	Key Strains	Benefits	Challenges
Tolerance to Gastrointestinal Conditions	Ability to survive in low pH and bile salt environments to reach the intestines alive and functional.	*Lactobacillus casei*, *Lactobacillus delbrueckii*	Survives stomach acidity and bile (up to 3% concentration). Promotes colonization and gut health.	Variability in strain resistance; not all strains survive harsh GI conditions.
Adhesion and Colonization	Capability to adhere to intestinal mucosa for prolonged retention and competitive exclusion of pathogens.	*Lactobacillus pentosus*	Enhances gut microbiota balance, prevents harmful bacteria colonization, and ensures sustained effects.	Adhesion abilities vary among strains; requires surface proteins or adhesins for effectiveness.
Antimicrobial Activity	Production of organic acids, hydrogen peroxide, and bacteriocins to inhibit pathogen growth.	*Lactobacillus* spp.	Protects against pathogens (Listeria monocytogenes, Salmonella enterica), boosts immune response, and supports gut health.	Antimicrobial efficacy depends on strain and environmental conditions.
Safety and Efficacy	Assessment of strain-specific benefits, regulatory standards, and consumer safety.	Varies by product and formulation	Generally safe when consumed in proper amounts; reduces gut-related issues and supports immunity.	Risk of side effects (e.g., bloating, infections in immunocompromised individuals), variability in product quality.

The Growing Role of Probiotics in Enhancing Fish Health and Sustainability in Aquaculture

Probiotics, particularly from the *Bacillus* genus, are increasingly utilized in aquaculture to promote fish health, growth, and environmental sustainability. These microorganisms improve digestive efficiency, bolster immune function, and create a healthier aquatic environment, reducing reliance on chemicals and antibiotics for disease control [37]. A key benefit of probiotics in aquaculture is enhanced digestion. By secreting enzymes that break down complex feedstuffs, probiotics improve the digestibility and absorption of essential nutrients such as proteins, fats, and carbohydrates. This enzymatic activity leads to lower feed conversion ratios (FCR), meaning fish require less feed to gain weight, which ultimately boosts growth performance [38]. Probiotics also play a crucial role in strengthening fish immunity. They produce antimicrobial substances like bacteriocins and organic acids, which inhibit the growth of harmful pathogens in the gut and throughout the fish's body. These beneficial microbes outcompete pathogens for resources and binding sites on the gut lining, helping maintain a balanced gut microbiota, which is vital for overall fish health [39]. Beyond the direct benefits to fish, probiotics contribute to the environmental sustainability of aquaculture systems. They aid in detoxifying nitrogenous wastes, such as ammonia and nitrites, which are byproducts of fish metabolism and feed breakdown. This detoxification process reduces osmotic imbalances and stress in fish, improving their health and productivity [40]. Additionally, probiotics help stabilize the microbial community within aquaculture systems, preventing harmful microbial blooms and reducing the need for antibiotics, supporting global efforts to minimize antibiotic use in food production. While probiotics offer numerous advantages, challenges remain regarding their efficacy in aquaculture [41]. Effective farm management, biosecurity, and disease prevention strategies are essential for maximizing probiotic benefits. High costs and limited availability may also pose barriers, particularly for small-scale farmers [42]. Nonetheless, probiotics show great potential in promoting fish growth, boosting immune defenses, and enhancing water quality in sustainable aquaculture systems.

Probiotics as a Sustainable Solution to Combat Antibiotic Resistance in Ornamental Fish

Probiotics are emerging as a viable alternative to antibiotics in aquaculture, particularly for controlling antibiotic-resistant bacteria in ornamental fish. By fostering healthy gut microbiota and reducing the prevalence of harmful pathogens, probiotics help maintain a balanced microbial community [43]. Indigenous probiotic strains have been effective in lowering the presence of common pathogens, such as *Flavobacterium psychrophilum*, in treated tanks. Furthermore, probiotic supplementation has been associated with a significant reduction in antibiotic-resistant bacteria within the gut of ornamental fish [8,44]. Research shows that fish receiving probiotics exhibit lower levels of antibiotic resistance compared to those treated solely with antibiotics. In addition to combatting resistance, probiotics enhance the overall health and performance of ornamental fish by promoting gut health, improving digestion, and boosting nutrient absorption. These benefits strengthen the fish's immune system, making them more resilient to infections and environmental stress [45]. However, the effectiveness of probiotics can vary across fish species and environmental conditions, requiring a more tailored approach. Continued research is essential to optimize probiotic formulations and better understand their mechanisms of action in different aquaculture environments. Despite these challenges, probiotics offer significant potential in addressing antibiotic resistance and promoting sustainable aquaculture practices, enhancing both fish health and the long-term viability of ornamental fish farming.

