

Probiotics in Fish Health: A Sustainable Strategy for Modern Aquaculture

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ABSTRACT

The recent growth of aquaculture has increased the risks associated with disease outbreaks, excessive use of antibiotics, antimicrobial resistance, and sustainable environmental management. Recent evidence has emphasized the potential of probiotics as novel biological resources for enhancing fish health and production efficiency. Probiotics, given as feed or water supplements, improve growth performance, feed efficiency, immune ability, and metabolism in aquatic animals. The fish gut contains a diverse and complex microbial community that is primarily involved in digestion, nutrient uptake, and immune responses. Probiotic supplementation can modulate this core microbiota, increase digestive enzyme secretion, and optimize lipid, carbohydrate, and protein metabolism, leading to improved feed conversion efficiency and physiological resistance. Moreover, probiotics can boost innate immunity by competitive exclusion, production of antimicrobial substances, and regulation of immune-related gene expression. Current developments focus on host-specific strain selection and the development of next-generation probiotics. In this way, probiotics play a significant role in sustainable aquaculture, as they reduce the use of antibiotics and minimize waste output in the environment. In conclusion, probiotics are essential elements in precision health management approaches. They promote productivity, disease resistance, and sustainability in modern aquaculture.

INTRODUCTION

Aquaculture has emerged as the fastest-growing food production industry in the world and now accounts for more than half of the aquatic animals consumed worldwide (Wuertz *et al.*, 2021; Torres-Maravilla *et al.*, 2024). As the capture fisheries continue to decline, fish farming has become an important component in ensuring global food security. However, the rapid intensification of fish farming has resulted in increased outbreaks of diseases caused by bacterial, viral, and parasitic pathogens, leading to significant economic losses (Pandiyan *et al.*, 2013). The extensive use of antibiotics to combat these diseases has resulted in antimicrobial resistance, which has raised significant concerns (Pandiyan *et al.*, 2013; Torres-Maravilla *et al.*, 2024).

On the other hand, studies have shown that the gut of fish is a diverse microbial environment that plays a crucial role in the digestion and metabolism of fish, as well as its immune system (Ringø *et al.*, 2022). Any imbalance in the gut microbiota of fish may affect its health and productivity. In this regard, the use of probiotics has been identified as a sustainable and eco-friendly alternative to antibiotics (Pandiyan *et al.*, 2013). Through the restoration of microbial balance, the promotion of the immune system, and the improvement of nutrient conversion, beneficial microbes are changing the way fish health is managed in the modern aquaculture industry (Torres-Maravilla *et al.*, 2024).

What Are Probiotics? Not Just for Humans

Probiotics are live microorganisms that have health benefits to the host when given in adequate amounts (Torres-Maravilla *et al.*, 2024). Although probiotics were originally linked to human nutrition, their use has been expanded extensively to aquaculture. In fish culture, probiotics can be administered via

feed or rearing water and can consist of live or dead microbial cells that promote host health and environment (Pandiyan *et al.*, 2013; Wuertz *et al.*, 2021).

In aquaculture, probiotics can improve growth rate, feed conversion, stress resistance, and disease protection (Wuertz *et al.*, 2021). Probiotics work by regulating gut microbiota, competing with pathogens, secreting antimicrobial compounds, activating the immune system, and increasing digestive enzyme activity (Pandiyan *et al.*, 2013). Moreover, probiotics regulate lipid, carbohydrate, and protein metabolism, which helps improve nutrient assimilation and production efficiency (Ringø *et al.*, 2022). Consequently, in contemporary aquaculture, probiotics are a scientifically proven and sustainable alternative to antibiotic-based health management.

How Probiotics Improve Fish Metabolism

Probiotics improve metabolic function in fish by acting synergistically in the gastrointestinal tract. The major documented advantages include:

Increased digestive enzyme activity – Activation of proteases, lipases, and amylases enhances nutrient digestion and feed conversion efficiency (Pandiyan *et al.*, 2013).

Improved lipid metabolism – Modulation of fat digestion and utilization of energy maintains balanced growth and metabolic efficiency (Ringø *et al.*, 2022).

Optimized carbohydrate metabolism – Stimulation of glucose homeostasis and short-chain fatty acid synthesis maintains metabolic balance (Ringø *et al.*, 2022).

Improved protein and amino acid metabolism – Activation of microbial digestion enhances

nutrient utilization and physiological functions (Ringø *et al.*, 2022).

Increased intestinal nutrient absorption – Improvement in gut structure and nutrient transporter expression enhances absorptive ability (Ringø *et al.*, 2022).

Natural Bodyguards: Probiotics and Immunity

Probiotics function as “biological bodyguards” in aquaculture by enhancing innate immunity and improving resistance to infectious diseases (Pandiyani *et al.*, 2013). Their first mode of action is competitive exclusion, where beneficial bacteria colonize intestinal adhesion sites and compete for nutrients, thus inhibiting the growth of pathogens. Some probiotic bacteria also produce antimicrobial substances like bacteriocins and organic acids that directly inhibit the growth of pathogenic microorganisms (Torres-Maravilla *et al.*, 2024). However, probiotics do not just inhibit pathogens; they also promote the immune system. They increase non-specific immune factors such as lysozyme activity, complement fixation, phagocytic activity, and respiratory burst activity (Pandiyani *et al.*, 2013).

