INVITED REVIEW

Microbiota of economically important fish in Colombia and Hungary: Probiotic strategies for growth and health improvement

Microbiota de peces de importancia económica en Colombia y Hungría: Estrategias probióticas para el crecimiento y la mejora de la salud

Microbiota de peixes de importância econômica na Colômbia e Hungria: Estratégias probióticas para o crescimento e melhoria da saúde

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Abstract

Background: The fish-associated microbiota plays a crucial role in maintaining health and enhancing productivity. However, compared with those of mammals, the composition and functions of the fish microbiota remain less understood. **Objective:** Analyze the role of the intestinal microbiota in the health and productive performance of economically important fish species in Colombia and Hungary, identifying similarities and differences to propose probiotic strategies adapted to the aquaculture conditions of both countries. **Methods:** A comprehensive analysis of the scientific literature was conducted to provide insights into diverse probiotic interactions and economically important fish species between Colombia and Hungary. **Results:** Improving growth performance, as reflected by increased specific growth rates, weight gain, and feed conversion ratios, is closely linked to microbiota modulation. These growth benefits are accompanied by elevated immune responses, including increased lysozyme activity, upregulated complement and cytokine expression (e.g., IL-1β and TNF-α), and increased antioxidant enzyme activity (e.g., superoxide dismutase [SOD] and catalase [CAT]). Several trials also reported improvements in digestive enzyme activity (amylase, protease, and lipase), and intestinal morphology. Additionally, shifts in gut microbiota composition, characterized by a greater abundance of beneficial bacteria (e.g., lactic acid bacteria) and a reduction in pathogenic populations, correlate with the upregulation of metabolic pathways involved in carbohydrate utilization and antioxidant defenses. **Conclusions:** Probiotic supplementation improves growth, feed efficiency, and immune responses in all species studied, with the greatest benefits observed in tilapia and carp. Overall, probiotics are an effective aquaculture strategy, though their efficacy is species-dependent, and higher in herbivorous/omnivorous fish than in carnivorous species.

Keywords: *Aquaculture, gastrointestinal microbiota, host microbial interactions, microbiome, probiotics.*

Resumen

Antecedentes: La microbiota asociada a los peces desempeña un papel crucial en el mantenimiento de la salud y la mejora de la productividad. Sin embargo, en comparación con los mamíferos, la composición y las funciones de la microbiota de los peces siguen siendo menos comprendidas. **Objetivo:** Este estudio tuvo como propósito analizar el papel de la microbiota intestinal en la salud y el desempeño productivo de especies de peces de importancia económica en Colombia y Hungría, identificando similitudes y diferencias que permitan proponer estrategias probióticas adaptadas a las condiciones acuícolas de ambos países. **Métodos:** Se realizó un análisis exhaustivo de la literatura científica con el fin de obtener información sobre diversas interacciones probióticas y especies de peces de importancia económica entre Colombia y Hungría. **Resultados:** El mejoramiento en el rendimiento del crecimiento se reflejó en mayores tasas específicas de crecimiento, mayor ganancia de peso y una mejor conversión alimenticia, y está estrechamente vinculada a la modulación de la microbiota. Estos beneficios en el crecimiento se acompañan de una mayor respuesta inmune, incluyendo un aumento en la actividad de la lisozima, una regulación positiva de la expresión de componentes del complemento y citocinas (por ejemplo, IL-1β, TNF-α) y una mayor actividad de enzimas antioxidantes (por ejemplo, superóxido dismutasa [SOD], catalasa [CAT]). Varios ensayos también reportan mejoras en la actividad de enzimas digestivas (amilasa, proteasa, lipasa) y en la morfología intestinal. Además, los cambios en la composición de la microbiota intestinal caracterizados por una mayor abundancia de bacterias beneficiosas (por ejemplo, bacterias ácido-lácticas) y una reducción de poblaciones patógenas se correlacionan con la regulación positiva de vías metabólicas involucradas en la utilización de carbohidratos y las defensas antioxidantes. **Conclusiones:** La suplementación con probióticos mejora el crecimiento, la eficiencia alimenticia y las respuestas inmunes en todas las especies estudiadas, con los mayores beneficios observados en tilapia y carpa. En general, los probióticos constituyen una estrategia efectiva en acuicultura, aunque su eficacia depende de la especie, siendo más alta en peces herbívoros/omnívoros que en especies carnívoras.

Palabras clave: *Acuicultura, interacciones microbianas del huésped, microbioma, microbiota gastrointestinal, probióticos.*

Resumo

Antecedentes: A microbiota associada aos peixes desempenha papéis cruciais na manutenção da saúde e no aumento da produtividade. No entanto, em comparação com a microbiota dos mamíferos, a composição e as funções da microbiota de peixes ainda são menos compreendidas. **Objetivo:** Este estudo teve como objetivo analisar o papel da microbiota intestinal na saúde e no desempenho produtivo de espécies de peixes de importância econômica na Colômbia e na Hungria, identificando semelhanças e diferenças que permitam propor estratégias probióticas adaptadas às condições aquícolas de ambos os países. **Métodos:** Foi realizada uma análise abrangente da literatura científica para fornecer insights sobre diversas interações probióticas e espécies de peixes economicamente importantes entre a Colômbia e a Hungria. **Resultados:** o melhor desempenho do crescimento refletido em maiores taxas de crescimento específico, maior ganho de peso e melhores taxas de conversão alimentar está intimamente ligada à modulação da microbiota. Esses benefícios no crescimento são acompanhados por respostas imunológicas elevadas, incluindo aumento da atividade da lisozima, regulação positiva da expressão de componentes do complemento e citocinas (por exemplo, IL-1β, TNF-α) e maior atividade de enzimas antioxidantes (por exemplo, superóxido dismutase [SOD], catalase [CAT]). Vários ensaios também relatam melhorias na atividade de enzimas digestivas (amilase, protease, lipase) e na morfologia intestinal. Além disso, as mudanças na composição da microbiota intestinal caracterizadas por uma maior abundância de bactérias benéficas (por exemplo, bactérias ácido-láticas) e uma redução nas populações patogénicas estão correlacionadas com a regulação positiva de vias metabólicas envolvidas na utilização de carboidratos e nas defesas antioxidantes. **Conclusões:** A suplementação de probióticos melhorou o crescimento, a eficiência alimentar e as respostas imunes em todas as espécies estudadas, com os maiores benefícios observados em tilápia e carpa. De forma geral, os probióticos representam uma estratégia eficaz na aquicultura, embora sua eficácia dependa da espécie, sendo maior em peixes herbívoros/omnívoros do que em espécies carnívoras.

