JMB Journal of Microbiology and Biotechnology

J. Microbiol. Biotechnol. 2022. 32(6): 681–698
https://doi.org/10.4014/jmb.2202.02032

Review

Single and Multi-Strain Probiotics Supplementation in Commercially Prominent Finfish Aquaculture: Review of the Current Knowledge

Md Afsar Ahmed Sumon[1†], Tofael Ahmed Sumon[2†], Md. Ashraf Hussain[3†], Su-Jeong Lee[4], Won Je Jang[4,5], S. M. Sharifuzzaman[6], Christopher L. Brown[7], Eun-Woo Lee[4,8], and Md. Tawheed Hasan[8,9†*]

[1]*Department of Marine Biology, King Abdulaziz University, Jeddah- 21589, Saudi Arabia*
[2]*Department of Fish Health Management, Sylhet Agricultural University, Sylhet-3100, Bangladesh*
[3]*Department of Fisheries Technology and Quality Control, Sylhet Agricultural University, Sylhet-3100, Bangladesh*
[4]*Biopharmaceutical Engineering Major, Division of Applied Bioengineering, Dong-Eui University, Busan 47340, Republic of Korea*
[5]*Department of Biotechnology, Pukyong National University, Busan 48513, Republic of Korea*
[6]*Institute of Marine Sciences, University of Chittagong, Chittagong 4331, Bangladesh*
[7]*FAO World Fisheries University Pilot Programme, Pukyong National University, Busan 48513, Republic of Korea*
[8]*Core-Facility Center for Tissue Regeneration, Dong-Eui University, Busan 47340, Republic of Korea*
[9]*Department of Aquaculture, Sylhet Agricultural University, Sylhet-3100, Bangladesh*

The Nile tilapia *Oreochromis niloticus*, Atlantic salmon *Salmo salar*, rainbow trout *Oncorhynchus mykiss*, olive flounder *Paralichthys olivaceus*, common carp *Cyprinus carpio*, grass carp *Ctenopharyngodon idella* and rohu carp *Labeo rohita* are farmed commercially worldwide. Production of these important finfishes is rapidly expanding, and intensive culture practices can lead to stress in fish, often reducing resistance to infectious diseases. Antibiotics and other drugs are routinely used for the treatment of diseases and sometimes applied preventatively to combat microbial pathogens. This strategy is responsible for the emergence and spread of antimicrobial resistance, mass killing of environmental/beneficial bacteria, and residual effects in humans. As an alternative, the administration of probiotics has gained acceptance for disease control in aquaculture. Probiotics have been found to improve growth, feed utilization, immunological status, disease resistance, and to promote transcriptomic profiles and internal microbial balance of host organisms. The present review discusses the effects of single and multi-strain probiotics on growth, immunity, heamato-biochemical parameters, and disease resistance of the above-mentioned finfishes. The application and outcome of probiotics in the field or open pond system, gaps in existing knowledge, and issues worthy of further research are also highlighted.

Keywords: Probiotics, growth, immunity, immune-related gene, disease resistances

Received: February 21, 2022
Accepted: June 3, 2022

First published online:
June 7, 2022

**Corresponding author*
Phone: +880-821-761952
Fax: + 880-821-761980
E-mail: tawheed7788@yahoo.com

†These authors contributed equally to this work.

pISSN 1017-7825
eISSN 1738-8872

Introduction

Aquaculture, the farming of aquatic organisms under controlled environments, is a diverse food producing activity growing annually by 4.5%, accounting for a value of USD 243.26 billion [1]. Data suggest that fish, macro-algae, molluscs and crustaceans are meeting the protein demand of an increasing global population, contributing 49.1, 27.3, 15.6, and 7.9%, respectively, to total aquaculture production, equalling ~20% of total global animal protein supplies [2]. Aquaculture practices have shifted from extensive to super-intensive to elevate production at the expense of huge amounts of artificial feeds and degradation of aquatic environments. Poor culture management causes immunosuppression, stress and creates suitable conditions for the proliferation of opportunistic microbial pathogens (bacteria, viruses, and parasites) leading to infectious disease outbreaks. Hemorrhage, exophthalmia, meningoencephalitis, anorexia, and disruption of the nervous system are common impacts of infectious diseases responsible for high mortality of in cultured fishes. To control diseases, antibiotics, drugs and vaccines are routinely used in aquaculture [3].

Vaccination is a well-established strategy for long-term disease protection, but it has been associated with

temporary loss of appetite and growth, intra-abdominal lesions and impaired antibody production in fish [4]. On the other hand, excessive use of antibiotics results in the development of antibiotic resistant pathogens [5, 6], immunosuppression in host and reduction or mass killing of normal microbiota in the culture environment and gut [7], including residual effects in human [8]. The magnitude of this problem can be severe; an estimated 1.7 million deaths were attributed to antibiotic resistant bacteria in 2019 [9]. Antibiotic-resistant pathogens have been isolated from fish and humans, and their applications in aquaculture are under strict regulation [2]. To address this concern, one productive line of research has focused on biologically benign approaches such as probiotics, prebiotics, immunostimulants and functional feeds that enhance host immunity to pathogens [10, 11].

The word "probiotics" means "for life" and is based on the Greek word's "pro" and "bios". Probiotics were first defined by Parker [12] as "organisms or substances engagement for the maintenance of the microbial balance in the intestine". These definitions were revised by Merrifield *et al.* [13] for aquatic organisms as, "a probiotic organism can be regarded as a live, dead or component of a microbial cell, which can be administered via feed or into rearing water, benefiting the host by improving growth performance, feed utilization, immune health status, infectious disease resistance, and stress responses which is achieved at least in part via improving the microbial balance in hosts or ambient environment". Probiotic research in the last decades has revealed positive effects on growth [14, 15], digestive enzymes activities and feed utilization [16], immunity with upregulation of immune related genes [17, 18], improvement of beneficial microbes in the gut and positive modification of intestinal structure [19], and disease protection [20, 21], leading to an eco-friendly aquatic environmental management [22] in fish and shellfish farming.

Previous reviews of probiotics in aquaculture have considered sustainability issues [3], carp culture [7], disease control [2], mitigation of challenges in aquaculture [23], uses in Chinese aquaculture [5] and so on. There is not a single review that has comprehensively addressed the effects of probiotics on prominent cultured finfishes (*i.e.*, tilapia *Oreochromis niloticus*, Atlantic salmon *Salmo salar*, rainbow trout *Oncorhynchus mykiss*, olive flounder *Paralichthys olivaceus*, common carp *Cyprinus carpio*, grass carp *Ctenopharyngodon idella* and rohu carp *Labeo rohita*) as relating to growth, haemato-immunological and disease responses. The novelty of the present review is to present up-to-date insights on the use of probiotics in commercially important finfish culture, highlighting their applications in field or open pond system. Probiotics effects on the host transcriptome profiles and aquatic environmental parameters are also discussed.

Probiotics Functionality Linked to Growth, and Cellular and Humoral Immunity

Probiotics not only reduce intestinal pathogens but also detoxify harmful compounds in feed through hydrolytic enzymes and the production of vitamins, biotin, and vitamin B12 [24, 25]. Growth elevation with improved feed utilization can ensure improved yields at lower production costs which are of value to aquaculture. Several authors have characterized responses to probiotics including alterations of digestive enzyme synthesis and release [26] and of intestinal structure to increase nutrient digestion and absorption [27], influencing the final body weight gain and production scale.

In aquaculture, probiotics can be supplemented through feed or water to manipulate the microbial balance in host and culture environment. Different nutrient specific digestive enzymes (*e.g.*, amylase, protease, chitinase and lipase) can be increased by probiotics in the intestine [28], improving digestion and absorption while removing toxicity. Jang *et al.* [29] mentioned that probiotics improved digestive process by enhancing beneficial bacterial population, microbial enzymatic activity, and microbial balance, ultimately improving digestibility and absorption of nutrients toward increased growth rates and diet digestibility. It is unknown whether digestive enzymes are produced directly by probiotics or by modulating synthesis and secretion of enzymes by intestinal cells, or possibly by both mechanisms. However, probiotics reportedly demonstrate in vitro extracellular amylase, cellulase, lipase and protease production and could potentially modulate those enzymatic functions in vivo [30].

Normal light microscopic observation on fish gut histology depicts an intact epithelium barrier, goblet cells, and well organised villi and microvilli. Supplemented probiotics metabolize the carbohydrates (oligosaccharides/prebiotics) of diet for their growth and survival in the intestine. A combined application of probiotics and prebiotics, termed synbiotics, produced significantly higher effects compared to each individual component [11, 31]. Fermentation of prebiotics by probiotics is reported to produce short chain fatty acids, which can be utilized as an energy source by intestinal epithelial cells [32], and cell proliferation ultimately increases goblet cell intensity, villus and micro villus height, width and density [33]. Alteration of these morphometric structures also can be found in intestinal thickness, fold of change, and mucus layer, contributing to the elevation of nutrient absorption. Higher nutrient absorption through increased absorption area in the intestine in response to probiotics supplementation showed positive changes in apparent digestibility coefficient [19] that correlated with fish growth and utilization of diets.

Probiotics mainly upregulate the fish innate immune parameters through antigen presenting dendritic cells (DCs) to maintain the linkage between innate and adaptive immunity [34]. Mucus on body surface, scale, skin, and gills serve as physical or epithelial barriers as a first line of defence in fish innate immune system. The role of probiotics to improve epithelial barrier is not well defined, but immunoglobulins (Ig), antibacterial peptides and complement proteins containing skin mucus lysozyme activity were enhanced after probiotics supplementation [35, 36]. Macrophage and phagocytic cells (natural killer cell, neutrophil, monocyte, lymphocyte, and cytotoxic cells) provide cellular immune defence in fish [37]. Interaction between microbial-associated molecular patterns (MAMPs) and pattern recognition receptors (PRRs) on DCs can stimulate and activate the phagocytic cells or increased production of cytokines [38]. Lactic acid bacteria (LAB), for examples *Bacillus* and bifidobacteria are commonly used gram-positive probiotics, and their cell wall components like peptidoglycans, lipopolysaccharides,

flagella, and microbial nucleic acids are collectively known as MAMPs. MAMPs are attracted by PRRs on DCs and after interaction/binding of MAMPS with PRRs, DCs stimulate and activate phagocytic cells [39] to locate and engulf invading pathogens. Stimulation of plasma cells by DCs produces antibodies which can pass through the enterocyte and neutralize the pathogens [8]. Moreover, binding of MAMPs with Toll-like receptors (TLR) and stimulation of T cells by DCs produce mostly pro-inflammatory cytokines [31]. Among different pro-inflammatory cytokines, tumor necrosis factor (TNF)-α stimulate neutrophil base immunity [40], interleukin (IL)-1β proliferate lymphocyte and macrophage [41], interferon (IFN)-γ stimulate resting macrophages to secrete IL-6 and IL-1β, and multi-functional IL-6 are responsible for B-lymphocyte differentiation and maturation [42] to elevate cellular innate immunity.

Humoral immunity refers to activities of bacteriolytic or haemolytic enzymes like myeloperoxidase or peroxidase, serum/skin mucus lysozyme, serum antiprotease, superoxide dismutase, serum bactericidal activity, alternative complement activity, transferrin and Ig in body or tissue fluids [10, 39, 43], which contribute to the elimination of pathogens. Serum proteomic study after *Bacillus* sp. JB-1 supplementation increased transferrin protein quantity in rainbow trout [44]. In human, oral administration of probiotics interacts with intestinal epithelial cells to enhance the production of macrophage chemoattractant protein-1, to send signals to other immune cells characterised by an increment of IgA^+ cells in the intestine, bronchus, and mammary glands [45]. *Lactobacillus acidophilus* La1 can persist in the gastrointestinal tract and act as an adjuvant to increase serum IgA titre to *Salmonella typhi* Ty21 in human [46]. *Lactococcus lactis* increased the expression of complement receptors and adjuvant potential of *Lactobacillus* GG to elevate the humoral immunity [47]. Lysozyme, defensins, cathelicidins, and phospholipase are antimicrobial peptides secreted by Paneth cells located in the bottom of intestinal crypts [48]. A transmission electron microscopic study depicted *Lactobacillus casei* CRL 431 and *Lactobacillus paracasei* CNCM I-1518 increased Paneth cells activity, apparently increasing the secretion of antimicrobial peptides in intestines [49].

Probiotics Effects on Cultured Finfish

Tilapia

Tilapia alone contributed 10% (5.377 million tonnes) of global aquaculture production in 2016 [1]. Nevertheless, its intensive production is more susceptible to stress-related disease and mass mortalities [50], and probiotics are viewed a promising potential solution [51].

The effects of single probiotic *L. plantarum* and its strains CGFM639, CCFM8661, and CR1T5 on tilapia were studied [52-55] (Table 1). Supplementation with 10^7 to 10^8 CFU g^{-1} of *L. plantarum* resulted in improvement of growth, feed intake and haemato-biochemical characters, similarly to its other strains CGFM639, CCFM8661 and CR1T5. Among these *L. plantarum* and CR1T5 increased protection against infection, and CGFM639 and CCFM8661 reduced aluminium toxicity and lead accumulation in liver, kidney, spleen, gill, and gonad. A combination of *L. plantarum* N11 + *Bacillus velezensis* H3.1 positively modulated tilapia cellular and humoral immunity [36].

Dietary *Clostridium butyricum* improved final body weight and feed digestion at 1.5×10^8 CFU g^{-1} [56], but not at 10^5 CFU g^{-1} [57] and protection against *A. hydrophila* and *S. agalactiae*, respectively. This probiotic decreased serum malondialdehyde and diamine oxidase but upregulated immune genes expression levels. Similar parameters were modulated along with increment of immunity, and digestive enzymes were also induced by *B. subtilis* HAINUP40 [58] and *B. licheniformis* DAHB1 [59]. Protection against *S. agalactiae* and *A. hydrophila* was also reported after feeding with a combination of *B. subtilis* and *B. licheniformis* [60] and various strains of *Bacillus* spp. [61], respectively.

