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Fish Gut Microbiota: Roles, Functional Mechanisms and Aquaculture Applications

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ABSTRACT

Gut bacteria play a crucial role in maintaining fish health, growth, immune function, and nutrient utilization, determining the long-term viability of fish culture systems. Understanding fish gut microbiota has become increasingly essential for boosting productivity and disease control as aquaculture continues to expand in scale. This review summarizes and synthesizes existing information about the variety, composition, and functional activities of gut bacteria in cultured fish species. According to 16S rRNA gene sequencing studies, the fish gut microbiota is dominated by a conserved core community consisting mostly of Proteobacteria, Fusobacteria, Firmicutes and Bacteroidetes, however there is substantial interspecific and environmental heterogeneity. Gut bacteria aid in digestion, immunological regulation, growth promotion, and stress tolerance while also interacting with the aquatic environment. The use of probiotics, prebiotics, and microbiome-based therapies in aquaculture has showed promise for increasing fish health and culture efficiency. This study addresses current advancements, problems, and future opportunities for gut microbiome research in fish culture, with a focus on its potential role in promoting sustainable aquaculture and food security.

Key Words - Gut microbiota; Aquaculture; Fish culture; Probiotics; Immune modulation; Sustainable fisheries

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INTRODUCTION

Aquaculture is one of the world's fastest-growing food production sectors, helping to meet rising demand for animal protein. However, the expansion of fish culture methods has resulted in issues such as disease outbreaks, decreased feed efficiency, and environmental stress. In recent years, the gut microbiota of fish has received attention as an important biological component impacting host health and production. (Aizpurua *et al.,* 2021)

The fish's gastrointestinal system contains a rich microbial community that forms symbiotic connections with the host. These microbes assist in absorbing nutrients, synthesize important metabolites, strengthen the immune system, and guard against pathogenic invasion. Understanding gut bacterial dynamics is thus crucial for creating sustainable and health-oriented fish production strategies. (Baldo *et al.,* 2019)

Fish Gut Microbiota Diversity and Composition:

Despite alterations to species and environments, the fish gut microbiota has a core community that is dominated by Proteobacteria, Fusobacteria, Firmicutes and Bacteroides. These bacterial groups have a role in metabolic flexibility and host adaptability under various kinds of culture conditions.

The variety of gut bacteria is influenced by host species, age, nutrition, trophic level, environment (freshwater or marine), water quality, temperature, and agricultural practices. Herbivorous and omnivorous fish have more microbial diversity than carnivorous species, indicating nutritional complexity and digestion needs. (Ofek *et al.,* 2021)

Gut Bacteria: Their Functional Roles in Fish Culture

Gut bacteria play an important role in the digestion of proteins, carbohydrates, and lipids by producing extracellular enzymes and fermentation products. These microbial activities help break down complex nutrients in feed, improving nutrient absorption and feed conversion efficiency, which are essential for intensive fish production. (Yukgehnaish *et al.,* 2020)

The gut microbiome also supports the fish immune system. Beneficial bacteria enhance innate immune responses, strengthen the intestinal mucosal barrier, and suppress harmful microbes through competitive exclusion and antimicrobial compound production, thereby reducing the risk of infections. (Ray *et al.,* 2012)

In addition, a balanced gut microbial community helps improve growth performance, feed utilization, and the ability of fish to tolerate environmental stresses such as temperature changes and high stocking density, making it vital for successful aquaculture systems. (Romero *et al.,* 2014)

Gut microbiome modulation through probiotics in aquaculture

The use of probiotics has emerged as an effective strategy for regulating gut microbiota in fish rearing systems. Probiotic microorganisms help maintain a balanced intestinal microbial community by competing with pathogenic bacteria, producing antimicrobial substances, and enhancing the host's immune responses. Common probiotic genera such as *Lactobacillus, Bacillus,* and *Enterococcus* have been widely reported to improve immune function, disease resistance, feed utilization, and overall growth performance in cultured fish species. (Zhang *et al.,* 2025)

In addition to probiotics, prebiotics are also increasingly used in aquaculture. Prebiotics are non-digestible feed ingredients that selectively stimulate the growth and activity of beneficial gut microbes. By promoting favourable microbial populations, prebiotics can enhance digestion, strengthen immunity, and improve gut health.