Palavras-chave: Aquicultura, interações microbianas do hospedeiro, microbioma, microbiota gastrointestinal, probióticos.

Introduction

The microbiota synergism is crucial in the animal´s overall health and production. Compared to mammals, the composition and function of fish microbiota are less understood, and studies on host-specific beneficial strains remain limited. Among fish species, the predominant phylum is *Proteobacteria,* followed by *Fusobacterium* (1). Evidence has demonstrated the impact of the microbiome on the growth parameters and physiological functions of fish (2). There is a significant microbial variation among fish-environment-microbiota interactions. However, there is still a lack of knowledge regarding the practice-driven modulation of the microbiota by probiotics and prebiotics in economically important fish species.

Intrinsic and extrinsic factors can influence the microbiota of fish. Moreover, the lack of interaction between fish and the environment can decrease the variety of bacteria in the gut. A reduced microbiota diversity can increase the susceptibility to infections (3); hence, it is fundamental to support beneficial microorganisms in the fish gut by adequate management practices.

Hungarian hybrid catfish production is the most important in Europe, as well as the production of common carp. On the other hand, Colombia stands out for its production of tilapia and trout. According to the FAO (4). Colombia's annual fish production is estimated to be approximately 200,000 tons. Hungary produces approximately 22,000 tons of freshwater fish per year. Despite being 12 times smaller in land area, Hungary achieves a higher fish yield per square kilometer (0.237 tons/km^2) than does Colombia (0.175 tons/km^2), largely driven by Hungary's advanced fishpond strategies, and a strong focus on nutrition, and the use of probiotics and prebiotics. These achievements provide a valuable example for Colombia, which could enhance its fish production by adopting similar practices in the country's most economically important fish species. Additionally, introducing new, highly profitable species such as African catfish and carp could further improve the industry. Such advancements could be supported by Colombia's favorable climatic and edaphic conditions, alongside the adoption of improved production techniques. Therefore, this review aimed to analyze the role of microbiota, probiotics in fish health and production, with a particular focus on insights that could be applied to Colombian aquaculture to improve productivity and economic sustainability.

Materials and methods

Search strategy

Studies were retrieved from the PubMed, SciELO, Redalyc, and Google Scholar databases by using the fish microbiome/microbiota AND/OR effect AND/OR Benefit AND/OR Colombia AND/OR Hungary AND/OR Probiotics AND/OR Profitability AND/OR Diet components AND/OR environmental factors AND/OR Aquaculture AND/OR Diseases AND/OR Immunity. Studies were selected for both countries in Spanish or English.

Data extraction and categorization

The PRISMA protocol was followed to select the dataset. Studies were screened based on the following criteria: articles that focus on *Oreochromis spp*., *Oncorhynchus mykiss*, *Clarias gariepinus*, and *Cyprinus carpio* fish species were included. As well, articles that described within the results, sample size, and experimental duration. Probiotic interventions were assessed by strain, concentration (CFU/g, CFU/ml, or CFU/kg), dosage, and supplementation period. The extracted outcomes included growth performance (specific growth rate [SGR] and feed conversion ratio [FCR]) and immune/physiological responses (lysozyme activity, hematological indices, and gene expression).

Data analysis and selection criteria

The synthesized data revealed patterns in the effects of probiotics on growth, immunity, and disease resistance. Studies with similar methodologies were compared to assess the consistency of the results.

Limitations and ethical considerations

Variability in probiotic strains, dosages, and experimental conditions might affect comparability. Additionally, incomplete immunological and physiological data in some studies could bias definitive conclusions. This study adhered to the provisions of Law 8430 of 1993, which established scientific, technical, and administrative standards for health research.

Results

A total of 795 studies were found related to the topic, and only articles published between 2009 and 2025 were selected through database searching. No duplicates were found, and 547 articles were excluded because they did not have data pertinent to this review scope. A total of 248 articles were assessed for eligibility, and 69 articles were selected to be included in this review. The articles containing relevant information related to the probiotic use in the species selected were classified according to their scientific relevance (Figure 1). This structured approach enabled the effective comparison of probiotic effects across species.

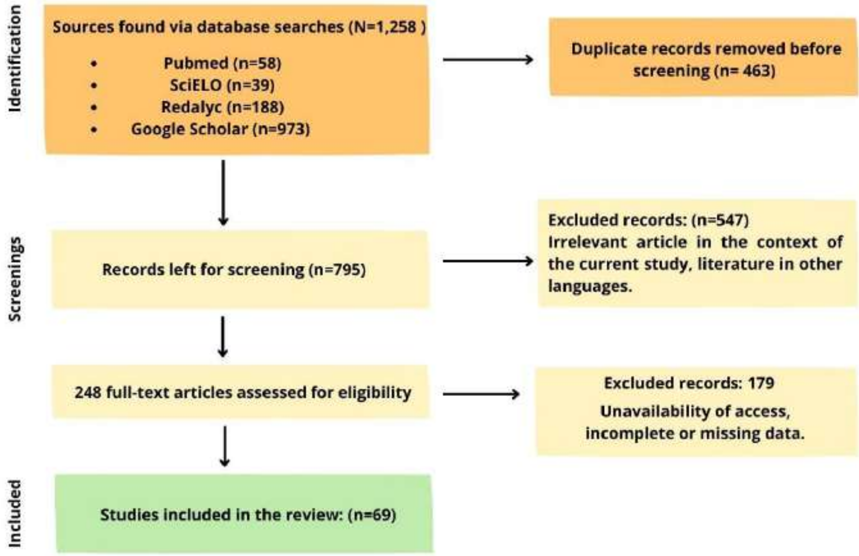

Figure 1. Flow diagram illustrating the systematic selection process of studies according to PRISMA guidelines. The chart outlines the number of records identified, screened, assessed for eligibility, and ultimately included in the final synthesis, with reasons for exclusion clearly indicated at each stage.