Table 2. Comparison of Probiotic and Antibiotic Effects on Gut Flora in Ornamental Fish

Parameter	Probiotics	Antibiotics
Gut Flora Diversity	Increases the diversity of beneficial bacteria (e.g., Lactobacillus, *Shewanella putrefaciens*) (Tapia-Paniagua *et al.*, 2014).	Decreases microbial diversity, leading to potential dysbiosis (Sayes *et al.*, 2018).
Pathogen Suppression	Modulates the intestinal microbiota to suppress harmful pathogens, reducing colonization by pathogens (e.g., *Pseudomonas fluorescens*) (Ghosh *et al.*, 2007).	May temporarily suppress pathogens but can lead to the development of antibiotic resistance (Mamun *et al.*, 2019).
Antibiotic Resistance	Reduces antibiotic-resistant bacteria in fish gut (Tapia-Paniagua *et al.*, 2014).	Increases the prevalence of antibiotic-resistant bacteria (Mamun *et al.*, 2019).
Impact on Natural Microbiota	Maintains or enhances natural microbial balance, promoting healthy gut flora (Sayes *et al.*, 2018).	Disrupts natural microbiota, causing imbalances and increased pathogen susceptibility (Sayes *et al.*, 2018).
Health and Survival Rates	Improves overall health, survival, and disease resistance in fish, especially in species like goldfish and swordtails (Tapia-Paniagua *et al.*, 2014).	Prolonged use can reduce survival and contribute to weaker disease resistance due to disruption of the microbiome (Mamun *et al.*, 2019).
Growth and Nutrient Absorption	Enhances digestion, nutrient absorption, and growth performance by supporting healthy microbial communities (Ghosh *et al.*, 2007).	May impair digestion and nutrient absorption due to gut dysbiosis (Mamun *et al.*, 2019).
Species Variability	Effectiveness varies across fish species and environmental conditions, requiring tailored probiotic formulations (Santos *et al.*, 2021).	Antibiotic effects are more uniform but can be detrimental across species if overused (Sayes *et al.*, 2018).
Environmental Sustainability	Supports sustainable aquaculture by promoting gut health and reducing antibiotic use (Santos *et al.*, 2021).	Contributes to environmental issues through antibiotic residues and resistant bacteria in water systems (Mamun *et al.*, 2019).

Health Benefits and Challenges of Enzymatic Activity in Probiotic Strains

Probiotic strains have been found to have diverse enzymatic capabilities, which are crucial for their health benefits, particularly in digestion and nutrient absorption. These properties vary significantly among different strains, necessitating a case-by-case evaluation for efficacy and safety. Tolerance to gastrointestinal conditions is essential, with many strains exhibiting varying levels of tolerance to factors such as pH and bile salts [46]. For instance, Lactobacillus strains can survive in acidic environments and tolerate bile concentrations up to 3%, demonstrating high stability in simulated GI conditions. Adhesion and colonization are also critical for probiotics, as effective strains must adhere to intestinal surfaces to prolong retention time [47]. Many probiotic strains produce antimicrobial substances that inhibit pathogenic bacteria, with Lactobacillus strains showing significant antagonistic activity against pathogens like Listeria and Salmonella. The production of antimicrobial peptides is a common trait among effective probiotics, contributing to gut health [48]. However, concerns about their safety and efficacy in commercial products persist, influenced by factors such as storage conditions. The enzymatic activity of probiotic strains is generally beneficial, but their effectiveness can vary based on environmental conditions and specific applications [49].

The Impact of Water Quality on Probiotic Efficacy in Aquaculture

Water quality plays a pivotal role in determining the effectiveness of probiotics in aquaculture, which are essential for promoting the health and growth of fish. Probiotics, such as Bacillus species, help regulate harmful bacteria, fostering a healthier environment for aquatic organisms. These beneficial microbes improve key water quality parameters, including the reduction of nitrogen levels and lowering of Vibrio bacteria counts [50]. In tilapia farming, the use of probiotics enhances feed conversion ratios and feed efficiency, highlighting better nutrient absorption and maintaining overall water quality. Additionally, probiotics contribute to increased survival rates of fish larvae during transportation, showcasing their ability to sustain water quality under stressful conditions [51]. In biofloc systems, probiotics boost both growth performance and immunity in species like *Macrobrachium rosenbergii*. However, their success is heavily reliant on maintaining optimal water conditions, emphasizing the need for continuous monitoring and regulation of water parameters to fully harness the benefits of probiotics in aquaculture systems [52].