Another promising approach is the use of synbiotics, which combine probiotics and prebiotics to achieve a synergistic effect. Synbiotics not only introduce beneficial microorganisms but also provide the substrates that support their growth and activity within the fish gut, leading to improved microbial balance and better physiological performance.

More recently, microbial community engineering has gained attention as an advanced strategy for aquaculture management. This approach focuses on intentionally shaping microbial communities in the fish gut and surrounding environment to create a stable and beneficial microbiome. Together, probiotics, prebiotics, synbiotics, and microbial community engineering represent sustainable alternatives to antibiotics and hold great potential for improving fish health, productivity, and environmental stability in modern aquaculture systems. (Hasan & Banerjee 2020)

Gut bacteria in fish play a central role in digestion, immune regulation, and growth, while also interacting with environmental factors such as feed composition and water quality. It emphasizes that microbiome-driven processes are key to enhancing fish health and supporting sustainable aquaculture practices (Fig.1). The dominant bacterial phyla in the fish gut microbiota are outlined along with their metabolic functions and their significance in enhancing nutrient utilization, digestion, and overall aquaculture productivity (Table 1). Commonly used probiotic genera in aquaculture are also highlighted, with emphasis on their functional roles in promoting fish health, boosting immune response, improving disease resistance, and increasing overall culture efficiency (Table 2).

Table 1. Dominant gut bacterial phyla and functional roles in fish culture:

Bacterial Phylum	Major Functions in Fish Gut	Genera	Relevance to Fish Culture
Bacteroidetes	Polysaccharide degradation, lipid metabolism	*Bacteroides, Flavobacterium*	Supports digestion of complex diets
Firmicutes	Carbohydrate fermentation, SCFA production, gut integrity	*Lactobacillus, Bacillus, Clostridium*	Improved feed efficiency and growth
Fusobacteria	Amino acid fermentation, vitamin synthesis	*Cetobacterium*	Common in freshwater fishes; vitamin B12 production
Proteobacteria	Protein digestion, nitrogen metabolism, immune stimulation	*Vibrio, Aeromonas, Shewanella*	Dominant core microbiota; adaptability to diet and environment

Table 2. Probiotic bacteria used in fish culture and their reported benefits

Probiotic Genus	Target Fish Species	Reported Benefits	References
Enterococcus	Trout, Seabass	Stress tolerance, immune modulation	Sullam *et al.,* (2012)
Bacillus	Tilapia, Shrimp, Carp	Improved growth, enzyme production	Egerton *et al.,* (2018)
Lactobacillus	Tilapia, Carp, Catfish	Enhanced immunity, pathogen inhibition	Nayak (2010); Ringø *et al.,* (2016)

Ecological and Environmental Consequences

Gut bacteria influence not only fish physiology but also the broader aquaculture ecosystem, including nutrient cycling and water quality. The fish gut microbiota participates in the breakdown of feed components and the transformation of nutrients such as nitrogen and phosphorus. When fish excrete waste products, these microbial by-products enter the surrounding water, where they interact with environmental microbial communities and contribute to nutrient recycling within the culture system. (Sun *et al.,* 2019)

In aquaculture ponds or tanks, the relationship between fish gut microbes, uneaten feed, and water microbial populations is closely inter connected. Uneaten feed and fish waste can promote the growth of certain microbial communities in the water, which may either support ecosystem balance or lead to the proliferation of harmful microbes if not properly managed. Beneficial microbial interactions can improve organic matter decomposition and maintain water quality, whereas microbial imbalance may result in poor water conditions and increased disease risk. (Kanika *et al.,* 2025)