1. Factors influencing the fish microbiota

Fish have transient and permanent microbiota (5). This microbiota differs in its origin: freshwater or seawater. Additionally, it has unique adaptive, immunological, and detoxification mechanisms. The transient microbiota is acquired by fish through ingestion and environmental interactions (e.g., osmotic stress) and is present in the gut for a short period of time (6). The permanent microbiota inhabits the entire life of the fish; for example, Atlantic salmon contain approximately $1x10^{8}$1x10 aerobic bacteria, and approximately $1x10^{5}$ anaerobic bacteria that live permanently in the intestinal tract (6).

Fish harbor both internal (gut) and external (skin, gills, mouth) microbiota, which play essential roles in digestion, immunity, and development (7). Common gut bacteria include *Vibrio*, *Aeromonas*, *Pseudomonas*, *Clostridium*, and *Cetobacterium*, whereas the external microbiota includes *Proteobacteria*, *Firmicutes*, *Fusobacteria*, and *Bacillus* (8,9). These microbes have different functionalities related to mucin secretion, immune regulation, and antimicrobial compound production (10). As shown in Figure 2, many of these microorganisms exhibit probiotic and health-promoting properties and are commercially used to enhance fish nutrition and health. Moreover, age, diet, and environmental factors can influence the development and proliferation of these bacteria in fish. Some bacteria are commonly found across species, like *Cetobacterium* (11). Among all the factors influencing aquaculture, fish feeding emerges as a crucial determinant of microbial communities. The quality of feed can have a significant impact on these communities. For instance, fishmeal is known to promote the growth of *Firmicutes*, while insect meal encourages the proliferation of chitin-degrading bacteria, and fish oil reduces the abundance of *Pseudomonas* (2).

Environmental factors such as water quality, sediment composition, and temperature also play a significant role in shaping the fish gut microbiota (Figure 2). This is evident in Benthic species like *Oreochromis mossambicus, which* harbor gut microbial communities that mirror those in the surrounding sediments. Higher temperatures also increase the proliferation of *Mycoplasma* and *Firmicutes* in rainbow trout (*Oncorhynchus mykiss*) (2).

Water quality is a critical factor in maintaining a healthy fish gut microbiota, as up to 83% of a fish's gut microbiota originates from the surrounding water (12). It's crucial to note that water pollution can lead to a reduction in microbial diversity and an increase in the spread of antibiotic-resistance genes (13-15). Even changes in salinity and temperature can have a rapid effect on the gut microbiota populations. For instance, in salmonids, changes in water salinity can alter the microbial composition, resulting in a decrease in Actinobacteria and Proteobacteria, and an increase in *Firmicutes* and *Clostridia*. The different intrinsic (fish immune status, diet, species, age, and gut microbiota) and extrinsic factors (depth, geographical location, physicochemical factors, salinity, contaminants, antibiotic residues, and external/environmental microbiota) that influence fish microbiota are shown in Figure 2.
Despite the implementation of strict biosecurity measures in modern aquaculture, the risk of disease outbreaks remains a concern—disease prevention mainly through increasing stress tolerance and reinforcing the immune system to protect the fish from disease. Biosecurity measures and probiotic supplementation have been the most effective, especially for *Lactobacillus* and *Bacillus* strains. Probiotics provide several advantages to fish farming in aquaculture systems, such as enhancement of fish immunity, nutrient absorption, and improved growth performance (16,17).

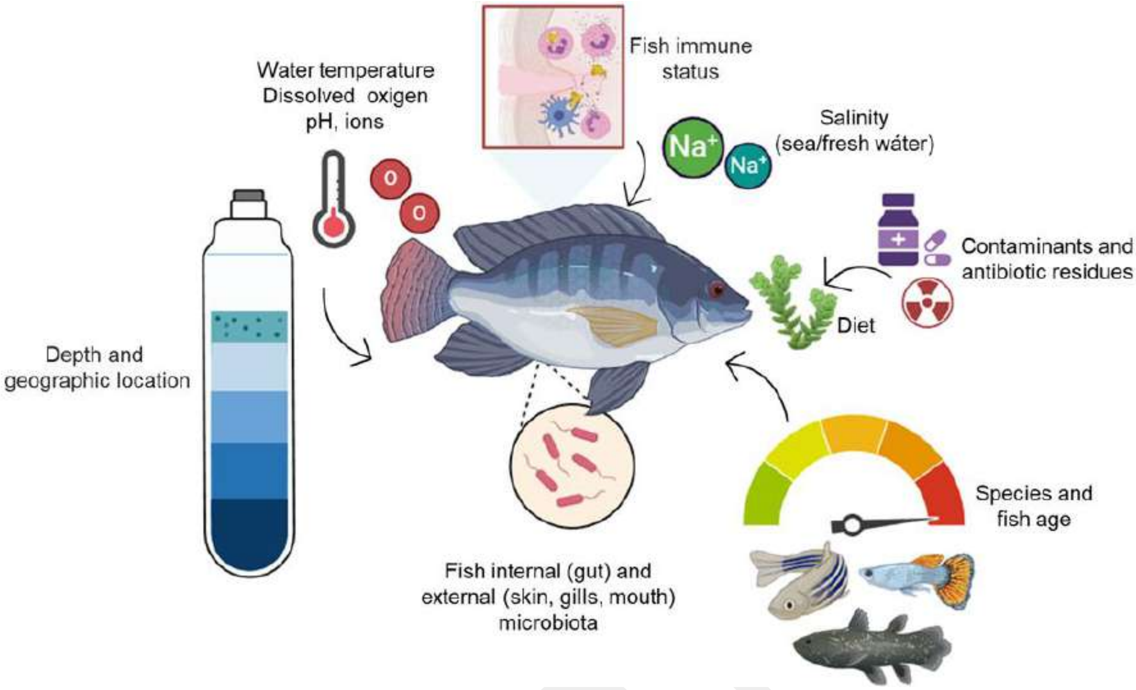

Figure 2. Environmental, host-specific, and dietary factors influencing the composition of fish external and internal microbiota. Both intrinsic and extrinsic factors modify the fish microbiota. Key intrinsic factors include fish species, age, and immune status (e.g., stress, parasite load), while extrinsic factors include water parameters such as oxygen levels, salinity, and pollutant concentrations.