Immunity modulation was also confirmed by *B. cereus* as a water supplement at 10^4 CFU ml^{-1} [62]. Combination of *Bacillus* with *Pediococcus* sp., *Enterococcus* sp. and *Lactobacillus* sp. did not produce any notable enhancement of digestive enzymes or other serum biochemistry parameters [63]. Expression of inflammatory, antimicrobial and T cell response genes after administration of *B. subtilis* ABP1 is an indication of its oral vaccine property [64]. *Paenibacillus ehimensis* NPUST1 [65] and *Aspergillus oryzae* [66] improved growth and immunological competence, but lowered the levels of glucose and cortisol in blood. Similarly, gut probiotic *Rummeliibacillus stabekisii* modulated the aforementioned parameters with enriched gut microbiota and inhibit *A. hydrophila* and *S. iniae* [67]. In addition, supplementation with *Psychrobacter maritimus* S and *P. namhaensis* S089 showed similar modulation except lower HSP70 [16, 68] and *B. amyloliquefaciens* increased fat digestibility [69]. *B. velezensis* TPS3N, *B. subtilis* TPS4 and *B. amyloliquefaciens* TPS17 [70]; *Bacillus* sp. KUAQ1 and KUAQ2 [71] improved tilapia innate immunity. In addition, intestinal lipase activity and morphometric alteration, viz. micro-villus height and width, goblet cells count, and muscle thickness were reported by the former *Bacillus* probiotics. Administration of *B. subtilis* WB60 with *L. lactis* for 8 weeks resulted in better growth, immunity and immune genes expression, villus height, without changing the haematology [72]. Similar modulations were observed after supplementation with *L. plantarum* L-137 [73] and only gene transcription by *L. plantarum* [74]. The *Bacillus* and *Lactobacillus* probiotics specified above conferred elevated protection against different infectious diseases caused by *E. faecalis, A. hydrophila*, and *S. agalactiae*.

Applications of three commercial probiotics, Protexin (multi-strain, 6×10^7 CFU g^{-1}), Biogen-S (*B. subtilis,* 10^{11} CFU g^{-1}) and Diamond V (*Saccharomyces cerevisiae,* 2.6×10^{10} CFU g^{-1}) increased growth and feed utilizations, immunity and immune genes transcription at 4^{th} and 8^{th} week [75]. Moreover, commercial multi-probiotics AquaStar Pond and EM resulted in higher immune gene transcription relative to single commercial preparation, MicroPan [76]. Available studies indicated that the commercial probiotics containing single bacterial species,

Table 1. Effects of probiotics supplementation on growth, feed utilizations, immunological and haemato-biochemical parameters, immune related gene expression and disease resistance in tilapia (*Oreochromis niloticus*).

Probiotics	Mode of administration and dosage	Duration	Effects on *O. niloticus*	References
Lactobacillus plantarum	Dietary supplementation at 10^7 CFU g^{-1}	60 days	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{TAC, RB, \& SL}\uparrow$, and NO & MDA$\downarrow$; HBP $_{Ht, TSP, Alb, Glb, \& Glu}\uparrow$; IDR $_{Aeromonas\ sobria}\uparrow$	[52]
L. plantarum CGFM639	Dietary supplementation at 10^8 CFU g^{-1}	4 weeks	GP $_{WG}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{SOD, GPx, CAT, \& TAC}\uparrow$, and MDA$\downarrow$; HBP $_{RBC \& WBC}\uparrow$, and ALT$\downarrow$; Aluminum toxicity$\downarrow$	[53]
L. plantarum CCFM8661	Dietary supplementation at 10^8 CFU g^{-1}	4 weeks	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{MPO, SL, GPx, \& TAC}\uparrow$, and MDA$\downarrow$; DEA $_{AmA \& PrA}\uparrow$; PbAT $_{Kidney, Liver, Spleen, Gill, Brain, Gonad, \& Muscle}\downarrow$	[54]
L. plantarum CR1T5	Dietary supplementation at 10^8 CFU g^{-1}	2 months	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{SL, ACA, PcA, \& RB}\uparrow$; IDR $_{Streptococcus\ agalactiae}\uparrow$	[55]
L. plantarum N11 & *Bacillus velezensis* H3.1	Dietary supplementation at 10^7 & 10^8 CFU g^{-1}	30 days	GP $_{WG, FBW, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{ACA, PcA, RB, SL, \& SMLA}\uparrow$; IDR $_{S.\ agalactiae}\uparrow$	[36]
Clostridium butyricum	Dietary supplementation at 1.5×10^8 CFU g^{-1}	8 weeks	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{ADC}\uparrow$, and FCR$\downarrow$; IP $_{SOD, SL, \& CAT}\uparrow$; HBP $_{TSP, Ht, Hb, AST, ALT, Lymphocyte, \& Monocyte}\uparrow$; mVH$\uparrow$; SR$\rightarrow$; IDR $_{A.\ hydrophila}\uparrow$	[56]
C. butyricum	Dietary supplementation at 10^4 to 10^7 CFU g^{-1}	56 days	GP $_{FBW \& SGR}\uparrow$; FUP $_{FCR}\rightarrow$; IP $_{TAC}\uparrow$, and MDA & DAO$\downarrow$; IRGE $_{IL-8, TNF-\alpha, MyD88, TLR2, \& IRAK-4}\uparrow$, and IL-10$\rightarrow$; IDR $_{S.\ agalactiae}\uparrow$	[57]
B. subtilis HAINUP40	Dietary supplementation at 10^8 CFU g^{-1}	8 weeks	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{RB, TAC, \& SOD}\uparrow$; DEA $_{PrA \& AmA}\uparrow$; IDR $_{S.\ agalactiae}\uparrow$	[58]
B. licheniformis DAHB1	Dietary supplementation at 10^5 & 10^7 CFU g^{-1}	4 weeks	GP $_{WG \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; HBP $_{TSP \& ALP}\uparrow$; IP $_{SL, RB, MPO, GPx, \& SOD}\uparrow$; IDR $_{A.\ hydrophila}\uparrow$	[59]
B. cereus	Water & dietary supplementation at 10^4 & 10^8 CFU g^{-1}, respectively	42 days	IP $_{SL, MPO, \& SOD}\uparrow$; HBP $_{ALP}\uparrow$; GutM$\uparrow$	[62]
B. subtilis + *B. licheniformis*	Dietary supplementation at 3 to 7 g Kg^{-1} feed	4 weeks	GP $_{WG \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{SL, SOD, \& CAT}\uparrow$; IRGE $_{\beta\text{-defensin, TGF-}\beta, \& HSP70}\uparrow$; DEA $_{PrA}\downarrow$; IDR $_{S.\ agalactiae}\uparrow$	[60]
B. amyloliquefaciens	Dietary supplementation at 60 mg/kg feed	42 days	GP $_{WG \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; Fat digestibility$\uparrow$	[69]
Bacillus sp., *Pediococcus* sp., *Enterococcus* sp. & *Lactobacillus* sp.	Dietary supplementation 10^6 & 2.3×10^6 CFU g^{-1}	8 weeks	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR \& PER}\uparrow$, and ADC$\rightarrow$; IP $_{RB\rightarrow}$, and GPx$\downarrow$, and ACA & CAT$\uparrow$; HBP $_{Ht, WBC, \& RBC}\rightarrow$; DEA $_{AmA, Lipase, Trypsin, \& Chymotrypsin}\rightarrow$; mVH$\uparrow$	[63]
Paenibacillus ehimensis NPUST1	Dietary supplementation at 10^6 & 10^7 CFU g^{-1}	2 months	GP $_{WG}\uparrow$; FUP $_{FCR \& FER}\uparrow$; IP $_{PcA, SOD, \& RB}\uparrow$; IRGE $_{IL-1\beta \& TNF-\alpha}\uparrow$; SR$\uparrow$; IDR $_{A.\ hydrophila \&\ S.\ iniae}\uparrow$	[65]
Aspergillus oryzae	Dietary supplementation at 10^6 & 10^8 CFU g^{-1}	60 days	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FER}\uparrow$; IP $_{RB, IgM, SL, SBA, MDA, SOD, GPx \& PcA}\uparrow$; HBP $_{TSP}\uparrow$, and Glu & Cortisol$\downarrow$; IRGE $_{IL-1\beta, TNF-\alpha, \& HSP70}\uparrow$; SR$\rightarrow$	[31]
Rummeliibacillus stabekisii	Dietary supplementation at 10^6 & 10^7 CFU g^{-1}	8 weeks	GP $_{WG \& FBW}\uparrow$; FUP $_{FCR}\downarrow$, and FER$\uparrow$; IP $_{PcA, RB, SL, \& SOD}\uparrow$; IRGE $_{IL-1\beta, TNF-\alpha, TGF-\beta, \& HSP70}\uparrow$; SR$\uparrow$; DEA $_{PrA, Xylanase, \& Cellulase}\uparrow$; GutM $_{Bacillus\ \&\ Lactobacillus}\uparrow$, and *Staphylococcus* & *Streptococcus*$\downarrow$; IDR $_{A.\ hydrophila \&\ S.\ iniae}\uparrow$	[67]
Psychrobacter namhaensis S089	Dietary supplementation at $(2.8 \& 5.6) \times 10^7$ CFU g^{-1}	50 days	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$, and PER, & PPV$\uparrow$; IP $_{RB}\uparrow$; HBP $_{TSP, RBC, WBC, Hb, Ht, Alb, Glb, AST, ALT, \& LDH}\uparrow$; IRGE $_{IL-4 \& IL-12}\uparrow$; DEA $_{PrA, AmA \& Lipase}\uparrow$	[68]
Psychrobacter maritimus S	Dietary supplementation at $(3.3 \& 6.6) \times 10^8$ CFU g^{-1}	50 days	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$, and PER$\uparrow$; IP $_{PcA, ACA, SL, \& SOD}\uparrow$; HBP $_{RBC, TSP, Alb, Glb, Hb, \& Ht}\uparrow$, and ALT, & AST$\downarrow$; IRGE $_{IL-4 \& IL-12}\uparrow$, and HSP70$\downarrow$; DEA $_{PrA, AmA, \& Lipase}\uparrow$	[16]
B. velezensis TPS3N; *B. subtilis* TPS4 & *B. amyloliquefaciens* TPS17	Dietary supplementation at 10^8 CFU ml^{-1}	4 weeks	IP $_{NO, SL, IgM, CAT, \& SOD}\uparrow$; HBP $_{ALP}\uparrow$; DEA $_{AmA\rightarrow}$, and Lipase$\uparrow$; mVH$\uparrow$; IDR $_{A.\ hydrophila}\uparrow$	[70]
Bacillus sp. KUAQ1 & *Bacillus* sp. KUAQ2	Dietary supplementation at $(1, 3, \& 5) \times 10^8$ CFU g^{-1}	8 weeks	GP $_{WG}\uparrow$, and SGR$\downarrow$; FUP $_{FCR}\downarrow$; IP $_{PcA, SOD, \& ACA}\uparrow$; IDR $_{S.\ agalactiae}\uparrow$	[71]
B. subtilis WB60 & *Lactococcus lactis*	Dietary supplementation at 10^7 & 10^8 CFU g^{-1}	8 weeks	GP $_{WG \& SGR}\uparrow$; FUP $_{FER \& PER}\uparrow$; HBP $_{AST, ALT, TSP, \& Glu}\rightarrow$; IP $_{SL, SOD, \& MPO}\uparrow$; IRGE $_{INF-\gamma, IL-1\beta, HSP70, \& TNF-\alpha}\uparrow$; mVH$\uparrow$; IDR $_{A.\ hydrophila}\uparrow$	[72]
Bacillus spp. (ANSCI9, BFAR9, RM3, and RM10)	Dietary supplementation at 10^8 CFU g^{-1}	30 days	GP $_{SGR, RGR}\uparrow$; FUP $_{FCR}\downarrow$; IDR $_{A.\ hydrophila}\uparrow$; SR$\uparrow$	[61]
L. plantarum L-137	Dietary supplementation at 2×10^{11} CFU g^{-1} & 50 mg Kg^{-1}	30 days	HBP $_{TSP, Alb, Glb, Hb, RBC, \& WBC}\uparrow$, and AST, ALT, ALP, Creatinine, Urea, & Bilirubin$\downarrow$; IP $_{CAT, GPx, SL, \& PcA}\uparrow$; IRGE $_{INF-\gamma}\rightarrow$, and IL-8 & IL-1$\beta\uparrow$, and CASP3 & HSP70$\downarrow$	[66]
L. plantarum	Dietary supplementation at 1.09×10^9 CFU Kg^{-1}	56 days	GP $_{WG}\rightarrow$; IRGE $_{IL-10, IL-17F, IL-8, \& IL-1\beta}\uparrow$; GutM$\uparrow$; IDR $_{Enterococcus\ faecalis}\uparrow$	[74]

Table 1. Continued.