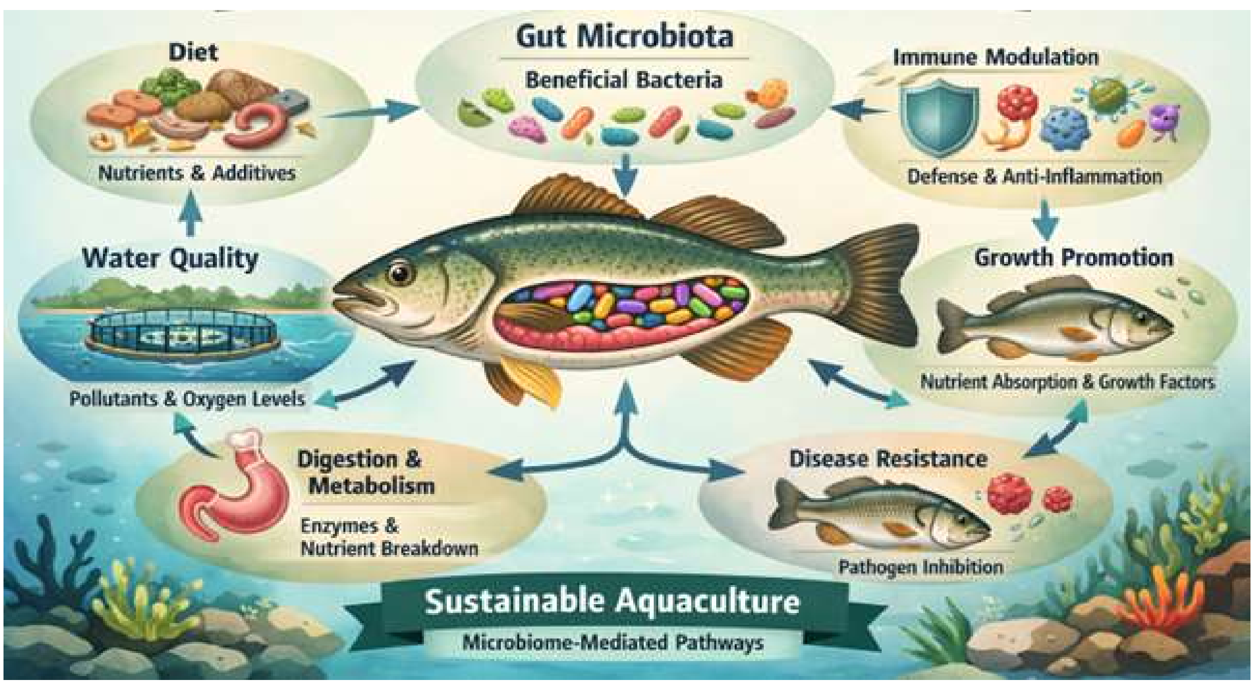

Figure 1. Overview of gut microbiota functions

Therefore, understanding these interactions highlights the importance of microbiome-based management strategies in aquaculture. Approaches such as the use of probiotics, optimized feeding practices, and monitoring microbial communities can help maintain a stable microbial environment. Such strategies not only support fish health and growth but also enhance water quality and ecosystem stability, contributing to more sustainable aquaculture production systems. (Chen *et al.,* 2022)

Challenges and Future Outlooks

Although significant progress has been made in fish gut microbiome research, several challenges still exist. A major limitation is the lack of standardized methodologies in sampling, sequencing, and data analysis, which makes it difficult to compare results across different studies. In addition, many findings are generated under controlled laboratory conditions and are not always easily applicable to commercial aquaculture systems where environmental factors such as water quality, feed, and stocking density vary.

Future research should focus on integrated multi-omics approaches, including metagenomics, meta-transcriptomics, and metabolomics, to better understand the functional roles of gut microbiota. Combining these approaches with controlled trials and field studies will help identify key microbial communities that enhance fish growth, immunity, and overall aquaculture sustainability.

CONCLUSION

Gut bacteria play a vital role in maintaining fish health, nutrition, and overall productivity in aquaculture systems. These microbial communities assist in digestion and nutrient absorption by breaking down complex compounds in feed and producing essential metabolites such as vitamins and short-chain fatty acids. They also contribute to immune system regulation, helping fish resist pathogenic infections and maintain a balanced internal environment.

In recent years, microbiome-based approaches such as probiotics, prebiotics, and synbiotics have gained attention as sustainable alternatives to antibiotics in aquaculture. These strategies aim to manipulate and maintain beneficial microbial populations in the fish gut, thereby improving feed efficiency, growth performance, and disease resistance.

Furthermore, understanding and managing the gut microbiome can enhance the nutritional quality and safety of fish products by promoting healthier growth and reducing the occurrence of harmful microbes. With continued research and the integration of advanced molecular tools, microbiome-based therapies hold great promise for improving fish health, supporting sustainable aquaculture practices, and ensuring higher quality aquatic food production.

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