2. The importance of healthy fish microbiota in Colombian and Hungarian aquaculture

A healthy fish microbiota improves the profits of the fish farming facility. Hence, its dysbiosis can lead to economic investment in veterinary assistance and medicines, and lower fish performance or death. These issues can significantly affect the enterprise's profits and compromise fish welfare. This review focuses on the most common cultivated species in Colombia and Hungary. In Hungary, the primary authority overseeing fish production and related health safety measures is the "National Food Chain Safety Office" (Nébih), which operates under the supervision of the "Chief Veterinary Officer" of Hungary. At the European level, Hungary aligns with regulations set by the European Food Safety Authority (EFSA). The Instituto Colombiano Agropecuario (ICA) is the most crucial official entity responsible for regulating agricultural and fishery production, as is the National Authority for Aquiculture and

Fishing (Acronym in Spanish AUNAP), which governs aquaculture and fishing activities in the country. These entities regulate all the legislations and regulations related to fish health, welfare and trading, and the use of probiotics is advised for fish farmers' farming operations in Colombia and Hungary.

Fish production in Colombia

Tilapia and rainbow trout are the most crucial fish production species in Colombia. These two species comprise 71.5% of fish production, and approximately 71,500 tons annually (4). In Colombia, *Oreochromis niloticus*, commonly known as Nile tilapia, contributes approximately 40% of the market share (4). The rainbow trout (*Oncorhynchus mykiss*) ranks second, representing 15.5% of the total production.

The predominant gut microbiota of Nile tilapia (*Oreochromis niloticus*) includes *Proteobacteria, Firmicutes*, *Cyanobacteria*, *Fusobacteriota*, and *Actinobacteria* (18,19). In June 2023, the Colombian Federation of Aquaculture raised an alarm regarding the presence of the *Streptococcus agalactiae* ST7 serotype in tilapia farms across Colombia. This situation resulted in significant fish mortality rates: 47% in Atlántico, 37% in Magdalena, 12% in Huila, and 10% in Tolima, affecting breeding, fingerling, raising, and fattening stages. The colonization and spread of the disease are attributed to overpopulation, high concentrations of ammonium, reduced oxygen levels, increased pH, and increased water temperature (20). To treat the outbreak in the country, fish farmers misused oxytetracycline and erythromycin antibiotics, which later made tilapia production more prone to future infections and antibiotic-resistant strains (21).

On the other hand, trout have a microbiota comprising mainly *Proteobacteria*, *Firmicutes*, and *Actinobacteria,* which dominate the intestinal microbiota of trout species (22). Despite changes in food and rearing density, rainbow trout have a sizable core gut microbiota that is essentially constant (23). Nonetheless, inside the gut, several bacterial communities exhibit geographic specialization (22). The microbiota composition appears to be influenced by host genetics; distinct bacterial groups are strongly related to trout families and may vary depending on the trout family (24). This research offers an optimistic outlook for the future of fish health, with probiotics showing potential to enhance fish health, as detailed in Table 1.

Table 1. Probiotic use advantages promote health in Nile tilapia (*Oreochormis niloticus*) and rainbow trout (*Oncorhynchus mykiss)*.

Study	Fish specie	Probiotic type or additive	Duration	Sample size	Specific growth rate (SGR)	Feed Conversion Ratio (FCR)	Immune parameters	Optimal dosage
Bahrami et al. (2023) (25)	*Oreochromis niloticus*	*Lactobacillus plantarum*	60 days	480	Significantly improved SGR: 3.12 ± 0.18%	Significantly reduced in probiotic group: 1.23 ± 0.20	Increased lysozyme activity, complement activities, respiratory burst, serum bactericidal activity	10^8 CFU g^{-1}
Jules-Bocamdé et al. (2020)(26)	*Oreochromis niloticus*	*Lactobacillus plantarum*	60 days	60	Significantly improved SGR: 0.33 ± 0.10%	Significantly reduced in probiotic group: 2.73 ± 0.2	Significantly improved innate immunity parameters	$1x10^8$ CFU
Dowidar et al. (2018)(27)	*Oreochromis niloticus*	Multi strain probiotic *Bacillus subtitlis, Saccharomyces cerevisiae*	8 weeks	240	Significantly higher SGR in probiotic groups: Multi strain probiotic:1.30± 0.18% *Bacillus subtitlis*: 1.29± 0.05% *Saccharomyces cerevisiae*: 1.21± 0.1%	Significantly reduced in probiotic groups: Multi strain probiotic (2.04± 0.02) *Bacillus subtitlis* (2.06± 0.08) *Saccharomyces cerevisiae* (2.19± 0.02)	Increased lysozyme activity, respiratory burst activity, upregulation of IL-1 and TNF	Multi strain probiotic: $6x10^7$ CFU *Bacillus subtitlis:* $1x10^{11}$ CFU *Saccharomyces cerevisiae*: 2.6 $x10^{10}$
Hossain et al. (2022)(28)	*Oreochromis niloticus*	*Multispecies (Bacillus* spp. *and Lactobacillus* spp.*)*	8 weeks	180	Significant improvements in addition of: 0.5 ml/L: 1.72 ± 0.13% 1 ml/L: 1.80± 0.19%	Significantly reduced in probiotic groups: 0.5 ml/L: 1.02 ± 0.22% 1 ml/L: 0.91± 0.26%	Not mention found	*Bacillus spp: $1x10^9$ CFU* *Lactobacillus* spp.*: $1X10^{11}$ CFU*