Probiotics	Mode of administration and dosage	Duration	Effects on *O. niloticus*	References
Protexin (*L. plantarum, L. rhamnosus, Bifidobacterium bifidum, E. faecium, Candida pintolepesii,* & *Aspergillus oryzae*), Biogen-S (*B. subtilis),* Diamond V (*Saccharomyces cerevisiae*)	Dietary supplementation at 6×10^7, 10^{11} & 2.6×10^{10} CFU g^{-1}	8 weeks	$GP_{FBW, WG, \& SGR}\uparrow$; $FUP_{FCR}\downarrow$; $IP_{RB, \& SL}\uparrow$; $HBP_{TSP, Alb, Glb, A/G Ratio, Hb, Ht, RBC, \& WBC}\uparrow$, and Glu, ALT, & AST$\downarrow$; $IRGE_{IL-1\beta \& TNF-\alpha}\uparrow$; $IDR_{A. hydrophila}\uparrow$	[75]
AlCare (*B. licheniformis*)	Dietary supplementation at 2×10^7 to 4.4×10^6 CFU g^{-1}	10 weeks	$GP_{FBW, WG, \& SGR}\uparrow$; $FUP_{FCR}\rightarrow$; $IP_{SL, SOD, \& ACA}\uparrow$; SR$\rightarrow$; $IDR_{S. iniae}\uparrow$	[77]
DVAQUA (*S. cerevisiae*)	Dietary supplementation at 2.0 g Kg^{-1} feed	8 weeks	$GP_{WG \& SGR}\rightarrow$; $FUP_{FCR}\rightarrow$; $IP_{SL, RB, PcA, \& ACA}\uparrow$; GutM$\uparrow$; SR$\rightarrow$	[78]
Organic Green & *B. pumilus*	Water supplementation at 10^8 CFU ml^{-1}	1, 2, & 8 months	$GP_{WG}\uparrow$; $HBP_{Ht, TLC, DLC, Neutrophils, Lymphocytes, Monocytes, Eosinophils, \& Basophils}\rightarrow$; $IP_{RB \& RLP}\uparrow$; SR$\uparrow$; $IDR_{A. hydrophila}\uparrow$	[79]
AquaStar Pond (*Bacillus* sp., *Pediococcus* sp., *Enterococcus* Sp.); EM (*Rhodopseudomonas* spp., *Lactobacillus* spp., Saccharomyces spp.); MicroPan (*Bacillus* spp.)	Dietary supplementation at 0.0015 g m^{-3} day^{-1}; 10 ml m^{-3} day^{-1}; 0.002 g m^{-3} day^{-1}	60 days	$GP_{FBW, WG \& SGR}\uparrow$; $FUP_{FER \& PER}\uparrow$; $IRGE_{GHR, IL-1\beta, TNF-\alpha \& IGF-1}\uparrow$, $HBP_{Alb, Glb, Glu, Hb, WBC, RBC, Lymphocyte, \& Monocyte}\uparrow$; $IP_{SL \& PcA}\uparrow$	[76]

Symbol →, no change; ↑, increase; ↓, decrease versus controls.
A/G: Albumin/Globulin; ACA: Alternative complement activity; ADC: Apparent digestibility coefficient; Alb: Albumin; ALP: Alkaline phosphatase; ALT: Alanine amino transferase; AmA: Amylase activity; AST: Aspartate amino transferase; CASP3: Caspase 3; CAT: Catalase; DAO: Diamine oxidase; DEA: Digestive enzyme activities; FBW: Final body weight; FCR: Feed conversion ratio; FER: Feeding efficiency ratio; FUP: Feed utilization parameters; Glb: Globulin; Glu: Glucose; GP: Growth parameters; GPx: Glutathione peroxidase; GutM: Gut microbiota; Hb: Haemoglobin; HBP: Haemato-biochemical parameters; HSP: Heat shock protein; Ht: Hematocrit; IDR: Infectious disease resistance; IgM: Immunoglobulin M; IL: *Interleukin*; INF: Interferon; IP: Immunological parameters; IRAK: Interleukin 1 receptor associated kinase; IRGE: Immune related gene expression; LDH: Lactate dehydrogenase; MDA: Malondialdehyde; MPO: Myloperoxidase; mVH: micro-Villous height; MyD: Myeloid differentiation factor; NO: Nitric oxide; PbAT: Pb accumulation in tissues; PcA: Phagocytic activity; PER: Protein efficiency ratio; PPV: Protein productive value; PrA: Protease activity; RGR: Relative growth rate; RB: Respiratory burst (NBT assay); RBC: Red blood cell; RLP: Relative level of protection; SBA: Serum bactericidal activity; SGR: Specific growth rate (%); SL: Serum lysozyme; SMLA: Skin mucus lysozyme activity; SOD: Superoxide dismutase; SR: Survival rate; ST: Salinity tolerance; TAC: Total anti-oxidant capacity; TGF: Transforming growth factor; TLC: Total leucocytic count; TLR: Toll-like receptor; TNF: Tumor necrosis factor; TSP: Total serum protein; WBC: White blood cells; WG: Weight gain (%).

namely AlCare (*B. licheniformis)*, Biogen (*B. subtilis*), and BioSaf (*S. cerevisiae*) resulted in improved growth [77] without affecting measured dietary digestion parameters [77, 78] (Table 1). Moreover, the use of commercial probiotics as water supplements enhanced protection against *A. hydrophila* [79].

Atlantic Salmon

Comparatively less information is available on the effects of probiotics in Atlantic salmon. Available information can be categorized into in vivo and in vitro studies as summarized in Table 2.

Wang *et al.* [80] assessed the effect of *B. velezensis* V4 CGMCC 10149 and *Rhodotorula mucilaginosa* CGMCC 1013 on juvenile salmon raised in a recirculating aquaculture system. After 62 days feeding with different doses of these strains, fish weight gain, immunity as well as disease resistance against *A. salmonicida* improved significantly. In the same species, administration with *P. acidilactici* MA18/5M containing commercial probiotic (Bactocell) upregulated TLR3, TNF-α, and IL-1β, enriched gut microbial community and probiotic count in the intestine [81]. Meanwhile, fish growth rate and protection against infectious pancreatic necrosis virus were not affected by this commercial probiotic. In another study, Bactocell reduced intestinal inflammation, maintaining intestinal homeostasis of Atlantic salmon after inducing inflammation with oxazolone [82].

Trout intestinal *Lactobacillus* (RII and RIII) was administered at a dose of ~10^8 CFU g^{-1}, where RIII enhanced species richness and phylogenetic bacterial community diversity in distal intestine [83]. Moreover, *Lab. fermentum* and *Lab. plantarum* modulated gill epithelium through upraising the number of mucous cells, surface area and lamina propria [84]. *Lactobacillus* was reported to be the dominant genus in the intestine of fish fed probiotics (Table 2). In vitro incubation of salmon foregut with 1 ml *Lab. delbrueckii* subsp. *lactis* (1.6×10^5 CFU ml^{-1}) exhibited that probionts adhere to the proximal intestinal mucus and did not cause any damage to morphology and integrity of the intestine [85]. Pre-incubation with the same probiotic offered protection against *A. salmonicida* infection. Similarly, Kristiansen *et al.* [86] showed that *Carnobacterium divergens* adhered to the proximal intestine following in vitro exposure at a concentration of 10^8 CFU ml^{-1} for 1 h and inhibited the growth of pathogenic *Y. ruckeri*. In another study, in vitro incubation of *C. divergens* prevented *A. salmonicida*- and *V. anguillarum*-induced damage in the foregut of Atlantic salmon to some extent [87].

Table 2. Effects of probiotic supplementation on growth, feed utilizations, immunological and haemato-biochemical parameters and disease resistance in Atlantic salmon (*Salmo salar*) aquaculture.

Probiotics	Mode of administration and dosage	Duration	Effects on *S. salar*	References
Bacillus velezensis V4 CGMCC 10149 (BVV4) & *Rhodotorula mucilaginosa* CGMCC 1013 (RM)	Dietary supplementation at BVV4 (5×10^6) + RM (5×10^7), BVV4 (1.5×10^7) + RM (1.5×10^8), & BVV4 (2.5×10^7) + RM (2.5×10^8) CFU g^{-1}	62 days	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{SOD, GPx, CAT, TAC, ACP, \& IgM}\uparrow$, MDA & NO$\downarrow$, and SL $\rightarrow$; HBP $_{ALT \& AST}\downarrow$; IDR $_{Aeromonas\ salmonicida}\uparrow$; SR$\uparrow$	[80]
Bactocell (*Pediococcus acidilactici* MA18/5M)	Dietary supplementation at 1.19×10^6 CFU g^{-1}	12 weeks	GP $_{FBW \& SGR}\rightarrow$; IRGE $_{MX\text{-}1, TLR3, TNF\text{-}\alpha, \& IL\text{-}1\beta}\uparrow$, and HSP70 & PCNA $\rightarrow$; GutM $_{Proteobcteria}\uparrow$, and Fusobacteria$\downarrow$; PCI$\uparrow$; IDR $_{IPNV}\rightarrow$	[81]
Bactocell (*P. acidilactici* MA18/5M)	Dietary supplementation at 10^{10} CFU Kg^{-1}	6 weeks	IRGE $_{MUL\text{-}1\beta, IL\text{-}1\beta, TNF\text{-}\alpha, \& INF\text{-}\gamma}\downarrow$; Gut Morphology $_{Goblet\ cells, intraepithelial\ lymphocytes\ (IELs), Supranuclear\ vacuoles\ in\ the\ villi, \& immune\ cells}\uparrow$	[82]
Lactobacillus RII & RIII	Dietary supplementation at ~ 10^8 CFU g^{-1}	20 days	GutM $_{Firmicutes, Tenericutes, Proteobacteria, Actinobacteria, \& Spirochaetes}\uparrow$	[83]
Lab. fermentum and *Lab. plantarum*	Dietary supplementation at 10^8 CFU g^{-1}	38 days	GME and GNE$\uparrow$; VH & LPW$\uparrow$	[84]
Lab. delbrueckii subsp. *lactis*	In vitro incubation at 1.6×10^5 CFU ml^{-1}	30 min	PCI$\uparrow$; IDR $_{A. salmonicida\ subsp.\ salmonicida}\uparrow$	[85]
Carnobacterium divergens	In vitro incubation at 10^8 CFU ml^{-1}	1 h	PCI$\uparrow$; Gut Morphology $_{Goblet\ cell}\rightarrow$ Pathogenic antagonism $_{Y. ruckeri}\uparrow$	[86]
C. divergens	In vitro incubation at 6×10^4 & 6×10^6 CFU ml^{-1}	1 h	IDR $_{A. salmonicida \& V. anguillarum}\uparrow$	[87]

Symbol $\rightarrow$, no change; $\uparrow$, increase; $\downarrow$, decrease versus controls.
ACP: Acid phosphatase; ALT: Alanine aminotransferase; AST: Aspartate aminotransferase; CAT: Catalase; FBW: Final body weight; FCR: Feed conversion ratio; FUP: Feed utilization parameters; GME and GNE: The area and number of mucous cells/μm^2 gill epithelium; GP: Growth parameters; GPx: Glutathione peroxidase; GutM: Gut microbiota; HBP: Haemato-biochemical parameters; HSP70: Heat shock protein; IDR: Infectious disease resistance; IgM: Immunoglobulin M; IL: Interleukin; INF: Interferon; IP: Immunological parameters; IPNV: Infectious pancreatic necrosis virus; IRGE: Immune related gene expression; LPW: Narrower lamina propria; MDA: Malondialdehyde; MUL: Mitochondrial ubiquitin ligase activator of NFκB1; MX-1: Interferon-induced GTP-binding protein; NO: Nitric oxide; PCI: Probiotic count in the intestine; PCNA: Proliferating cell nuclear antigen; SGR: Specific growth rate (%); SL: Serum lysozyme; SOD: Superoxide dismutase; SR: Survival rate; TAC: Total anti-oxidant capacity; TLR: Toll-like receptor; TNF: Tumor necrosis factor; VH: villi height; WG: Weight gain (%).

Rainbow Trout

Rainbow trout contributed 2% of total global finfish production in 2016 [1]. Numerous benefits of probiotics have been reported in rainbow trout aquaculture, for example, both *L. plantarum* and its strain KC426951 promoted growth and immunity with some exceptions in heamato-biochemical parameters [88, 89] (Table 3). The former probiotic increased alkaline phosphatase (ALP), IgM, and hemoglobin to a significant level, whereas the latter one only increased white blood cells with no alteration of hemoglobin, mean corpuscular volume, and red blood cells concentration. In contrast to the results reported by Soltani *et al.* [89], some haematological parameters like ALP, triglyceride and total cholesterol depicted improved modulation after *Lab. rhamnosus* treatment [90].

Dietary supplementation with LABs *L. buchneri, L. fermentum*, and the yeast *S. cerevisiae* together for 130 days improved innate immunity and immune genes transcription without alteration of heamato-biochemical parameters [91]. Modulation of these parameters was also observed after feeding with various strains of LAB [92, 93]. Administration with *L. plantarum, Lac. lactis,* and *Leuconostoc mesenteroides* upregulated IL-8 & 10, TNF-α, and IgT and decreased IL-1β, TNF-α and TLR5 transcription before and after *Lac. garvieae* infection, respectively directly in contrast to results reported by Pérez-Sánchez *et al.* [94] (Table 3).

Combination of *Bacillus* sp. with *Lactobacillus* sp. reportedly elevated humoral immunity, intestinal structure and decreased plasma phenoloxidase [95]. The dietary administration of *Bacillus* sp. and *B. licheniformis* individually or in combination showed improved [96], unchanged [63], and decreased [97] results in weight gain and specific growth rate. Humoral immunity was elevated with *B. subtilis* + *B. licheniformis*, but this combination had no influence on serum biochemical parameters apart from total leukocytes.

Trout gut probiotics *Kocuria* SM1 and *Rhodococcus* SM2 failed to induce changes in growth, digestive enzymes, and haematology, with the exceptions of lowered trypsin and increased hemoglobin levels [30]. In another study, single administration of *Kocuria* SM1 improved immunity and serum biochemistry [98]. Besides these, *Kocuria* SM1-fed rainbow trout fingerlings decreased mortality by 10-28% from 73-92% in response to *V. anguillarum* challenge. Dietary administration of *Enterobacter cloacae* and *B. mojavensis* showed improved protection from *Y. ruckeri*, where survival rate increased to 99.2% compared to 35% in the control group [99]. Probiotics like *E. casseliflavus* positively modulated serum biochemistry by decreasing malondialdehyde and lymphocytes without changing alanine and aspirate aminotransferase [100]. Supplementation of *Bifidobacterium animalis* PTCC-1631 and *Bif. lactis* PTCC-1736 at the lowest dose (10^7 CFU g^{-1}) improved fish body weight and

Table 3. Effects of probiotic supplementation on growth, feed utilizations, immunological and haemato-biochemical parameters, immune related gene expression and disease resistance in rainbow trout (*Oncorhynchus mykiss*).