Moreover, probiotics regulate cytokine expression and immune genes, thus modulating the inflammatory response and improving systemic immunity (Ringø *et al.*, 2022). Probiotics also play a role in maintaining the integrity of the intestinal barrier through the enhancement of mucosal integrity and the optimization of the symbiotic relationship between microbiota and gut-associated lymphoid tissues (Ringø *et al.*, 2022). This is because the enhanced barrier function limits the translocation of pathogens and helps to maintain immune homeostasis, especially under stress, which is common in intensive aquaculture. The probiotics work through the above comprehensive immunological functions to improve disease

resistance, survival rates, and the reduction of reliance on antibiotics in modern aquaculture.

Native vs Commercial Probiotics: Does Origin Matter?

The source of probiotic bacteria is an important consideration that determines their efficacy in aquaculture. Most commercial probiotics were designed for use in terrestrial animals and were later modified for fish farming (Pandiyani *et al.*, 2013). While they are effective, there is growing evidence that host-associated (autochthonous) probiotics—bacteria that are already found in the fish gut—have greater efficacy (Wuertz *et al.*, 2021). Autochthonous bacteria are better suited to the host’s gastrointestinal environment, including pH, bile, enzymes, and immune interactions. This makes them better suited for colonization and survival in the gut, leading to a more stable modification of the host microbiota (Wuertz *et al.*, 2021).

Successful colonization is important for maintaining the “core microbiome,” which is vital for nutrient processing and immune function (Ringø *et al.*, 2022). Conversely, some allochthonous probiotics may have only transient effects if they are not able to colonize the gut for a long time, often requiring continuous supplementation (Pandiyani *et al.*, 2013). As a result, the selection of probiotics based on host specificity, compatibility, and functionality has come to be increasingly recognized as essential for maximizing their benefits in aquaculture (Wuertz *et al.*, 2021; Ringø *et al.*, 2022).

The Future: Designer and Recombinant Probiotics

However, recent breakthroughs in microbial genomics and biotechnology are making it possible to design probiotics with specific purposes in aquaculture. Unlike traditional probiotics, which were chosen for general applications, designer probiotics are chosen for

specific properties like metabolic regulation, immune system activation, and pathogen suppression, according to current knowledge of fish gut microbiota (Wuertz *et al.*, 2021; Ringø *et al.*, 2022). This trend is a clear move towards precision microbiome management.

Moreover, genetically engineered probiotics are being considered as novel technologies that can be used to express antimicrobial peptides, immunomodulatory compounds, or vaccine antigens. These genetically modified probiotics can be used as biologic vectors to improve specific immune protection and decrease the need for antibiotics (Pandiyan *et al.*, 2013; Torres-Maravilla *et al.*, 2024). Although regulatory and biosafety issues are important, these novel probiotic technologies have great potential for improving disease management and sustainability in modern aquaculture practices.

Sustainability Angle: Probiotics as Eco-Friendly Tools

Sustainability has emerged as a pressing issue in aquaculture, particularly with regard to the overuse of antibiotics, environmental pollution, and the development of antimicrobial resistance. Probiotics are being increasingly identified as environmentally friendly alternatives that promote fish health and minimize the need for antibiotics, thus contributing to the containment of resistant bacterial strains (Pandiyan *et al.*, 2013).

Apart from their role in disease management, probiotics also promote feed efficiency and nutrient utilization by inducing digestive enzymes and modulating metabolic functions (Ringø *et al.*, 2022). This results in a reduction in nutrient waste, organic matter, and ammonia production in aquaculture systems, thereby making a positive contribution to water quality and environmental sustainability. Some probiotic strains also have the ability to modulate microbial populations in the culture

environment and inhibit opportunistic pathogens, thus making a positive contribution to fish health in intensive aquaculture systems. Through their ability to promote immune resilience, metabolic efficiency, and ecological balance, probiotics have emerged as a biologically sustainable approach to sustainable aquaculture development (Ringø *et al.*, 2022).

CONCLUSION: Probiotics and the Future of Sustainable Aquaculture

Probiotics have proven to be a significant tool in contemporary aquaculture, showing evident efficacy in growth promotion, feed conversion, metabolism, and immune stimulation (Pandiyan *et al.*, 2013; Ringø *et al.*, 2022). By regulating the gut microbiota and maintaining a stable core microbiome, probiotics enhance nutrient metabolism and boost disease resistance in intensive aquaculture systems (Wuertz *et al.*, 2021).

Notably, probiotics offer a sustainable substitute for antibiotics in disease management. By mechanisms of competitive exclusion, antimicrobial substance production, and immune activation, probiotics can decrease the need for chemotherapeutic agents and mitigate antimicrobial resistance issues (Pandiyan *et al.*, 2013). Enhanced feed conversion and metabolic efficiency also help mitigate environmental concerns (Ringø *et al.*, 2022). With the progress of microbiome science and the development of host-specific strains, probiotics are increasingly being positioned at the forefront of precision health management and sustainability in aquaculture (Torres-Maravilla *et al.*, 2024).

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