Midhun et al. (2022)(29)	*Oreochromis niloticus*	*Paenibacillus polymyxa HGA4C and Bacillus licheniformis HGA8B*	*60 days*	72	Significanly improved SGR: *Paenibacillus polymyxa HGA4C:* 1.43± 0.21% *Bacillus licheniformis HGA8B:* 1.56± 0.17%	Significantly reduced in probiotic groups: *Paenibacillus polymyxa HGA4C:* 0.11± 0.01 *Bacillus licheniformis HGA8B:* 0.10± 0.01	Upregulation of TLR-2, IL-10, TNF- , MUC 2	*Paenibacillus polymyxa HGA4C: 1x10*^{6} CFUg^{-1} *Bacillus licheniformis HGA8B: 1x10*^{8} CFUg^{-1}
Kuebutornye et al. (2020)(30)	*Oreochromis niloticus*	*B. velezensis TPS3N, B. subtilis TPS4, B. amylolique-faciens TPS1*	4 weeks	900	Significantly increased in probiotic groups: *B. velezensis TPS3N:* 1.70± 0.06% *B.subtilis TPS4:* 1.79± 0.09% *B. amylolique-faciens TPS1:* 1.65± 0.05%	Significantly reduced in probiotic groups: *B. velezensis TPS3N:* 1.11± 0.04 *B.subtilis TPS4:* 1.03± 0.02 *B. amylolique-faciens TPS1:* 1.14± 0.05	Increased NO, IgM, LZM, ACP, AKP, SOD, CAT; upregulation of TNF- , TLR-2, C-LYZ	*B. velezensis TPS3N:* 1x10^{8} CFU/mL *B.subtilis TPS4:* 1x10^{8} CFU/mL *B. amylolique-faciens TPS1:* 1x10^{8} CFU/mL
Li et al. (2019)(31)	*Oreochromis niloticus*	*Clostridium butyricum*	56 days	250	Significantly improved SGR at 1 x 10^{5} CFU g^{-1}	No significant differences found	Increased serum antioxidant capacity, C3, C4; upregulation of TNF- , IL-8, MyD88, TLR2	1x10^{4} , 1x10^{5}, 1x10^{6}, 1x10^{7} CFU g^{-1}
Li et al. (2022)(32)	*Oreochromis niloticus*	*Lactobacillus reuteri*	8 weeks	420	Significantly improved SGR at 10^{10} *L. reuteri* CFU/kg: 3.92 ± 0.04%. 10^{11} *L. reuteri* CFU/kg: 3.91 ± 0.02%	No significant differences found	Upregulation of Hif1 , ZO-1k, and occluding were upregulated with increasing dietary inclusion of *L. reuteri*	10^{11} CFU/kg

Noshair et al. (2023)(33)	*Oreochromis niloticus*	*Lactobacillus rhamnosus*	3 months	150	Significantly improvement in probiotic groups: *L. rhamnosus* 0.5×10^{10}CFU/kg: 0.38 ± 0.01% 1×10^{10} CFU/kg: 0.39 ± 0.01% 1.5×10^{10} CFU/kg: 0.42 ± 0.01% 2×10^{10} CFU/kg: 0.39 ± 0%	Significantly reduced in probiotic groups: *L. rhamnosus* 0.5×10^{10} CFU/kg: 1.5 ± 0.01 1×10^{10} CFU/kg: 1.4 ± 0.07 1.5×10^{10} CFU/kg: 1.3 ± 0.08 2×10^{10} CFU/kg: 1.4 ± 0.04	Increased leukocyte count, Hb, RBCs, Hct, MCH, MCHC, MCV, PLT, WBC	1.5×10^{10} CFU/kg
Tan et al. (2019)(34)	*Oreochromis niloticus*	*Rummeliibacillus stabekisii*	8 weeks	270	Not mention found	Significantly reduced in probiotic groups: 10^6 CFU/g: 1.11± 0.07 10^6 CFU/g: 1.16 ± 0.04	Increased phagocytic activity, respiratory bursts, SOD, lysozyme activity; upregulation of IL-1 , TNF- , TGF- , HSP70	10^6 CFU/g 10^6 CFU/g
Fan et al. (2021)(35)	*Oncorhynchus mykiss*	*Clostridium butyricum, Bacillus coagulans Astragalus polysaccharides* (APS)	42 days	360	Significantly improvement in probiotic groups: *C. butyricum* + *B. coagulans*: 1.71 ± 0.02% *C. butyricum* + *B. coagulans* + APS: 2.19± 0.07%	Significantly reduced in probiotic groups: *C. butyricum* + *B. coagulans*: 1.31 ± 0.02 *C. butyricum* + *B. coagulans* + APS: 0.92± 0.05	Superoxide dismutase (SOD), total antioxidant capacity (T-AOC), catalase (CAT) activities	*C. butyricum* (10^9 CFU/kg) + *B. coagulans* (10^9 CFU/kg) + APS (100 g/kg)
Merrifield et al. (2010)(36)	*Oncorhynchus mykiss*	*Bacillus subtilis, Bacillus licheniformis,*	10 weeks	240	No significant differences found	Significantly reduced in probiotic groups: *E. faecium: 0.93* ± 0.02	Serum lysozyme activity, leukocyte levels Increased with *Bacillus* probionts	*E. faecium*. Exact *CFU* not mentioned

		Enterococcus faecium				*B. licheniformis* + *B. subtilis* + *E. faecium:* 1.31 ± 0.03	and *Bacillus* + *E. faecium*	
Mohammadian et al. (2019)(37)	*Oncorhynchus mykiss*	*Lactobacillus delbrukei subsp. bulgaricus, Lactobacillus acidophilus, Citrobacter farmeri*	60 days	300	Significantly improvement in probiotic groups: *L. bulgaricus:* 0.42 ± 0.01% *C. farmeri:* 0.42 ± 0.05% *L. acidophilus:* 0.67 ± 0.03%	Significantly reduced in probiotic groups: *L. bulgaricus:* 0.67 ± 0.01 *C. farmeri:* 1.26 ± 0.14 *L. acidophilus:* 0.75 ± 0.03	Serum lysozyme, complement activities, cytokine Significant increases observed expression	*L. bulgaricus*: 5 x 10^7 CFU/g^{-1}
Wang et al. (2024)(38)	*Oncorhynchus mykiss*	*Clostridium butyricum* at varying levels (0, 1.6 × 10^6, 1.2 × 10^7, 1.1 × 10^8, and 1.3 × 10^9 CFU/g^{-1})	12 weeks	300	Significantly improvement in the probiotic concentration of 1.1 × 10^8 CFU/g^{-1}: 1.61 ± 0.03%	Significantly reduced at the concentration of 1.1 × 108 CFU/g: 1.08 ± 0.02	Serum lysozyme, immunoglobulin M, immune-related gene expression Significant elevation in the concentration of 1.1 × 10^8 CFU/g^{-1}	1.1 × 10^8 CFU/g^1