Table 3. Enzymatic Profiles and Applications of Probiotic Strains

Probiotic Strain	Enzymatic Activity	Key Functions	Applications
Bacillus paranthracis	Amylase (31,788.59 IU), Cellulase (4,487.486 IU), Pectinase (13.98986 IU)	Enhances digestion and nutrient absorption by breaking down carbohydrates and plant fibers	Aquaculture, agriculture, industrial enzyme production
Lactic Acid Bacteria (Lacticaseibacillus	High oxalate degradation	Prevents kidney stones by degrading oxalates	Human health, kidney health

paracasei, Lactiplantibacillus plantarum)			
Lactobacillus rhamnosus	Invertase, Inulinase	Aids in carbohydrate fermentation, valuable in silage production	Food processing, animal feed production
Probiotic Yeasts (Saccharomycopsis fibuligera)	Protease, Amylase	Breaks down proteins and starch, useful in food applications	Food industry, fermentation processes
Lactobacillus rhamnosus GG	Acyl-hydrolase/Lipase	Involved in lipid metabolism	Gut health, human health, metabolic support
Bacillus cereus, Bacillus subtilis	α-Glucosidase, Amylase, Lipase, Protease	Hydrolyzes carbohydrates, fats, and proteins, improves digestion and feed conversion	Aquaculture, agriculture, improved feed efficiency
Bacillus subtilis (from rice agrocenosis)	Fibrinolytic, Keratinase	Breaks down fibrin and keratin	Industrial use, agricultural waste processing
Lactobacillus sporogenes	Unknown (enhances gut microflora)	Improves gut health and growth metrics in ornamental fish	Aquaculture, ornamental fish health
Lactobacillus plantarum (SHY21-2)	Unknown (protects against Aeromonas hydrophila)	Reduces infection and inflammation in fish, maintains intestinal integrity	Aquaculture, disease prevention in fish
Lactobacillus spp.	General enzymatic activity improving digestion	Enhances digestion and nutrient absorption, particularly in ornamental fish	Ornamental fish health, aquaculture, safe for fish diets