Probiotics	Mode of administration and dosage	Duration	Effects on *O. mykiss*	References
Lactobacillus plantarum KC426951	Dietary supplementation at 2×10^7 CFU g^{-1}	72 days	GP $_{FBW \& WG}\uparrow$; FUP $_{FCR}\downarrow$; HBP $_{WBC}\uparrow$, and Hb, MCV, MCH, MCHC, & RBC$\rightarrow$	[88]
L. plantarum	Dietary supplementation at 10^8 CFU g^{-1}	60 days	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$, and PER$\uparrow$; IP $_{IgM \& ACA}\uparrow$; HBP $_{RBC, MCH, MCHC, MCV, WBC, Heterophil, \& Lymphocytes}\rightarrow$	[89]
L. rhamnosus	Dietary supplementation at 10^9 & 10^{11} CFU g^{-1}	30 days	HBP $_{TC, ALP, TG, TSP, \& Ht}\uparrow$	[90]
L. buchneri, L. fermentum & *Saccharomyces cerevisiae*	Dietary supplementation at 10^7 CFU g^{-1}	130 days	GP $_{WG \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{RB}\downarrow$; HBP $_{TSP, Alb, Glb, TC, TG, \& RBC}\rightarrow$, and WBC$\uparrow$; IRGE $_{TNF\text{-}\alpha \& IL\text{-}1\beta}\uparrow$	[91]
L. delbrukei subsp. *bulgaricus, L. acidophilus* & *Citrobacter farmeri*	Dietary supplementation at 5×10^7 CFU g^{-1}	60 days	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$, and FER$\uparrow$; IP $_{SL, SBA, \& ACA}\uparrow$, and RB$\downarrow$; HBP $_{Ht, Hb, ALP, WBC, MCV, \& MCH}\uparrow$, and RBC$\rightarrow$, and MCHC$\downarrow$; IRGE $_{IL\text{-}1\beta, IL\text{-}8, IL\text{-}10, IGF\text{-}1, \gamma\text{-}GTP, \& FATP}\uparrow$; DEA $_{Trypsin, AmA, \& Lipase}\uparrow$, and PrA$\rightarrow$	[93]
L. delbrueckii subsp. *bulgaricus*	Dietary administration at 10^8 CFU g^{-1}	66 days	GP $_{WG, DWG \& SGR}\uparrow$; FUP $_{FER \& PER}\uparrow$ $_{FCR}\downarrow$; HBP $_{Alb, ALP\text{-}liver}\downarrow$; IP $_{SOD, CAT, GSH}\uparrow$	[92]
L. plantarum, Lactococcus lactis, & *Leuconostoc mesenteroides*	Dietary administration at 10^6 CFU g^{-1}	36 days	IRGE $_{IL\text{-}10, IL\text{-}1\beta, TNF\text{-}\alpha, IgT, \& IL\text{-}8}\uparrow$, and IL-1β, TNF-α, & TLR5 (after infection)$\downarrow$; IDR $_{Lac. garvieae}\uparrow$	[94]
Bacillus sp. + *Pedicoccus* sp., *Enterococcus* sp. + *Lactobacillus* sp. + *P. acidilactici*	Dietary supplementation at 8.6×10^5, 1.6×10^6, 2.6×10^4 & 7.2×10^4 CFU g^{-1}	8 weeks	GP $_{FBW \& WG}\uparrow$; FUP $_{FCR}\downarrow$, and PER$\uparrow$; IP $_{SL \& ACA}\uparrow$, and MPO$\downarrow$; mVH$\uparrow$	[95]
B. subtilis, B. licheniformis	Dietary supplementation at (7.79, 8.36, 8.05, & 8.23) $\times 10^1$ CFU g^{-1}	10 weeks	GP $_{WG}\downarrow$, and SGR$\uparrow$; FUP $_{FCR}\downarrow$, and PER$\uparrow$; IP $_{SL}\uparrow$; HBP $_{Ht, Lymphocytes, Granulocytes \& Thrombocytes}\rightarrow$, and WBC$\uparrow$; TVC$\uparrow$	[97]
B. subtilis & *B. licheniformis*, & *B. subtilis* + *B. licheniformis*	Dietary supplementation at 2×10^9 CFU kg^{-1}	8 weeks	GP $_{WG \& SGR}\uparrow$; FUP $_{FER \& PER}\uparrow$; IP $_{SOD, MPO, RB, \& SL}\uparrow$; HBP $_{AST, ALT, Glu, \& TC}\rightarrow$	[96]
B. subtilis & *B. cereus toyoi*	Dietary supplementation at 6×10^3 & 1.5×10^6 CFU g^{-1}	20 weeks	GP $_{WG \& SGR}\rightarrow$; FUP $_{FER \& PER}\rightarrow$; IP $_{SL}\downarrow$, and ACA$\uparrow$; mVH$\rightarrow$	[63]
B. subtilis ABP1 & ABP2	Dietary supplementation 10^5, 10^6, and 10^7 CFU g^{-1}	1 week	IP $_{IgM}\uparrow$; HBP $_{MCH\ II}\uparrow$	[64]
Kocuria SM1 & *Rhodococcus* SM2	Dietary supplementation at ~10^7(SM1) or ~10^8 (SM2) CFU g^{-1}	14 days	GP $_{FBW \& SGR}\rightarrow$; FUP $_{FCR \& PER}\rightarrow$; DEA $_{PrA}\rightarrow$, & Trypsin$\downarrow$; HBP $_{Hb}\uparrow$, and ALP, ACP, Urea, Creatinine, & Glu$\rightarrow$	[30]
Kocuria SM1	Dietary supplementation at ~10^8 CFU g^{-1}	2 weeks	IP $_{SBA, RB, \& SL}\uparrow$; HBP $_{TSP \& WBC}\uparrow$; IDR $_{Vibrio\ anguillarum}\uparrow$;	[98]
Enterobacter cloacae & *B. mojavensis*	Dietary supplementation at 10^8 CFU g^{-1}	60 days	HBP $_{Hb, WBC, Neutrophils, Lymohocytes, \& Monocytes}\uparrow$, and Eosinophils & RBC$\rightarrow$; IDR $_{Y.\ ruckeri}\uparrow$; SR$\uparrow$	[99]
Enterococcus casseliflavus	Dietary supplementation at 10^7, 10^8, 10^9 CFU g^{-1}	8 weeks	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{IgM \& RB}\uparrow$; HBP $_{TSP, RBC, WBC, Ht, Alb, Hb, MCH, MCHC, Neutrophils, Monocyte, \& Lysozyme}\uparrow$, and MCV & Lymphocytes$\downarrow$, and AST, ALT, LDH, & Glb$\rightarrow$	[100]
Bifidobacterium animalis PTCC-1631 & *Bif. lactis* PTCC-1736	Dietary supplementation at (1, 2, & 3) $\times 10^7$ CFU g^{-1}	8 weeks	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FI \& FCR}\downarrow$ $_{and\ FCE}\rightarrow$; GutM$\uparrow$	[101]
Bio Aqua (*P. acidilactici, E. faecium, B. subtilis, L. acidophilus, L. plantarum, L. casei, L. rhamnosus, B. bifidum* & *S. cerevisiae*)	Dietary supplementation at (1, 2, & 4) $\times 10^9$ CFU g^{-1}	8 weeks	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{PER}\uparrow$, and FCR$\downarrow$; RP $_{ED, RF, FR, \& HR}\uparrow$; HBP $_{TSP, Alb, Glb, \& A/G\ Ratio}\uparrow$, and RBC, WBC, Hb, Ht, Lymphocyte, Monocyte, Eosinophils, Basophils, MCV, MCH, & MCHC$\rightarrow$, and Glu, TG, & TC$\downarrow$	[14]
Proviotic (*L. bulgaricus*)	Dietary supplementation 460 mg Kg^{-1}	60 days	GP $_{FBW \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; HBP $_{Glu}\uparrow$, and Urea, TSP, Alb, ALT, ALP, Ca, P, Mg, TG, & TC$\downarrow$	[103]
PrimaLac (*L. acidophilus, L. casei, E. faecium,* & *Bif. bifidium*)	Dietary supplementation 1.5 g Kg^{-1}	8 weeks	GP $_{FBW, WG, \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; HBP $_{LDH, ALP, ALT, AST, TG, Glu, Cortisol, \& TC}\downarrow$; DEA $_{PrA, AmA, \& Lipase}\uparrow$; SR$\uparrow$	[15]
Aqualase (*S. cerevisiae* & *S. elipsoedas*)	Dietary supplementation at 10^{10} CFU g^{-1}	8 weeks	GP $_{WG \& SGR}\uparrow$; FUP $_{FCR}\downarrow$; IP $_{SL, IgM, \& RB}\uparrow$, HBP $_{TSP}\uparrow$, and ALP$\rightarrow$; DEA $_{Trypsin, AmA, \& Lipase}\uparrow$	[102]
Bacillus sp., *Pediococcus* sp., *Enterococcus* sp. & *Lactobacillus* sp.	Dietary supplementation 2×10^9 CFU kg^{-1}	9 weeks	GP $_{FBW \& WG,}\rightarrow$; IP $_{ACA \& GPx}\uparrow$, and CAT & SL$\rightarrow$; GutM$\rightarrow$	[150]

Symbol →, no change; ↑, increase; ↓, decrease versus controls.

A/G: Albumin-Globulin; ACA: Alternative complement activity; ACP: Acid phosphatase; ADC: Apparent digestibility coefficient; Alb: Albumin; ALP: Alkaline phosphatase; ALT: Alanine transaminase, AmA: Amylase activity; AST: Aspartate amino transferase; Ca: Calcium; CAT: Catalase; DWG: Daily weight gain; DEA: Digestive enzyme activity; ED: Egg diameter; FATP: Fatty acid transport protein; FBW: Final body weight; FCE: Feed conversion efficiency; FCR: Feed conversion ratio; FER: Feed efficiency ratio; FLs: Fingerlings; FR: Fertilization rate; FUP: Feed utilization parameters; Glb: Globulin; Glu: Glucose; GP: Growth parameters; GSH: Glutathione; GPx: Glutathione peroxidase; GTP: Gamma glutamyl transpeptidase; GutM: Gut micorbiota; Hb: Haemoglobin; HBP: Haemato-biochemical parameters; HR: Hatching rate; Ht: Hematocrit; IDR: Infectious disease resistance; Ig: Immunoglobulin; IGF: Insulin-like growth factor; IL: *Interleukin*; IP: Immunological parameters; IRGE: Immune related gene expression; LDH: Lactate dehydrogenase; LPV: Lipid productive value; MCH: Mean corpuscular haemoglobin; MCHC: Mean corpuscular haemoglobin concentration; MCV: Mean corpuscular volume; Mg: Magnesium; MPO: Myloperoxidase; mVH: micro-Villous height; P: Potassium; PcA: Phagocytic activities; PER: Protein efficiency ratio; PPO: Plasma peroxidase; PPV: Protein productive value; PrA: Protease activity; RB: Respiratory burst (NBT assay); RBC: Red blood cells; RF: Relative fecundity; RP: Reproductive parameters; SAP: Serum antiprotease activity; SBA: Serum bactericidal activity; SGR: Specific growth rate (%); SL: Serum lysozyme; SOD: Superoxide dismutase; SR: Survival rate; TC: Total cholesterol; TG: Triglyceride; TLR: Toll like receptor; TNF: Tumor necrosis factor; TSP: Total serum protein; TVC: Total viable counts; VCCS: Vertebral column compression syndrome; WBC: White blood cell; WG: Weight gain (%).

digestibility compared to higher doses and to the control group [101] (Table 3).

Treatment with a commercial probiotic, Proviotic containing *L. bulgaricus* and Aqualase (mixture of *S. cerevisiae* and *S. elipsoedas*) demonstrated better growth and diet digestion [102, 103]. Similarly, PrimaLac composed of *L. acidophilus*, *L. casei*, *E. faecium* and *Bif. bifidium* elevated these two parameters along with protease, amylase and lipase activity in the intestine [15].

Common Carp

Common carp is among the most important commercially cultured fish in the world contributing 8% of total global finfish aquaculture production in 2016 [1]. Probiotics reportedly affect growth, immunological parameters, and disease protection in common carp [7]. Administration of *L. delbrueckii* for 8 weeks showed improved production, feed intake and various digestive enzymes including protease, amylase, lipase, Na+/K+-ATPase, creatine kinase and γGT activity [104, 105]. Moreover, similar to *L. delbrueckii*, *Lactobacillus* sp. and

Table 4. Effects of probiotic supplementation on growth, feed utilizations, immunological and haemato-biochemical parameters and disease resistance in common carp (*Cyprinus carpio*).