Abbreviations: SGR: Specific growth rate; FCR: Feed conversion ratio

Fish production in Hungary

In Hungary, the most important fish species produced is common carp, with a market size of 11037 tons/year (39), and the total carp production is approximately 16000 tons. In addition to common carp, three other species are produced (silver carp; *Hypophthalmichthys molitrix*, bighead carp; *Hypophthalmichthys nobilis*, grass carp; and *Ctenopharyngodon idella*) (4). Moreover, Hungary leads the European Union in the production of the hybrid *Clarias gariepinus* × *Heterobranchus longifilis.* Annually, 5303 tons/year are produced, as reported by AKI (2024). To develop a hybrid, one female *Clarias gariepinus* catfish and one male *Heterobranchus longifilis* catfish are bred. This hybrid achieves the required weight of 1.5--2 kg in only 8 months, hence becoming highly efficient for market demand. These hybrids are often reared in geothermal or thermal water bodies, where warm water accelerates growth and feed conversion efficiency. Owing to their fast growth and efficient feed conversion, these hybrids have become very popular. In addition, the culture of hybrid catfish is a promising alternative for Colombia because of its warm climate, which allows the development of intensive aquaculture and enhances its viability even more.

The microbiota of African catfish is highly influenced by age and diet. The fingerling gut is dominated by *Pseudomonas* and *Cetobacterium somerae*, whereas adults show increased diversity and prevalence of *Streptococcus* and *Propionibacterium acnes*. Despite the dietary preferences of carp sp. *Proteobacteria*, *Firmicutes*, and *Bacteroidetes* are dominant across the carp species cultivated in Hungary (40). In large head carp and common carp, *Cetobacterium* is dominant (41). However, supplementation of grass carp with fava beans may increase microbial diversity (42). In common carp, pathogenic bacteria can appear in the presence of tapeworm (*Khawia japonensis*) infection and an abundance of *Cetobacterium* and *Vibrio* (41). The prevention of disease is key in Hungarian aquaculture. Research on prebiotic and probiotic supplementation in common carp has been conducted in Hungary. Carotenoid and anthocyanin extracts from discarded seeds were supplemented. A greater number of *Clostridium* and *Lactobacillus* species decrease the populations of *Shewanella*, *Pseudomonas*, *Acinetobacter*, and *Aeromonas,* which are potentially harmful or pathogenic (43). In a different study in common carp, 840 fish were supplemented with probiotics (*Bifidobacterium*, *Bacillus*, *and Lactobacillus*) and humic acid (Ca, Mg, P, Fe, Mn, Cu, Mo, Co, and Se) for 11 weeks, and a high-fat and high-protein diet was used. SGR was significantly reduced in the groups supplemented with the humic acid and probiotic mixture of *Bifidobacterium* sp. and *Bacillus* sp. *Lactobacillus* sp. at concentrations of 0.50%, 1% and 2%. At the end of the experiment, the final body weight of the fish supplemented with probiotics was significantly greater, with the best final weight reached at the inclusion of 1% probiotics (9.64 g) (44). Understanding the correct use of probiotics can optimize fish growth, improve health outcomes, and support sustainable aquaculture practices (Table 2).

Table 2. Advantages of probiotic use to promote health in African catfish (*Clarias gariepinus*) and common carp (*Cyprinus carpio)*.

Study	Fish specie	Probiotic type or additive	Duration	Sample size	Specific growth rate (SGR)	Feed Conversion Ratio (FCR)	Immune parameters	Optimal dosage
Al-Dohail et al. (2009)(45)	*Clarias gariepinus*	*Lactobacillus acidophilus*	12 weeks	600	Significantly improvement in probiotic group: 4.17 ± 0.05%	Significantly reduced in the probiotic group: 1.13 ± 0.07	Immunoglobulin (mg mL−1) count significant different to control with 9.50 ± 0.14	3.01 x 10^7 CFU/g^{-1}
Lawal et al. (2019)(46)	*Clarias gariepinus*	*Bacillus subtilis*	8 weeks	150	Significantly increased in the probiotic groups: *B. subtilis* 10^9 UFC/ml: 1.58±0.07%	Significantly reduced in the probiotic groups: *B. subtilis* 10^9 UFC/ml: 1.17±0.04	No significant difference in White Blood Cells (WBC), Lymphocytes (LYM), Monocytes (MONO)	10^9 CFU/ml
Opasola and Fawole, (2013)(47)	*Clarias gariepinus*	*Lactobacillus acidophilus*	90 days	300	1.92%	0.09	Not mention found	1.5 ml per diet
Putra et al. (2020)(48)	*Clarias gariepinus*	*Bacillus* NP5	45 days	180	Significantly increased in the probiotic group: 2.55±0.28%	Significantly reduced in *Bacillus* NP5 of 1 x 10^9 CFU/mL: 1.22 ±0.23	Increased leukocyte count, phagocytic index	1.2%