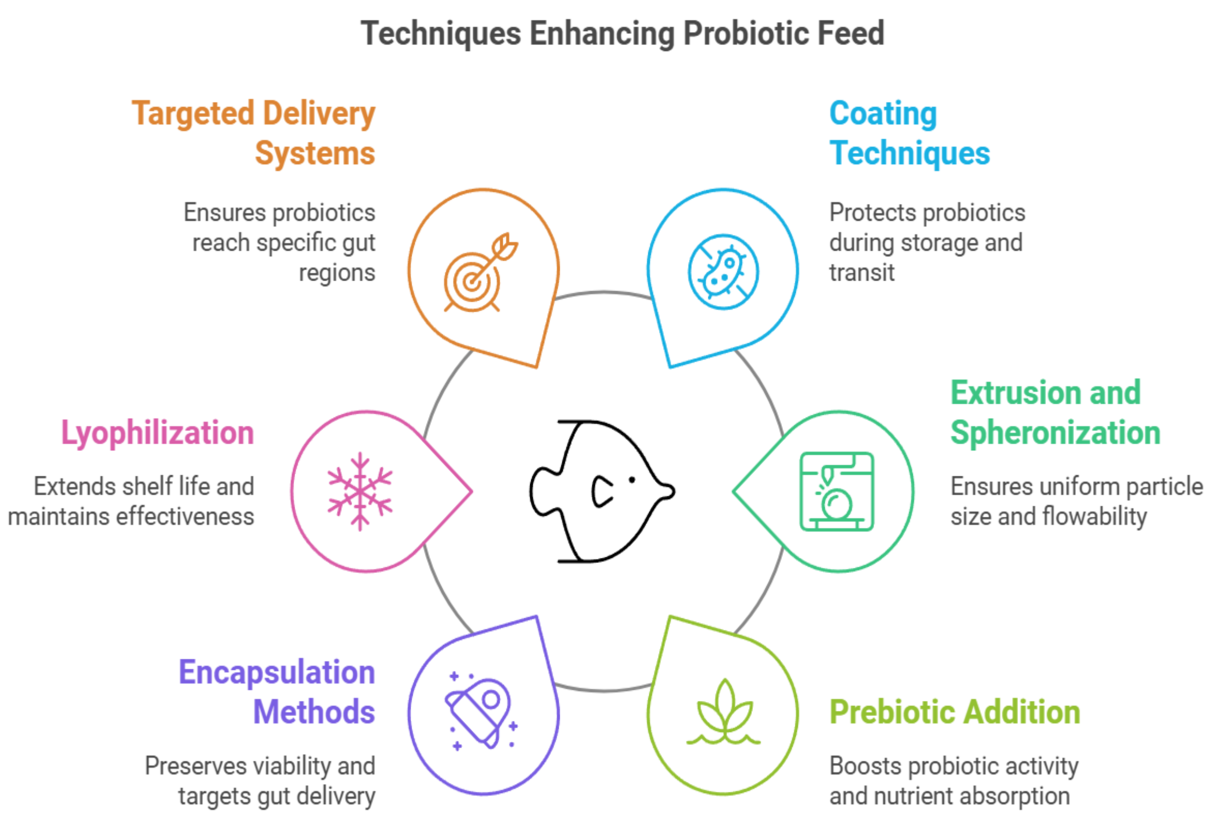

Figure 1. Illustration of Techniques and Innovations in Enhancing Probiotic Feed Formulation

Impact of Cadmium Toxicity on Aquatic Species

Cadmium (Cd) toxicity poses a significant threat to aquatic species, especially fish and crustaceans. Different species exhibit varying degrees of sensitivity to Cd, with *Artemia franciscana* showing a higher tolerance compared to other aquatic organisms. However, prolonged Cd exposure triggers oxidative stress in fish, leading to disruptions in immune function. In species like Sparus aurata, chronic exposure can damage vital organs like the hepatopancreas, where the production of protective proteins such as metallothionein is impaired [53]. Carnivorous fish, such as *Channa marulius* and *Mystus seenghala*, accumulate Cd in their tissues, with *M. seenghala* being particularly vulnerable to Cd toxicity. Cd toxicity causes immune system dysregulation, disrupts gene expression, and induces oxidative stress, which severely compromises fish health. It interferes with the structure and function of lymphoid organs and immune cells, leading to immune deregulation and inflammation. For example, Cd exposure in common carp impairs gut immunity by reducing microbial diversity, which affects overall gut health [54]. The generation of reactive oxygen species (ROS) from Cd exposure overwhelms the fish's antioxidant defenses, causing oxidative stress—a key factor in Cd-induced immunotoxicity [55]. Transcriptome analyses in *Nile* *tilapia* have shown that Cd exposure alters the expression of numerous immune-related genes, revealing a dose-dependent immune response. The cumulative effects of Cd on various tissues and systems emphasize the need for comprehensive evaluations of environmental pollutants and their impact on aquatic life [56]. These physiological changes not only threaten the health of individual species but also have broader ecological and economic consequences. Although the adverse effects of Cd on fish immunity are well-documented, some studies have suggested that certain species may develop adaptive responses, indicating a complex relationship between Cd exposure and species resilience [57].

Impact of Chlorpyrifos Toxicity on Fish Immune Function and Oxidative Stress

Chlorpyrifos (CPF) toxicity poses a significant threat to the immune systems of fish, triggering oxidative stress, inflammation, and apoptosis. Prolonged exposure to CPF in largemouth bass results in reduced activity of antioxidant enzymes and heightened expression of pro-inflammatory genes, indicating severe immune impairment [58]. In common carp, CPF disturbs the redox balance in lymphocytes, leading to the activation of inflammatory pathways and hindering T-cell receptor functionality. Histological studies on *Pseudetroplus maculatus* reveal that sublethal CPF exposure causes marked immune alterations, including reduced lysozyme and complement levels [59]. Additionally, transcriptome analysis in common carp has identified 773 genes with differential expression linked to immune system pathways. These findings underscore CPF's systemic impact on fish immunity and its potential ecological risks.

CONCLUSION

The review highlights the critical role of probiotics in addressing health, environmental, and sustainability challenges in ornamental fish aquaculture. Probiotics, particularly strains from the *Bacillus* and *Lactobacillus* genera, have proven effective in enhancing fish gut health, improving immune function, and promoting growth. They offer an environmentally sustainable alternative to traditional antibiotics, mitigating concerns about antibiotic resistance and ecological degradation. Probiotics support better feed conversion, reduce pathogenic infections, and improve water quality, creating a healthier and more sustainable aquaculture environment. However, challenges remain in optimizing probiotic applications due to variability in strain effectiveness across species and environmental conditions. Tailored formulations and further research into strain-specific benefits are essential to maximize their potential. Addressing these gaps will help enhance the economic viability and ecological sustainability of ornamental fish farming. The findings underline the importance of integrating probiotics into aquaculture practices, ultimately contributing to the industry's growth while preserving environmental health.

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