Probiotics	Mode of administration and dosage	Duration	Effects on *C. carpio*	References
Lactobacillus delbrueckii	Dietary supplementation at 10^5 to 10^8 CFU g^{-1}	8 weeks	GP $_{FBW\ \&\ WG}\uparrow$; FUP $_{FCR}\downarrow$; HBP $_{ALP}\rightarrow$; IP $_{IgM,\ SL,\ MPO,\ ACP,\ SOD,\ CAT,\ GPx,\ \&\ TAC}\uparrow$, and MDA$\downarrow$; IRGE $_{TNF\text{-}\alpha,\ IL\text{-}8,\ IL\text{-}1\beta,\ \&\ NF\text{-}\kappa Bp65}\downarrow$, and IL-10 & TGF-$\beta\uparrow$; IDR $_{Aeromonas\ hydrophila}\uparrow$; SR$\uparrow$	[105]
L. delbrueckii	Dietary supplementation at 10^5 to 10^8 CFU g^{-1}	8 weeks	GP $_{FBW,\ WG,\ and\ SGR}\uparrow$; FUP $_{PER}\uparrow$; DEA $_{PrA,\ AmA,\ Lipase,\ Na^+/K^+\text{-}ATPase,\ CK,\ \&\ \gamma GT}\uparrow$	[104]
Lactobacillus sp., *Nitrosomonas* sp. and *Bacillus* spp.	Water supplementation at 10^8 CFU ml^{-1}	10 days	IRGE $_{TNF\text{-}\alpha,\ CD4^+\ and\ CD8^+}\uparrow$	[106]
L. plantarum 44[a]	Dietary supplementation at (1.5, 3, & 4.5) × 10^6 CFU mg^{-1}	60 days	GP $_{SGR\ \&\ TGC}\uparrow$; FUP $_{PER}\uparrow$, and FCR$\downarrow$; IP $_{SL}\uparrow$; DEA $_{PrA\ \&\ AmA}\uparrow$, and Lipase$\rightarrow$; HBP $_{RBC,\ Ht,\ Hb,\ Leucocyte,\ MCH,\ MCHC,\ \&\ Glb}\uparrow$, and Cortisol & Glu$\downarrow$, and Alb$\rightarrow$	[107]
L. plantarum	Dietary supplementation at 10^8 CFU g^{-1}	14 days	IP $_{PcA\ (Head\ kidney)\ \&\ \lambda\text{-}globulin}\uparrow$, and SBA$\downarrow$, and PcA (Spleen), RB, SL, & CP$\rightarrow$; HBP $_{B\ lymphocytes\ \&\ TSP}\uparrow$; IDR $_{A.\ hydrophila}\uparrow$	[108]
Bacillus coagulans MTCC 9872, *B. licheniformis* MTCC 6824 & *Paenibacillus polymyxa* MTCC 122	Dietary supplementation at 10^9 CFU g^{-1}	80 days	GP $_{FBW\ \&\ SGR}\uparrow$; FUP $_{FCR\ \&\ PER}\uparrow$; IP $_{SL,\ RB,\ \&\ MPO}\uparrow$; IDR $_{A.\ hydrophila\ \&\ Vibrio\ harveyi}\uparrow$; SR$\uparrow$	[110]
B. coagulans	Dietary supplementation at (1, 2, &4) × 10^7 CFU g^{-1}	45 days	GP $_{FBW\ \&\ WG}\uparrow$; IP $_{ACA,\ SL,\ MPO\ \&\ RB}\uparrow$;	[109]
Lactobacillus sp. & *Bacillus* sp.	Dietary supplementation at 0.75, 1.5, & 2.25 g kg^{-1}	60 days	GP $_{WG}\uparrow$; FUP $_{FE}\uparrow$; DEA $_{PrA}\uparrow$; WQP $_{pH\ \&\ Temp}\uparrow$ and DO$\downarrow$	[111]
Pediococcus acidilactici	Dietary supplementation at 6 × 10^8 CFU g^{-1}	60 days	GP $_{FBW\ \&\ SGR}\downarrow$; FUP $_{FCR\ \&\ PER}\downarrow$; IP $_{Ig}\uparrow$; DEA $_{PrA}\uparrow$; HBP $_{TSP}\uparrow$; IRGE $_{TNF\text{-}\alpha\ \&\ SL}\downarrow$	[112]
P. pentosaceus	Dietary supplementation at 10^7, 10^8, & 10^9 CFU g^{-1}	45 days	GP $_{FBW,\ WG\ \&\ SGR}\uparrow$; IP $_{ACA\ \&\ SL}\uparrow$; DEA $_{AmA,\ PrA,\ Trypsin,\ \&\ Chymotrypsin}\uparrow$, and Lipase$\rightarrow$; HBP $_{WBC,\ Hb,\ Ht,\ \&\ Alb}\uparrow$, and TC & Glu$\rightarrow$; IDR $_{A.\ hydrophila}\uparrow$	[113]
Primalac (*L. acidophilus, L. casei, E. faecium,* & *B. bifidium*)	Dietary supplementation at 1 & 1.5 g kg^{-1}	8 weeks	GP $_{WG}\uparrow$, and SGR$\downarrow$; FUP $_{FCR}\downarrow$; HBP $_{WBC}\uparrow$, and RBC, Hb, Ht, MCV, MCH, & MCHC$\downarrow$; SR$\uparrow$	[115]
Primalac	Dietary supplementation at 1 & 2 g kg^{-1}	60 days	GP $_{FBW,\ WG,\ \&\ SGR}\uparrow$; FUP $_{FCR}\downarrow$; DEA $_{AmA,\ lipase\ \&\ protease}\uparrow$; HBP $_{TSP}\uparrow$, and ALT, ALP, AST, TG, Glu, Cortisol, & TC$\downarrow$; IP $_{total\ IgM,\ SL,\ MPO,\ ACH50,\ SOD,\ CAT,\ GPx,\ \&\ MDA}\uparrow$; SR$\uparrow$	[114]
B. subtilis	Dietary supplementation at 4 × (10^6 & 10^8) CFU 100 g^{-1}	180 days	GP $_{WG\ \&\ SGR}\uparrow$; FUP $_{FCE}\uparrow$, and FCR$\downarrow$; DNA: RNA$\uparrow$	[151]

Symbol →, no change; ↑, increase; ↓, decrease versus controls.

ACA: Alternative complement activity; ACP: Acid phosphatase; ACH50: Alternative complement; Alb: Albumin; ALP: Alkaline phosphate; ALT: Alanine aminotransferase; AST: Aspartate aminotransferase; AmA: Amylase activity; CAT: Catalase; $CD4^+$: Cluster of differentiation 4; $CD8^+$: Cluster of differentiation 8; TC: Total cholesterol; CK: Creatine kinase; CP: Ceruloplasmin; DEA: Digestive enzyme activities; DO: Dissolved oxygen; FBW: Final body weight; FCE: Feed conversion efficiency; FCR: Feed conversion ratio; FUP: Feed utilization parameters; Glb: Globulin; Glu: Glucose; GP: Growth parameters; GPx: Glutathione peroxidase; GT: Glutamyl transpeptidase; GutM: Gut microbiota; Hb: Haemoglobin; HBP: Haemato-biochemical parameters; HSP: Heat shock protein; Ht: Haematocrit; IDR: Infectious disease resistance; Ig: Immunoglobulin; IL: Interleukin; iNOS: Inducible nitric oxide synthase; IP: Immunological parameters; IRGE: Immune related gene expression; MCH: Mean corpuscular haemoglobin; MCHC: Mean corpuscular haemoglobin concentration; MCV: Mean corpuscular volume; MDA: Melanodialdehyde; MPO: Myloperoxidase; NF: Nuclear Factor; PcA: Phagocytic activity; PER: Protein efficiency ratio; PrA: Protease activity; RB: Respiratory burst (NBT assay); RBC: Red blood cell; SBA: Serum bactericidal activity; SGR: Specific growth rate (%); SL: Serum lysozyme; SOD: Superoxide dismutase; SR: Survival rate; TAC: Total anti-oxidant capacity; TC: Total cholesterol; TG: Triglyceride; TGC: Thermal growth coefficient; TGF: Transforming growth factor; TNF: Tumor necrosis factor; TSP: Total serum protein; WBC: White blood cell; WG: Weight gain (%); WQP: Water quality parameters.

Bacillus spp. modulated immune-gene transcription when used as water supplements [106]. Comparable modulation of parameters was noted after 60 days administration of *L. plantarum* 44[a], although the probiotic had no effects on lipase and haematological parameters [107]. In another study, same probiotic supplementation unveiled better serum biochemistry, phagocytic and λ-globulin activity in head kidney and protection against *A. hydrophila*, whereas phagocytic activity in spleen remains unchanged [108] (Table 4).

Supplementation with *B. coagulans*, *B. licheniformis* and *P. polymyxa* (MTCC 122) at 10^9 CFU g^{-1} influenced growth and feed utilizations, innate immunity [109], survival percentage, protection from *A. hydrophila* and *V. harveyi* [110]. Combined applications of *Lactobacillus* sp. with *Bacillus* sp. at 0.75, 1.5 and 2.25 g kg^{-1} improved protease activity in the intestine and modulated water quality parameters like pH, temperature and lowered dissolved oxygen concentration [111]. Administration of *P. acidilactici* [112] and *P. pentosaceus* [113] for 60 and 45 days, respectively, exhibited contrasting results. *P. acidilactici* improved feed conversion ratio, but decreased final body weight and daily weight gain, protease activity and immune gene expression. On the other hand, *P. pentosaceus* improved growth and digestive enzymes activity. However, both probiotics increased innate immunity and serum biochemistry (Table 4). Commercial probiotic mixture viz. Primalac® elicited a similar pattern of results, but only level of white blood cells and serum total protein increased among all haemato-biochemical parameters [114, 115].

Japanese/Olive Flounder

Olive flounder is among increasingly commercially important cultured marine species in Northeast Asian countries like China, Japan, Korean peninsula and some other countries [11]. This fish is widely accepted all over the world due to fast growth, taste, palatability, wide range of environmental adaptation and disease resistance. In 2018, its production was 37,239 metric ton equaling ~52% of total fisheries production in the Republic of Korea [116].

Extensive studies have focused on the use of single *L. lactis* BFE920 (LLBF) [17, 117], LLBF and *L. plantarum* FGL0001 (LPFG) [17] as well as single and combination of LLBF and LPFG [35] in olive flounder. LLBF and LPFG were isolated from bean sprouts and the hindgut of olive flounder respectively, and their probiotic properties were confirmed in vitro before dietary supplementation. LLBF was also administered orally as vaccine after cloning with *E. tarda* membrane protein and *S. iniae* antigen termed as OmpA, FlgD, and OmpA-FlgD [118] and SiMA [117] respectively (Table 5). These oral vaccines increased transcription levels of cluster of differentiation (CD) 4-1, CD4-2, CD8-α, T-bet, INF-γ, weight (20-21%) and feed digestion. Both vaccines also elevated antigen specific antibodies in fish tissues, as well as protection against *E. tarda* (5×10^5 CFU ml^{-1}; LD_{80}) and *S. iniae* (10^5 CFU ml^{-1}) producing 82% higher rates of survival relative to controls. Individual supplementation of probiotics LLBF and LPFG at 10^7 CFU g^{-1} increased expression levels of regulatory and pro-inflammatory genes, respectively [17] (Table 5). In addition, gut permeability was increased by LPFG compared to control and LLBF, and immune tone was stable for 30 days. Similar concentration level with combination of LLBF and LPFG increased levels of immunity and immune genes transcription and conferred higher protection against *S. iniae* challenge [35].

Except Sporolac, Lactobacil and mixture of probiotics improved immune parameters and resistance against lymphocystis. In other studies, infectious *S. parauberis*-injected flounder fed mixed probiotics [119] and *Uronema marinum* infected group fed individual *L. plantarum*, *L. acidophilus*, *L. sakei*, *B. subtilis* and *S. cerevisiae* [120] at 0.1% and 2.42×10^8 CFU g^{-1} respectively. In both cases, fish production, haematology and immunity levels were higher in disease infected probiotics treated groups as compared to controls. Among individual probiotics only *L. plantarum* elevated survival in *U. marinum* infected fish compared to other 4 probiotics and control. Another commercial LAB probiotic, *L. fermentum* was supplemented at 0.5% for 8 weeks to compare the effects with yacon, ginger and blueberry at 0.1% [121]. Commercial probiotics showed no effects except higher protection against *S. iniae* infection.

A probiotic *Bacillus* SJ-10 (BSJ-10) was isolated from Korean traditional fermented food [122] and complete genome sequence demonstrated similarity with two well-known olive flounder probiotics, *B. subtilis* and *B. licheniformis* [123, 124]. Dietary supplementation with this probiotic both live [21, 116] and heat-killed (HK) [125] forms at 10^8 CFU g^{-1} for 8 weeks increased rates of diet digestion and growth. Live and HK BSJ-10 and mixture with *L. plantarum* KCCM 11322 (3:1) protect olive flounder against streptococcosis [21, 43, 125] and edwardsiellosis [116]. Two different forms of BSJ-10 demonstrated no effect on heamto-biochemistry and intestinal structure, but both increased immunity and cytokines production in different localised organs like liver, kidney, gill and spleen (Table 5). Live BSJ-10 increased probiotics count in the intestine, but had no effect on IL-6, CD4-1 and CD4-2 transcription, and were able to ferment β-glucooligosaccharides and barley β- glucan as a synbiotic disease biocontrol model in olive flounder. Treatment with 3:1 *Bacillus* sp. SJ-10 and *L. plantarum* KCCM 11322 at $0.75 + 0.25 \times 10^8$ CFU g^{-1} feed resulted in improved growth, immunity and disease resistance in olive flounder [43]. Similarly, feeding with *B. subtilis, B. pumilus* and *B. licheniformis* demonstrated identical patterns of response in olive flounder [22]. Among these probiotics, *B. subtilis* and *B. licheniformis* improved disease protection compared to control. In addition, only *B. subtilis* increased fish survival and decreased ammonia concentration (5 days experiment) in controlled culture environments. Jang *et al.* [29] used vegetative cells of BSJ-10 and noted improved growth and feed utilization, and spore-modulated immune genes transcription, leading to improved richness and diversity of intestinal bacterial population.

A study with individual (BSJ-10 and *L. plantarum*) [28] and multi-strain probiotics [126] as supplemented with 30% reduced fish meal diet was found to maintain intestinal homeostasis and immune competence in olive flounder. Both BSJ-10 and *L. plantarum* increased lipase and trypsin, but amylase activity was only improved by BSJ-10. Individual and multi-probiotics also improved concentrations of proteobacteria, actinobacteria, and

Table 5. Effects of probiotic supplementation on growth, feed utilizations, immunological and haemato-biochemical parameters and disease resistance in olive flounder (*Paralichthys olivaceus*).