Reda et al. (2018)(49)	*Clarias gariepinus*	*B. subtilis, B. amyloliquefaciens, B. cereus*	30 days 60 days	300	Significant differences with the supplementation of *B. subtilis*, B. *amyloliquefaciens and B. cereus* improved SGR after 30 and 60 days (no specific values)	Significantly reduced with *Bacillus sp especially with B. cereus* (no specific values)	Increased lysozyme activity, nitric oxide, Immunoglobulin M (IgM)	1×10^{10} CFU/kg
Umaru and Agbugui, (2022)(50)	*Clarias gariepinus*	*Saccharomyces cerevisiae*	3 months	150	Significantly increased in the probiotic groups: *S. cerevisiae* at 4.125 x 10^6 UFC/ml: 1.5 ml: 1.57 ± 0.01% 2 ml: 1.57 ± 0.01%	Significantly reduced in the probiotic group: 2 ml: 1.34 ± 0.01	Not mention found	2 ml per 80 L
Ahmadifar et al. (2020)(51)	*Cyprinus carpio*	*Pediococcus pentosaceus*	45 days	Randomly selected 132 fish	Significantly increased in the probiotic group: 10^8 CFU g−1: 0.493 ± 0.168%	Not mention found	Red blood cells (RBCs), white blood cells (WBCs), hemoglobin (Hb), hematocrit (HCT) increased; Lysozyme, antibody, complement activities enhanced	10^8 CFU g^{-1}

Alishahi et al. (2018) (52)	*Cyprinus carpio*	*Lactobacillus plantarum, Lactobacillus bulgaricus*	75 days	480	No significant differences found, highest SGR: *L. bulgaricum*: 0.12 ± 0.01%	No significant differences found, lowest FCR ratio: *L. bulgaricum*: 2.75 ± 0.37	Not mention found	$5x10^{7}$ CFU g^{-1}
Pandey et al. (2022)(53)	*Cyprinus carpio*	*Lactobacillus plantarum*	120 days	Not mention found	Significantly increased in the probiotic group of 10^{9} CFU/g^{-1}: 1.09%	Significantly decreased in the probiotic group of 10^{9} CFU/g^{-1}: 1.97	Hemoglobin (Hb), total erythrocyte count (TEC), total leukocyte count (TLC), packed cell volume (PCV), mean corpuscular hemoglobin (MCH), mean corpuscular hemoglobin concentration (MCHC) improved; Total serum protein and globulin increased	10^{9} CFU/g^{-1}
Gupta et al. (2014)(54)	*Cyprinus carpio*	*Bacillus coagulans, Bacillus licheniformis, Paenibacillus polymyxa*	80 days	240	Significantly increased in the probiotic group of *P. polymyxa* 10^{9} CFU/g^{-1}: 0.76 ± 0.31%	Significantly decreased in the probiotic groups 10^{9} CFU/g^{-1}: *B. coagulans:* 5.16 ± 1.13 *B. licheniformis:* 5.13 ± 1.17 *P. polymyxa:* 4.26 ± 0.98	Lysozyme, respiratory burst, myeloperoxidase increased	*P. polymyxa* 10^{9} CFU/g^{-}

Nejad and Yazdkhasti, (2023)(55)	*Cyprinus carpio*	*Lactobacillus plantarum, Lactobacillus bulgaricus, Lactobacillus acidophilus, Lactobacillus rhamnosus*	180 days	Significantly increased in the probiotic combination group 5×10^8 CFU g^{-1}: 3.94± 0.15%	Significantly decreased in the probiotic combination group 5×10^8 CFU g^{-1}: 1.73 ± 0.27	Complement, lysozyme, serum bactericidal activity increased	5×10^8 CFU g^{-1}

Abbreviations: SGR: Specific growth rate; FCR: Feed conversion ratio.

Discussion

The aquaculture practices in Hungary and Colombia are similar in that both regions have successfully utilized probiotics to enhance fish health, growth, and immune responses, despite differing environmental and operational conditions. These practices have contributed to improved water quality and fish performance, with probiotics helping to modulate gut health and microbiota across various species. This similarity is significant in the context of reducing antibiotic use because probiotics offer an environmentally friendly alternative that not only supports fish welfare and productivity but also helps decrease reliance on antibiotics (56). By improving water quality and health through probiotic application, both regions can mitigate issues related to antimicrobial resistance and environmental contamination, promoting more sustainable aquaculture practices (57).

The inclusion of probiotics showed differences in specific growth rate (SGR), feed conversion ratio (FCR), and immune responses among fish species. In *Oreochromis niloticus* (tilapia), the SGR ranged from ~0.33% to 3.92% (32). Moreover, most studies reported significant reductions in FCR with probiotics, indicating improved feed efficiency. Regarding immune parameters, strong enhancements were found in lysozyme activity, complement activity, and respiratory burst. The highest SGR (3.9%) was achieved with a concentration of $1x10^8$ CFU/mL of *Lactobacillus reuteri* (32). The best FCR was achieved with the inclusion of *Bacillus subtilis* TPS, with a reduction to 1.03 (30,32). The optimal inclusion period for probiotics was reported between four to eight weeks. Probiotic supplementation was shown to be highly effective in improving both growth and immunity, often simultaneously. Multi-strain and *Lactobacillus*-based probiotics were most frequently used.

In *Oncorhynchus mykiss* (rainbow trout), probiotics showed lower improvements, and some studies reported no significant effects on SGR, which ranged from 0.39% to 2.19% (33,35). The best result was obtained with a probiotic mix of *Clostridium butyricum*, *Bacillus coagulans*, and Astragalus polysaccharides (APS) after 42 days of supplementation at concentrations of *C. butyricum* (10^9 CFU/kg), *B. coagulans* (10^9 CFU/kg), and APS (100 g/kg) (35). Most studies reported significant reductions in FCR with probiotics, ranging from 0.67 to 1.16 (52, 34). However, improvements in SGR were lower compared to *O. niloticus*. Immune responses, including lysozyme activity, complement, antioxidant enzymes (SOD, CAT, T-AOC), and immune gene expression, were improved.

In *Clarias gariepinus* (African catfish), most studies reported significant increases in growth and feed conversion. The best SGR outcome (4.17%) was achieved with the inclusion of *Lactobacillus acidophilus* at a dosage of 3.01×10^7 CFU/g for 12 weeks (45). FCR ranged from 1.17 to 1.34, with reductions reported in all trials analyzed (46,50). Improvements in immune parameters, including IgM, lysozyme, phagocytic index, and leukocyte counts, were reported, though not all studies included immune data. Catfish responded well to probiotics in terms of both growth and feed efficiency, with immune benefits observed but less consistently reported than in tilapia.

In a 180-day trial with *Cyprinus carpio* (common carp), the SGR was 3.94% and significantly increased in the probiotic combination group (*Lactobacillus plantarum, L. bulgaricus, L. acidophilus, L. rhamnosus*) at 5×10^8 CFU/g (55). *C. carpio* also showed the highest FCR among species, with a value of 5.16 after an 80-day trial using *Bacillus coagulans* (10^9 CFU/g). The lowest FCR (1.34) was reported by Umaru et al. (50), with supplementation of 2 ml per 80 L of *Saccharomyces cerevisiae*. Furthermore, improvements in blood parameters (RBCs, Hb, HCT, TEC, PCV, MCH, MCHC) were observed, indicating a healthier circulatory system that supports better metabolism, growth, and resilience to stress. Immune markers such as lysozyme, complement, antibodies, respiratory burst, myeloperoxidase, and serum bactericidal activity were also enhanced, showing significant improvements in overall health and feed efficiency.

All four fish species analyzed showed improvements in SGR and FCR with probiotic supplementation. *O. niloticus* and *C. carpio* exhibited the highest values for both parameters. These results can be explained by several factors: (a) Digestive tract system**:** Omnivorous/herbivorous species such as *O. niloticus* and *C. carpio* have a larger intestine compared to carnivorous species like *O. mykiss* and *C. gariepinus*. This larger intestinal proportion allows easier colonization by probiotics and greater carbohydrate fermentation, resulting in prolonged effects (58). (b) Native microbiota**:** Species such as *O. niloticus* and *C. carpio* host higher proportions of *Lactobacillus*, *Bacillus*, and *Enterococcus*, enabling synergy with supplemented probiotics (52,59) (c) Metabolism and nutritional requirements**:** *O. mykiss* and *C. gariepinus* have diets primarily based on protein and fats, which limit the production of probiotic metabolites such as volatile fatty acids, enzymes, and vitamins (60). (d) Environmental conditions**:** The resilience of *O. niloticus* and *C. carpio* to a wider range of temperatures, pH, and oxygen levels enhances probiotic colonization and adaptation (61). (e)

Immune response**:** *O. niloticus* and *C. carpio* have a highly active innate immune system, making them more responsive to probiotic stimulation (62,63).

Future perspectives

The use of probiotics to increase feed efficiency, health, and overall welfare of fish is key to sustainable fish farming practices. In this review, the use of probiotics from the families *Lactobacillaceae, Bacillaceae, Clostridiaceae, and Enterococcaceae* is highlighted as promising for enhancing fish growth, feed efficiency, and immune response. Hence, it is important to further investigate potential probiotic concentrations in longer trials, as these appear to yield greater improvements in productive parameters. It is also advised to incorporate artificial intelligence (AI) to aid in the selection, formulation, and administration of probiotic strains to fish (64,65). Additionally, predictive modeling contributes to the dynamic adjustment of probiotic supplementation based on environmental parameters such as water quality, temperature, and pathogen presence (66). By integrating optimized probiotic dosages with artificial intelligence, traditional fish farming practices can be improved toward more sustainable and environmentally responsible aquaculture (67,68). This approach can also enhance the economic output of Colombian and Hungarian aquaculture in both national and international markets, while reinforcing the long-term sustainability of fish farming.

Conclusions

The aquaculture practices in Hungary and Colombia, despite their geographical and species differences, exhibit notable similarities, especially in the way they successfully incorporate probiotic supplementation to promote fish health, enhance growth, and improve immune function across various cultured species, such as common carp in Hungary and tilapia, catfish, and native fish like bocachico in Colombia. The probiotic supplementation improved specific growth rate (SGR)**,** feed conversion ratio (FCR**)**, and immune responses across all four species studied (tilapia, rainbow trout, African catfish, and common carp) in both countries. The species *Oreochromis niloticus* (Tilapia) and *Cyprinus carpio* (Common carp) showed the highest improvements in SGR and FCR. *Oncorhynchus mykiss* (Rainbow trout) showed lower and sometimes inconsistent improvements**,** particularly in growth. *Clarias gariepinus (*African catfish) responded well in terms of growth and FCR**.** Across species, probiotics stimulated lysozyme activity, complement, antibodies, phagocytosis, antioxidant enzymes, and immune gene expression**,** improving disease resistance and overall health. The best strains were for

Tilapia: *Lactobacillus reuteri* (10^{11} CFU/kg) achieved the highest SGR. Catfish: *Lactobacillus acidophilus* (3.01×10^7 CFU/g) achieved the best SGR (4.17%). Trout: A probiotic mix (*Clostridium butyricum* + *Bacillus coagulans* + Astragalus polysaccharides) gave the best combined immune and growth benefits. Carp: Multi-strain probiotics (*Lactobacillus spp.* mix) reached the best improvements in both growth and FCR. Probiotics are an effective strategy to enhance growth performance, feed efficiency, and immunity in aquaculture. However, their efficacy is species-dependent, being stronger in herbivorous/omnivorous fish (tilapia, carp) than in carnivorous ones (trout, catfish). A healthy microbiota can enhance the immune response and growth parameters and maximize them. Understanding the adequate use of probiotics in fish can increase productive performance and welfare. A comparison of the microbiota of Colombia and Hungary, which are economically important fish species, can aid in adaptation in the aquaculture of different fish species in Colombia and open a market possibility. In addition, understanding tilapia and rainbow trout microbiota and ideal probiotic supplementation can be a tool for increasing aquaculture productivity.

Declarations

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Conflict of interest

The authors declare that they have no conflicts of interest.

Author contributions

NYMC: Conceptualization, methodology, data curation, validation and writing review & editing. MAGM: Data curation, formal analysis and writing original draft. CTT: Data curation, formal analysis, and writing original draft. SMC: Conceptualization, validation, formal analysis, supervision, and writing original draft. NEA: Conceptualization, validation, methodology, supervision, project administration, and writing review & editing. PB: Conceptualization, validation, methodology, supervision, project administration, and writing review & editing.

Use of artificial intelligence (AI)

No AI or AI-assisted technologies were used during the preparation of this work.

Data availability

The data sets used in the current study are available from the corresponding author on request.

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