Probiotics	Mode of administration and dosage	Duration	Effects on *P. olivaceus*	References
Lactococcus lactis BFE920	Dietary supplementation at 10^7 CFU g^{-1} as oral vaccination	4 weeks	$GP_{WG}\uparrow$; $FUP_{FCR}\downarrow$; $IRGE_{CD4\text{-}1, CD4\text{-}2, CD8\alpha, T\text{-}bet, INF\text{-}\gamma, TLR5M, IL\text{-}1\beta, \& IL\text{-}12p40}\uparrow$; Antigen-specific antibodies$\uparrow$; $IDR_{Edwardsiella\ tarda}\uparrow$	[118]
L. lactis BFE920	Dietary supplementation at 10^7 CFU g^{-1} as oral vaccination	4 weeks & 3 Months	$GP_{WG}\uparrow$; $FUP_{FCR}\downarrow$; Antigen-specific antibodies$\uparrow$; $IRGE_{CD4\text{-}1, CD4\text{-}2, CD8\alpha, \& T\text{-}bet}\uparrow$; $IDR_{Strepcoccus\ iniae}\uparrow$	[117]
L. lactis BFE920 (LLBF) & *Lactobacillus plantarum* FGL0001 (LPFG)	Dietary supplementation at 10^7 CFU g^{-1}	30 days	$IRGE_{LLBF\ transcript\ FOXP3, IL\text{-}10, TGF\text{-}\beta1, CD18, \& CD83}\uparrow$, and $_{LPFG\ transcript\ IL\text{-}1\beta, CD18, T\text{-}bet, \& INF\text{-}\gamma}\uparrow$; Gut permeability $_{LPFG}\uparrow$; Immune tone $_{30\ days}$; $IDR_{E.\ tarda}\uparrow$	[17]
L. lactis BFE920, *L. plantarum* FGL0001, & their combination	Dietary supplementation at 10^7 CFU g^{-1}	30 days	$GP_{WG}\uparrow$; $IP_{RB, PcA, \& SMLA}\uparrow$; $IRGE_{TNF\text{-}\alpha, IL\text{-}6, \& IL\text{-}8}\uparrow$; $IDR_{S.\ iniae}\uparrow$	[35]
L. plantarum + *L. brevis* + *L. acidophilus* + *Bacillus subtilis* + *Saccharomyces cerevisiae*	Dietary probiotics mixtures in which each probiotic amount is 0.1%	12 weeks	$GP_{WG}\uparrow$; $IP_{RB, PcA, SL, \& ACA}\uparrow$; $HBP_{ALT, AST, Glu, \& TSP}\uparrow$	[119]
L. plantarum, *L. acidophilus*, *L. sakei*, *B. subtilis*, *S. cerevisiae*	Dietary supplementation of each probiotic at 2.42×10^8 CFU g^{-1}	8 weeks	$GP_{WG}\uparrow$; $FUP_{FER}\uparrow$; $IP_{RB \& SL}\uparrow$; $HBP_{ALT, AST, TSP, \& Glu}\uparrow$; $SR_{Lab.\ plantarum}\uparrow$	[120]
L. fermentum	Dietary supplementation at 0.5%	8 weeks	$GP_{FBW, WG, \& SGR}\rightarrow$; $FUP_{FER \& PER}\rightarrow$; $HBP_{ALT, AST, TC, TG \& TSP}\rightarrow$; $IDR_{S.\ iniae}\uparrow$	[121]
Bacillus SJ-10	Dietary supplementation at 10^8 CFU g^{-1}	8 weeks	$GP_{FBW, WG \& SGR}\rightarrow$; $FUP_{FCR}\downarrow$ $_{\& PER}\uparrow$; $IP_{RB, SOD, \& SL}\uparrow$, and $_{SAP \& MPO}\rightarrow$; $HBP_{ALT, AST, Glu, TC, \& TSP}\rightarrow$; $IRGE_{TNF\text{-}\alpha, IL\text{-}1\beta, \& IL\text{-}10}\uparrow$, and $_{IL\text{-}6, CD4\text{-}1, \& CD4\text{-}2}\rightarrow$, PCI$\uparrow$; $IDR_{S.\ iniae}\uparrow$; mVH$\rightarrow$	[6]
Bacillus SJ-10	Dietary supplementation of heat-killed probiotic at 10^8 CFU g^{-1}	8 weeks	$GP_{FBW, WG \& SGR}\uparrow$; $FUP_{FCR}\downarrow$ $_{\& PER}\uparrow$; $IP_{SOD \& SL}\uparrow$, and $_{RB, SAP \& MPO}\rightarrow$; $HBP_{ALT, AST, Glu, TC, \& TSP}\rightarrow$; $IRGE_{TNF\text{-}\alpha, IL\text{-}6, \& IL\text{-}1\beta}\uparrow$, and $_{IL\text{-}10}\rightarrow$; $IDR_{S.\ iniae}\uparrow$; mVH$\rightarrow$	[125]
Bacillus SJ-10	Dietary supplementation at 10^8 CFU g^{-1}	8 weeks	$GP_{WG \& SGR}\uparrow$; $FUP_{FER \& PER}\uparrow$; $IDR_{E.\ tarda}\uparrow$	[116]
Bacillus sp. SJ-10 and *Lab. plantarum* KCCM 11322	Dietary supplementation at 10^8 CFU g^{-1}	8 weeks	$GP_{WG}\uparrow$; $IP_{SOD, SL, RB, MPO}\uparrow$; $IDR_{streptococcosis}\uparrow$	[43]
B. subtilis, B. pumilus, B. licheniformis	Dietary supplementation of each probiotic at 0.5%	8 weeks & 5 days	$GP_{FBW}\uparrow$; $FUP_{FCR}\downarrow$ $_{\& PER}\uparrow$; $IP_{RB \& SOD}\uparrow$, and $_{SL, SAP, \& MPO}\rightarrow$; $SR_{B.\ subtilis}\uparrow$; $IDR_{S.\ iniae}\uparrow$; $WQP_{Ammonia}\downarrow$ $_{by\ B.\ subtilis}$	[22]
Bacillus SJ-10, *Lab. plantarum*	Dietary supplementation at 10^8 CFU g^{-1}	8 weeks	$DEA_{AmA, Lipase, \& Trypsin}\uparrow$, GutM $_{Proteobacteria, Actinobacteria, \& Acidobacteria}\uparrow$; $IRGE_{BSJ\text{-}10\ transcript\ TNF\text{-}\alpha, IL\text{-}6, IL\text{-}1\beta, \& IL\text{-}10}\uparrow$, and $_{CD4\text{-}1, INF\text{-}\gamma, CD4\text{-}2, CD\text{-}18, \& CD\text{-}83}\rightarrow$; mVH and VH$\rightarrow$; $IDR_{S.\ iniae}\uparrow$	[28]
Bacillus SJ-10	Dietary supplementation at 10^8 CFU g^{-1}	8 weeks	$GP_{FBW, WG \& SGR}\uparrow$; $FUP_{FCR}\downarrow$ $_{\& PER}\uparrow$, $IRGE_{BSJ\text{-}10\ transcript\ TNF\text{-}\alpha \& IL\text{-}1\beta}\uparrow$, GutM $_{Richness \& Diversity}\uparrow$; $IDR_{S.\ iniae}\uparrow$	[29]
B. licheniformis SK3927 + *B. amyloliquefaciens* SK4079 + *B. subtilis* SK4082+ *Lab. brevis* SK1751+ *Lab. plantarum* SK3494 + *S. cerevisiae* SK3587	Dietary supplementation at 10^8 – 10^9 CFU Kg^{-1}	12 weeks	$GP_{FBW, WG, \& SGR}\rightarrow$; $FUP_{FER, FCR \& PER}\rightarrow$; $IP_{MPO, SL, \& IgM}\rightarrow$, and $_{GPx}\uparrow$; $SR\rightarrow$; GutM $_{Lactobacillus, Marinilactibacillus, \& Globicatella}\uparrow$, and $_{Bifidobacterium \& Streptomyces}\downarrow$; $IRGE_{TNF\text{-}\alpha, IL\text{-}1\beta, \& IL\text{-}6}\uparrow$	[126]
Lac. lactis BFE920	Dietary supplementation at 10^6, 5×10^6, 2.5×10^7, 1.25×10^8 CFU g^{-1} in laboratory & 2.5×10^7 CFU g^{-1} in field experiment	2 weeks & 3 months	$_{2\ weeks}\ IDR_{Streptococcus\ iniae}\uparrow$; $GP_{WG}\uparrow$; $FUP_{FER}\uparrow$; $IP_{RB \& MPO}\uparrow$; $IRGE_{IL\text{-}12 \& INF\text{-}\gamma}\uparrow$; $IDR_{S.\ iniae}\uparrow$	[152]

Symbol →, no change; ↑, increase; ↓, decrease versus controls.

ACA: Alternative complement activity; ALT: Alanine aminotransferase; AmA: Amylase activity; AST: Aspartate aminotransferase; CD: Cluster of differentiation; DEA: Digestive enzyme activities; FBW: Final body weight; FCR: Feed conversion ratio; FER: Feed efficiency ratio; FOX: Forkhead box; FUP: Feed utilization parameters; Glu: Glucose; GP: Growth parameters; GPx: Glutathione peroxidase; GutM: Gut microbiota; Hb: Haemoglobin; HBP: Haemato-biochemical parameters; IDR: Infectious disease resistance; Ig: Immunoglobulin; IL: *Interleukin;* INF: Interferon; IP: Immunological parameters; IRGE: Immune related gene expression; MPO: Myloperoxidase; mVH: micro-Villous height; PcA: Phagocytic activity; PCI: Probiotic count in the intestine; PER: Protein efficiency ratio; RB: Respiratory burst (NBT assay); SAP: Serum antiprotease activity; SGR: Specific growth rate (%); SL: Serum lysozyme; SMLA: Skin mucus lysozyme activity; SOD: Superoxide dismutase; SR: Survival rate (%); TC: Total cholesterol; TG: Triglyceride; TGF: Transforming growth factor; TNF: Tumor necrosis factor; TRL5M: Membrane-anchored toll-like receptor 5; TSP: Total serum protein; WG: Weight gain (%).

acidobacteria, and *Lactobacillus, Marinilactibacillus* and *Globicatella* in the intestine, while also elevating cytokines transcription levels. Moreover, multiple and individual probiotics had no effects on production and intestinal structure respectively but improved infectious disease resistance of experimentally-cultured fish.

Grass Carp

Grass carp is predominant among cultured finfishes, comprising 11% of total global aquaculture production in 2016 [1] with production increasing to over 5.7 million tons in 2018; FAO ranked grass carp as the #1 aquacultured species worldwide in 2020 [127]. Several studies have examined the effects of probiotics in grass carp. Dietary *B. licheniformis* FA6 enhanced production, humoral immunity, upregulated immune gene transcription, intestinal morphology and *Aeromonas* infection protection in grass carp [128]. Identical results [129] along with modulation of intestinal microbiome [130] were noted after dietary supplementation of *B. subtilis* Ch9, and both *B. methylotrophicus* WM-1 [131] and *Streptomyces amritsarensis* N1-32 [132] contributed in the modulation of immunity and aeromonosis protection (Table 6).

Individual and mixture of *Shewanella xiamenensis* A-1, *S. xiamenensis* A-2, and *A. veronii* A-7 at 10^8 CFU g^{-1} feed enhanced cellular and humoral immunity, serum biochemistry, gene transcription and offered *A. hydrophila* protection [133]. Administration of *S. xiamenensis* A-1, *A. veronii* A-7 and *B. subtilis* modulate the gut microbiota either singly or in combination, in which proportions of *Cetobacterium*, *Citrobacter*, *Vibrio*, *Enterococcus* and *Streptococcus* were increased, although a decreasing number was noted for *Pseudomonas* and *Flavobacterium* [134].

Several studies were carried out to examine the effects of probiotics on water quality parameters and microbiota

Table 6. Effects of probiotic supplementation on growth, feed utilizations, immunological and haemato-biochemical parameters and disease resistance in grass carp (*Ctenopharyngodon idellus*).

Probiotics	Mode of administration and dosage	Duration	Effects on *C. idellus*	References
Bacillus licheniformis FA6	Dietary supplementation at 10^5 to 10^6 CFU g^{-1}	70 days	GP $_{WG \& SGR}$↑; IP $_{SOD}$↑, and MDA↓; IRGE $_{IL\text{-}10, SOD, \& CAT}$↑, and IL-1β, TNFα, TLR3, TLR7, & MyD88↓; Intestinal morphology $_{VH \& Muscle thickness}$↑; IDR $_{Aeromonas\ hydrophila}$↑	[128]
B. subtilis Ch9	Dietary supplementation at 2.4×10^7 CFU g^{-1}	42 days	GP $_{FBW, WG, \& SGR}$↑; IP $_{TAC, SOD, \& CAT}$↑, and MDA↓; IRGE $_{IL\text{-}10, SOD, CAT, \& GPx}$↑, and TNF-α, IL-8, & IL-1β↓; IDR $_{A.\ hydrophila}$↑	[129]
B. subtilis Ch9	Dietary supplementation at 10^7 CFU g^{-1}	8 weeks	GP $_{FBW, WG, \& SGR}$↑; HBP $_{ALT, HDL}$↑, and AST, TG, Alb, TP & TC→; GutM↑; Fatty liver disease↓	[130]
B. methylotrophicus WM-1	Dietary supplementation at 10^3, 10^5 & 10^7 CFU g^{-1}	90 days	IP $_{SOD}$↑; IDR $_{A.\ hydrophila}$↑; SR↑	[131]
Streptomyces amritsarensis N1-32	Dietary supplementation at 10^7 & 10^9 CFU g^{-1}	28 days	GP $_{WG}$→; IP $_{SL, SOD, \& ACP}$↑; IRGE $_{IgM, TLR4, MyD88, Nrf2, \& Keap1}$↑, and TNF-α→; IDR $_{A.\ veronii}$↑	[132]
Shewanella xiamenensis A-1, 2, & *Aeromonas veronii* A-7	Dietary supplementation at 10^8 CFU g^{-1}	28 days	IP $_{RB, PcA, C3, \& SL}$↑; HBP $_{TSP, Alb, \& Glb}$↑; IRGE $_{IL\text{-}8, IL\text{-}1\beta, Lysozyme\ C, \& TNF\text{-}\alpha}$↑; IDR $_{A.\ hydrophila}$↑	[133]
S. xiamenensis A-1, *A. veronii* A-7 & *B. subtilis*	Dietary supplementation at 10^8 CFU g^{-1}	28 days	GutM $_{Cetobacterium,\ Citrobacter,\ Vibrio,\ Enterococcus, \& Streptococcus}$↑, and $_{Pseudomonas \& Flavobacterium}$↓	[134]
Pseudomonas stutzeri F11	Water supplementation at 10^5 CFU ml^{-1}	9 days	WQP $_{Ammonia, Nitrite, \& Total\ nitrogen}$↓, and Nitrate→; Water Microbiota $_{Bacteroidetes \& Firmicutes}$↑, and $_{Proteobacteria, Actinobacteria, \& Verrucomicrobia}$↓	[135]
B. licheniformis BSK-4	Water supplementation at 10^8 CFU m^{-3}	18 days	WQP $_{Nitrite, Nitrate, \& Total\ nitrogen}$↓, and Ammonia↑; Water Microbiota $_{Proteobacteria \& Firmicutes}$↑, and $_{Actinobacteria \& Bacteroidetes}$↓	[136]
P. stutzeri SC221-M & *B. cereus* BSC24	Water supplementation at 10^5 & 3×10^5 CFU ml^{-1}	6 days	WQP $_{TDS, Ammonium, Nitrite, Total\ nitrogen, \& COD}$↓; Water Microbiota $_{Proteobacteria}$↑, and $_{Bacteroidetes \& Actinobacteria}$↓	[137]
B. natto NT	Dietary supplementation at (1.8, 3.73, 5.60, 7.47, & 9.33) × 10^9 CFU 100 g^{-1}	56 days	GP $_{FBW, WG \& SGR}$↑; FUP $_{FCR}$↓; SR→; GRGE $_{miR\text{-}1a, miR\text{-}181a, miR\text{-}206, \& miR\text{-}23a}$↑, and MyoG, MEF2C, & SRF↓, and miR-133a & miR-101a→	[153]

Symbol →, no change; ↑, increase; ↓, decrease versus controls.

ACP: Acid phosphatase; ALT: Alanine aminotransferase; AST: Aspartate aminotransferase; Alb: Albumin, AmA: Amylase activity; C3: Complement C3; CAT: Catalase; COD: Chemical oxygen demand; DEA: Digestive enzyme activities; FBW: Final body weight; FCR: Feed conversion ratio; FUP: Feed utilization parameters; Glb: Globulin; GP: Growth parameters; GPx: Glutathione peroxidase; GRGE: Growth related gene expression; GutM: Gut microbiota; HDL: High-density lipoprotein; HBP: Haemato-biochemical parameters; IDR: Infectious disease resistance; Ig: Immunoglobulin; IL: Interleukin; IP: Immunological parameters; IRGE: Immune related gene expression; Keap1: Kelch-like ECH-associated protein 1 gene; LDL: Low-density lipoprotein; MDA: Malondialdehyde; MEF2C: Myocyte enhancer factor 2C; MPO: Myloperoxidase; MyD: Myeloid differentiation factor; MyoG: Myogenin; Nrf: Nuclear factor (erythroid-derived 2)-like 2 gene; PcA: Phagocytic activity; PrA: Protease activity; RB: Respiratory burst (NBT assay); SGR: Specific growth rate (%); SL: Serum lysozyme; SOD: Superoxide dismutase; SR: Survival rate; SRF: Serum response factor; TAC: Total anti-oxidant capacity; TC: Total cholesterols; TG: Triglyceride; TDS: Total dissolved solids; TLR: Toll like receptor; TNF: Tumor necrosis factor; TSP: Total serum protein; VH: Villous height; WG: Weight gain (%); WQP: Water quality parameters.

in the culture environment of grass carp. The addition of *P. stutzeri* F11 [135] and *B. licheniformis* BSK-4 [136] in water led to reduction of ammonia, nitrite, total nitrogen and altered microbial populations at 9 and 18 days, respectively (Table 6). In another study, application of individual and mixture of *P. stutzeri* SC221-M and *B. cereus* BSC24 in culture water improved the rearing water quality as revealed by lower levels of total dissolved solids, chemical oxygen demand, ammonium, nitrite and total nitrogen compared to the control after 6-days post-treatment [137]. Moreover, these probiotics increased proteobacteria and decreased bacteroidetes and actinobacteria in ambient water.

Rohu Carp

Labeo rohita, commonly known as Indian major carp or rohu, is among the most cultured fish species in South Asia due to its commercial value, fast growth rate, consumer preferences and comparative simplicity in weaning to artificial diets [138, 139]. Global production of rohu was 1.843 million tons in 2016, contributing 3% of total global finfish production [1]. Weakened immune system and lack of necessary digestive enzymes in juveniles can lead to higher rates of pathogenic bacterial infection and relatively poor feed utilization [138, 140]. Efforts have been made continuously to subdue these problems, including many involving applications of probiotics.

Higher serum IgM levels were recorded after 30 days, and the level decreased after 60 days. Similarly, mixtures of these probiotics with *B. subtilis* VSG1 modulated and generally improved similar immunological parameters,

Table 7. Effects of probiotic supplementation on growth, feed utilizations, immunological and haemato-biochemical parameters and disease resistance in rohu fish (*Labeo rohita*).

Probiotics	Mode of administration and dosage	Duration	Effects on *L. rohita*	References
Bacillus subtilis VSG1, *L. plantarum* VSG3, & *P. aeruginosa* VSG2	Dietary supplementation at (0.33, 0.5 & 1) × 10^8 CFU g^{-1}	60 days	$GP_{WG\ \&\ SGR}\uparrow$; $FUP_{FCR}\downarrow$; $IP_{SL,\ ACA,\ PcA,\ RB,\ SOD,\ \&\ IgM}\uparrow$; $IDR_{A.\ hydrophila}\uparrow$	[141]
B. subtilis, L. lactis, & *Saccharomyces cerevisiae*	Dietary supplementation at 10^{11} CFU Kg^{-1}	30 days	$GP_{WG}\uparrow$; $HBP_{TSP,\ Glb,\ \&\ RBC}\uparrow$, and Glu, ACP, ALP, & WBC$\downarrow$; $IP_{RB,\ MPO,\ \&\ IgM}\uparrow$; $IRGE_{HSP70}\uparrow$; Apoptosis$\downarrow$	[142]
B. methylotrophicus, B. amyloliquefaciens, & *B. licheniformis*	Dietary supplementation at 10^7 CFU g^{-1}	60 days	$GP_{WG\ \&\ SGR}\uparrow$; $FUP_{PER}\uparrow$, and $FCR\downarrow$; $HBP_{Hb,\ RBC,\ WBC,\ TSP,\ Platelet,\ Glu,\ AST,\ \&\ ALT}\uparrow$; $IP_{SL,\ ACA,\ PcA,\ RB,\ IgM,\ MPO,\ \&\ SAP}\uparrow$; $DEA_{PrA,\ AmA,\ \&\ Lipase}\uparrow$; $IDR_{A.\ hydrophila}\uparrow$	[143]
B. aerophilus KADR3	Dietary supplementation at 10^7, 10^8 & 10^9 CFU g^{-1}	3 & 6 weeks	$HBP_{TSP}\uparrow$; $IP_{SL,\ ACA,\ PcA,\ RB,\ SOD,\ \&\ IgM}\uparrow$; $IDR_{A.\ hydrophila}\uparrow$	[20]
B. amyloliquefaciens CCF7	Dietary supplementation at 10^5, 10^7 & 10^9 CFU g^{-1}	70 & 28 days	$HBP_{Glb,\ Alb,\ \&\ TSP}\uparrow$, and AST & ALT$\downarrow$; $IP_{SOD,\ SL,\ CAT,\ \&\ IgM}\uparrow$, and MDA$\downarrow$; $IDR_{A.\ hydrophila}\uparrow$	[144]
B. amyloliquefaciens COFCAU_P1	Dietary supplementation at 10^7, 10^8 & 10^9 CFU g^{-1}	30 days	$HBP_{Alb,\ Glb\ \&\ TP}\uparrow$; $IP_{MPO,\ SOA\ \&\ antiprotease}\uparrow$; $IDR_{A.\ hydrophila}\uparrow$; $IRGE_{TNF\text{-}\alpha\ \&\ IL\text{-}1\beta}\uparrow$; $SR\uparrow$	[145]
Geotrichum candidum QAUGC01	Water supplementation at 10^9 CFU L^{-1}	70 days	$GP_{WG\ \&\ SGR}\uparrow$; $DEA_{PrA,\ AmA,\ \&\ Cellulase}\uparrow$; $IDR_{Staphylococcus\ aureus}\uparrow$; $SR\uparrow$	[140]
G. candidum QAUGC01 & *B. cereus*	Dietary supplementation at 10^9 CFU g^{-1}	11 weeks	$GP_{FBW\ \&\ SGR}\uparrow$; $DEA_{PrA,\ AmA,\ \&\ Cellulase}\uparrow$; $IDR_{A.\ hydrophila}\uparrow$; $GutM\uparrow$; $SR\uparrow$	[138]
Enterococcus faecium QAUEF01, *E. faecium* QAUEF01 + *G. candidum* QAUGC01	Dietary supplementation at 10^9 CFU g^{-1}	90 days	$GP_{WG\ \&\ SGR}\uparrow$; $FUP_{FCE}\uparrow$, and $FCR\downarrow$; $HBP_{RBC,\ WBC,\ Hb,\ \&\ Lymphocyte}\uparrow$; $DEA_{PrA\ \&\ Cellulase}\uparrow$; $GutM\uparrow$	[146]
S. cerevisiae	Dietary supplementation at 0.5, 0.75 & 1%	60 days	$GP_{WG}\uparrow$; $FUP_{PER}\uparrow$, and $FCR\downarrow$; $HBP_{Hb,\ RBC,\ WBC,\ ALT,\ \&\ AST}\uparrow$; $DEA_{PrA\ \&\ AmA}\uparrow$; $IDR_{A.\ hydrophila}\uparrow$	[147]
G. candidum QAUGC01	Dietary supplementation at 10^9 CFU g^{-1}	11 weeks	$GP_{WG}\uparrow$; $HBP_{Hb,\ RBC,\ WBC,\ Ht,\ \&\ TSP}\uparrow$, and AST, ALT, TC, & $TG\downarrow$; $IP_{RB,\ SL,\ IgM,\ \&\ PcA}\uparrow$; $IRGE_{HSP70}\uparrow$; $DEA_{PrA,\ AmA,\ \&\ Cellulase}\uparrow$	[154]
Lactobacillus spp., *Streptococcus faecium, B. bifidum, B. subtilis, Sacchromyces* spp., *Torulopsis* & *Aspergillus oryzae*	Dietary supplementation at 1 & 1.5 g Kg^{-1}	30 days	$GP_{FBW\ \&\ SGR}\uparrow$; $SR\uparrow$	[155]

Symbol →, no change; ↑, increase; ↓, decrease versus controls.

ACA: Alternative complement activity; ACP: Acid phosphatase; ALP: Alkaline phosphatase; ALT: Alanine aminotransferase; AmA: Amylase activity; AST: Aspartate aminotransferase; CAT: Catalase; DEA: Digestive enzyme activities; FCE: Feed conversion efficiency; FCR: Feed conversion ratio; FUP: Feed utilization parameters; Glb: Globulin; Glu: Glucose; GP: Growth parameters; GutM: Gut microbiota; Hb: Haemoglobin; HBP: Haemato-biochemical parameters; HSP70: Heat shock protein; IDR: Infectious disease resistance; IgM: Immunoglobulin M; IL: Interleukin; IP: Immunological parameters; IRGE: Immune related gene expression; MDA: Malondialdehyde; MPO: Myloperoxidase; PcA: Phagocytic activity; PER: Protein efficiency ratio; PrA: Protease activity; RB: Respiratory burst (NBT assay); RBC: Red blood cell; SAP: Serum antiprotease activity; SBA: Serum bactericidal activity; SGR: Specific growth rate (%); SL: Serum lysozyme; SOA: Superoxide anion; SOD: Superoxide dismutase; SR: Survival rate; TC: Total cholesterols; TG: Triglyceride; TNF: Tumor necrosis factor; TSP: Total serum protein; WBC: White blood cell; WG: Weight gain (%).

including disease resistance [141] (Table 7). Feeding of *B. subtilis*, *L. lactis* and *S. cerevisiae* mixture at different culture temperatures (28, 31, 34, and 37°C) reduced the degree of apoptosis, augmented the transcription of HSP70, positively modulated haemato-biochemistry and innate immunity compared to the control [142]. Supplementation with *B. methylotrophicus*, *B. amyloliquefaciens* and *B. licheniformis* either singly or in combination elevated digestive enzymes activity, immunity and offered a significant degree of infection protection [143]. Similarly, disease protection and immunity alteration were observed after administration with *B. aerophilus* KADR3 [20], *B. amyloliquefaciens* CCF7 [144] and COFCAU_P1 [145] (Table 7).

Improved protease, amylase and cellulose resulting on good growth in rohu fingerlings were observed after adding *Geothichum candidum* QAUGC01 to rearing water [140]. Similarly, *G. candidum* QAUGC01, *B. cereus* and *G. candidum* QAUGC01 + *B. cereus* at 10^9 CFU g^{-1} elevated gut microbiome, digestive enzymes and survivability against *A. hydrophila* infection [138]. Similar parameters modulation with improvements in the growth increment were observed after administration of single *E. faecium* QAUEF01 and its combination with *G. candidum* QAUGC01 [146] and *S. cerevisiae* [147].

Probiotics Application under Farming Condition

Most studies on probiotics were conducted under laboratory conditions, in which water and ambient environmental parameters are subject to rigid control. The role of probiotics in open systems under farming conditions remains minimally studied. While performance of probiotics under uncontrolled field levels is subject to uncertainty, commercial manufacturers of probiotics frequently boast that their products are highly effective for farm level application.

Tilapia cultured in earthen ponds treated with two doses of *B. pumilus* and a commercial probiotic for 8 months showed increase growth, immunity and haematological parameters, and *A. hydrophila* infection protection [79] (Table 1). Artificially cultured fishes are subjected in the hatchery to water quality and other parameters that can compromise the consistent production of healthy juveniles [148], although probiotic applications among broodstock, embryos and larvae have been studied inadequately. Female rainbow trout brood stock in raceway ponds supplemented with multi-probiotics before spawning season demonstrated production of eggs with higher diameters, increased fecundity, fertilization and hatching, yolk sac absorption, and eye development [14]. These results are consistent with beneficial responses to multiple-species LAB probiotic applications in the zebrafish hatchery, which led to consistent improvements in every measurable parameter of larval performance [149]. Moreover, multi probiotics supplementation in rainbow trout during grow out in floating cages led to improved haemato-immunological responses and operational taxonomic units in the intestine [150] (Table 3).

Common carp (2.75 g) cultured in raceways and fed with *B. sublitis* for 180 days at $4 \times 10^{6\,\&\,8}$ CFU g^{-1} showed elevated production and feed utilizations as contrasted with controls [151]. Moreover, probiotics increased muscle RNA-DNA ratio along with crude lipid, protein, and ash content in the body (Table 4). Single supplementation of *L. lactis* BFE920 at different concentrations increased protection against streptococcosis (68-77%) after 2 weeks. Subsequently, 2.5×10^7 CFU g^{-1} was chosen for field experiment for 3 months in 12,000 olive flounder [152]. That experiment revealed that probiotics fed group displayed improved immunity and immune related gene expression, resulting in 65.7% survival relative to 5.7% in control group when challenged with *S. iniae* (Table 5).

Cage culture of grass carp (~44 g) for 56 days with *B. natto* NT supplementation improved body weight and feed utilization [153]. Myostatin and myocyte enhancer factor C were downregulated, whereas micro-RNA (miR)-1a, miR-181a, miR-23a, and miR-206 transcription were upregulated compared to control group (Table 6). Rohu carp in earthen ponds displayed improved immunity and digestive enzyme activities along with enhanced tissue HSP70 expression after 11 weeks feeding with encapsulated *G. candidum* QAUGC01 [154]. Multi-probiotics administration in that species in outdoor tanks resulted in higher survival of hatchlings and fry at 8 and 38 days, respectively but those differences were no longer detectable after 68 days [155] (Table 7).

Research Gaps and Concluding Remarks

Some urgency is attached to the transition from the use and at times excessive use of antibiotics to control pathogens in aquaculture. The effectiveness of antibiotics is counteracted by intense selection favouring resistance, leading to the emergence of dangerously capable pathogens. The hazards of routine antibiotic applications are well-recognized now, and alternatives are critically needed. Probiotics are being marketed to aquaculture professionals, but it is generally true that their effectiveness in any given situation is uncertain.

Probiotics are typically found among microorganisms inhabiting the digestive tracts of healthy aquatic species, and their presence has been found to induce beneficial changes such as improved growth, immunity, and survival. Although the concept of promoting improved health by altering the population structure of the microbiome has gained favour, the mechanisms involved are far from clear. Probiotic organisms decrease the likelihood of the impairment or mortality of culture subjects by pathogens through a poorly understood complex of mechanisms, and more specific understanding of these mechanisms is highly desired. Interactive mechanisms of probiotic species with intestinal cells of host subjects require further investigation and analysis.

Probiotics contribute to the development of an unfavourable environment for the proliferation of pathogens, thereby disabling opportunistic microbes including many pathogens, thereby reducing the prevalence of outbreaks of infectious organisms. This can happen by direct and indirect means, for example by generating metabolites that are inhibitory to pathogens, or that promote activation of the immune system, or sometimes simply by competing for nutrients and environmental niches. As discussed above, activation of growth- and

immune-related genes have been observed and may be more symptomatic of beneficial health effects than unknown causative factors. Further study of the mechanisms resulting in beneficial impacts of probiotic organisms may lead to more effective treatments and ultimately to improved environmental management of commercially cultured fishes and invertebrates.

Acknowledgments

This study was supported by Brain Pool Scholarship (Grant no.: 2021H1D3A2A01099381) funded by National Research Foundation of Korea (NRF) and NRF grant funded by Ministry of Education (Grant no.: 2021R1I1A1A01049238).

Conflict of Interest

The authors have no financial conflicts of interest to declare.

References

1. FAO. 2018. Fisheries Department, Fishery Information, Data and Statistics Unit. FishStatJ, a tool for fishery statistics analysis. *Global aquaculture production: Quantity 1950–2016; Value 1950–2016; Global capture production: 1950–2016; 2018-03-16.* .
2. Hoseinifar SH, Sun Y-Z, Wang A, Zhou Z. 2018. Probiotics as means of diseases control in aquaculture, a review of current knowledge and future perspectives. *Front. Microbiol.* **9:** 2429.
3. Dawood MA, Koshio S, Abdel-Daim MM, Van Doan H. 2019. Probiotic application for sustainable aquaculture. *Rev. Aquac.* **11:** 907-924.
4. Berg A, Rødseth OM, Hansen T. 2007. Fish size at vaccination influence the development of side-effects in Atlantic salmon (*Salmo salar* L.). *Aquaculture* **265:** 9-15.
5. Wang A, Ran C, Wang Y, Zhang Z, Ding Q, Yang Y, *et al.* 2019. Use of probiotics in aquaculture of China—a review of the past decade. *Fish Shellfish Immunol.* **86:** 734-755.
6. Hasan MT, Jang WJ, Lee S, Kim KW, Lee BJ, Han HS, *et al.* 2018a. Effect of β-glucooligosaccharides as a new prebiotic for dietary supplementation in olive flounder (*Paralichthys olivaceus*) aquaculture. *Aquac. Res.* **49:** 1310-1319.
7. Dawood MA, Koshio S. 2016. Recent advances in the role of probiotics and prebiotics in carp aquaculture: a review. *Aquaculture* **454:** 243-251.
8. Hasan MT, Je Jang W, Lee JM, Lee B-J, Hur SW, Gu Lim S, *et al.* 2019a. Effects of immunostimulants, prebiotics, probiotics, synbiotics, and potentially immunoreactive feed additives on olive flounder (*Paralichthys olivaceus*): a review. *Rev. Fisheries Sci. Aquac.* **27:** 417-437.
9. Murray CJ, Ikuta KS, Sharara F, Swetschinski L, Aguilar GR, Gray A, *et al.* 2022. Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. *Lancet* **399:** 629-655.
10. Sharifuzzaman S, Austin B. 2017. Probiotics for disease control in aquaculture. pp. 189-222. *Diagnosis and control of diseases of fish and shellfish*. Publisher: John Wiley & Sons, Inc.
11. Hasan MT, Jang WJ, Kim H, Lee B-J, Kim KW, Hur SW, *et al.* 2018b. Synergistic effects of dietary *Bacillus* sp. SJ-10 plus β-glucooligosaccharides as a synbiotic on growth performance, innate immunity and streptococcosis resistance in olive flounder (*Paralichthys olivaceus*). *Fish Shellfish Immunol.* **82:** 544-553.
12. Parker R. 1974. Probiotics, the other half of the antibiotic story. *Anim. Nutr. Health* **29:** 4-8.
13. Merrifield DL, Dimitroglou A, Foey A, Davies SJ, Baker RT, Bøgwald J, *et al.* 2010a. The current status and future focus of probiotic and prebiotic applications for salmonids. *Aquaculture* **302:** 1-18.
14. Akbari Nargesi E, Falahatkar B, Sajjadi MM. 2020. Dietary supplementation of probiotics and influence on feed efficiency, growth parameters and reproductive performance in female rainbow trout (*Oncorhynchus mykiss*) broodstock. *Aquac. Nutr.* **26:** 98-108.
15. Naderi Farsani M, Bahrami Gorji S, Hoseinifar SH, Rashidian G, Van Doan H. 2020. Combined and singular effects of dietary primalac® and potassium diformate (KDF) on growth performance and some physiological parameters of rainbow trout (*Oncorhynchus mykiss*). *Probiotics Antimicrob. Proteins* **12:** 236-245.
16. Makled SO, Hamdan AM, El-Sayed A-FM. 2020. Growth promotion and immune stimulation in nile tilapia, *Oreochromis niloticus*, fingerlings following dietary administration of a novel marine probiotic, *Psychrobacter maritimus* S. *Probiotics Antimicrob. Proteins* **12:** 365-374.
17. Beck BR, Song JH, Park BS, Kim D, Kwak J-H, Do HK, *et al.* 2016. Distinct immune tones are established by *Lactococcus lactis* BFE920 and *Lactobacillus plantarum* FGL0001 in the gut of olive flounder (*Paralichthys olivaceus*). *Fish Shellfish Immunol.* **55:** 434-443.
18. Park Y, Kim H, Won S, Hamidoghli A, Hasan MT, Kong IS, *et al.* 2020. Effects of two dietary probiotics (*Bacillus subtilis* or *licheniformis*) with two prebiotics (mannan or fructo oligosaccharide) in Japanese eel, *Anguilla japonica*. *Aquac. Nutr.* **26:** 316-327.
19. Akter MN, Hashim R, Sutriana A, Siti Azizah MN, Asaduzzaman M. 2019. Effect of *Lactobacillus acidophilus* supplementation on growth performances, digestive enzyme activities and gut histomorphology of striped catfish (*Pangasianodon hypophthalmusSauvage*, 1878) juveniles. *Aquac. Res.* **50:** 786-797.
20. Ramesh D, Souissi S, Ahamed TS. 2017. Effects of the potential probiotics *Bacillus aerophilus* KADR3 in inducing immunity and disease resistance in *Labeo rohita*. *Fish Shellfish Immunol.* **70:** 408-415.
21. Hasan MT, Jang WJ, Kim H, Lee B-J, Kim KW, Hur SW, *et al.* 2018c. Synergistic effects of dietary *Bacillus* sp. SJ-10 plus β-glucooligosaccharides as a synbiotic on growth performance, innate immunity and streptococcosis resistance in olive flounder (*Paralichthys olivaceus*). *Fish Shellfish Immunol.* **82:** 544-553.
22. Cha J-H, Rahimnejad S, Yang S-Y, Kim K-W, Lee K-J. 2013. Evaluations of *Bacillus* spp. as dietary additives on growth performance, innate immunity and disease resistance of olive flounder (*Paralichthys olivaceus*) against *Streptococcus iniae* and as water additives. *Aquaculture* **402:** 50-57.
23. Wang Y-B, Li J-R, Lin J. 2008a. Probiotics in aquaculture: challenges and outlook. *Aquaculture* **281:** 1-4.
24. Huang W, Chang J, Wang P, Liu C, Yin Q, Zhu Q, *et al.* 2018. Effect of the combined compound probiotics with mycotoxin–degradation enzyme on detoxifying aflatoxin B1 and zearalenone. *J. Toxicol. Sci.* **43:** 377-385.
25. Sugahara H, Odamaki T, Fukuda S, Kato T, Xiao J-z, Abe F, *et al.* 2015. Probiotic *Bifidobacterium longum* alters gut luminal metabolism through modification of the gut microbial community. *Sci. Rep.* **5:** 1-11.
26. Jang WJ, Lee S-J, Jeon M-H, Kim T-Y, Lee JM, Hasan MT, *et al.* 2021a. Characterization of a *Bacillus* sp. KRF-7 isolated from the intestine of rockfish and effects of dietary supplementation with mannan oligosaccharide in rockfish aquaculture. *Fish Shellfish Immunol.* **119:** 182-192.

27. Nguafack TT, Jang WJ, Hasan MT, Choi YH, Bai SC, Lee E-W, *et al.* 2020. Effects of dietary non-viable *Bacillus* sp. SJ-10, *Lactobacillus plantarum*, and their combination on growth, humoral and cellular immunity, and streptococcosis resistance in olive flounder (*Paralichthys olivaceus*). *Res. Vet. Sci.* **131:** 177-185.
28. Jang WJ, Lee JM, Hasan MT, Lee B-J, Lim SG, Kong I-S. 2019a. Effects of probiotic supplementation of a plant-based protein diet on intestinal microbial diversity, digestive enzyme activity, intestinal structure, and immunity in olive flounder (*Paralichthys olivaceus*). *Fish Shellfish Immunol.* **92:** 719-727.
29. Jang WJ, Hasan MT, Lee GH, Lee B-J, Hur SW, Lee S, *et al.* 2021b. Comparison of spore or vegetative *Bacillus* sp. supplementation on physiological changes and gut microbiota of the olive flounder (*Paralichthys olivaceus*). *Aquaculture* **535:** 736355.
30. Sharifuzzaman S, Al-Harbi A, Austin B. 2014. Characteristics of growth, digestive system functionality, and stress factors of rainbow trout fed probiotics *Kocuria* SM1 and *Rhodococcus* SM2. *Aquaculture* **418:** 55-61.
31. Dawood MA, Eweedah NM, Moustafa EM, Farahat EM. 2020a. Probiotic effects of *Aspergillus oryzae* on the oxidative status, heat shock protein, and immune related gene expression of Nile tilapia (*Oreochromis niloticus*) under hypoxia challenge. *Aquaculture* **520:** 734669.
32. Barroso C, Ozorio RO, Afonso A, Moraes JR, Costas B. 2016. Immune responses and gut morphology in Senegalese sole (*Solea senegalensis*) fed dietary probiotic supplementation and following exposure to *Photobacterium damselae* subsp. piscicida. *Aquac. Res.* **47:** 951-960.
33. Kashem MA, Uddin MN, Hossain MM, Hasan MT, Haque SA, Khan MNA, *et al.* 2014. Effect of oxytetracycline on bacterial load of *Labeo rohita* (Rohu) fish in culture pond. *Glo. Adv. Res. J. Microbiol.* **3:** 018-024.
34. Kordon AO, Karsi A, Pinchuk L. 2018. Innate immune responses in fish: Antigen presenting cells and professional phagocytes. *Turkish J. Fish. Aquat. Sci.* **18:** 1123-1138.
35. Beck BR, Kim D, Jeon J, Lee S-M, Kim HK, Kim O-J, *et al.* 2015. The effects of combined dietary probiotics *Lactococcus lactis* BFE920 and *Lactobacillus plantarum* FGL0001 on innate immunity and disease resistance in olive flounder (*Paralichthys olivaceus*). *Fish Shellfish Immunol.* **42:** 177-183.
36. Van Doan H, Hoseinifar SH, Khanongnuch C, Kanpiengjai A, Unban K, Srichaiyo S. 2018. Host-associated probiotics boosted mucosal and serum immunity, disease resistance and growth performance of Nile tilapia (*Oreochromis niloticus*). *Aquaculture* **491:** 94-100.
37. Dobaño C, Moncunill G. 2018. Naturally acquired immunity (NAI). pp. 1-15. *Encyclopedia of malaria. Springer New York, New York, NY.*
38. Hoseinifar SH, Mirvaghefi A, Amoozegar MA, Sharifian M, Esteban MÁ. 2015. Modulation of innate immune response, mucosal parameters and disease resistance in rainbow trout (*Oncorhynchus mykiss*) upon synbiotic feeding. *Fish Shellfish Immunol.* **45:** 27-32.
39. Akhter N, Wu B, Memon AM, Mohsin M. 2015. Probiotics and prebiotics associated with aquaculture: a review. *Fish Shellfish Immunol.* **45:** 733-741.
40. Kim Y-R, Kim E-Y, Choi S-y, Hossain MT, Oh R-K, Heo W-S, *et al.* 2012. Effect of a probiotic strain, *Enterococcus faecium*, on the immune responses of olive flounder (*Paralichthys olivaceus*). *J. Microbiol. Biotechnol.* **22:** 526-529.
41. Kono T, Ponpornpisit A, Sakai M. 2004. The analysis of expressed genes in head kidney of common carp *Cyprinus carpio* L. stimulated with peptidoglycan. *Aquaculture* **235:** 37-52.
42. Scheller J, Chalaris A, Schmidt-Arras D, Rose-John S. 2011. The pro-and anti-inflammatory properties of the cytokine interleukin-6. *Biochim. Biophys. Acta* **1813:** 878-888.
43. Hasan MT, Jang WJ, Lee B-J, Hur SW, Lim SG, Kim KW, *et al.* 2021. Dietary supplementation of *Bacillus* sp. SJ-10 and *Lactobacillus plantarum* KCCM 11322 combinations enhance growth and cellular and humoral immunity in olive flounder (*Paralichthys olivaceus*). *Probiotics Antimicrob. Proteins* **13:** 1277-1291.
44. Brunt J, Hansen R, Jamieson DJ, Austin B. 2008. Proteomic analysis of rainbow trout (*Oncorhynchus mykiss,* Walbaum) serum after administration of probiotics in diets. *Vet. Immunol Immunopathol.* **121:** 199-205.
45. Galdeano CM, Cazorla SI, Dumit JML, Vélez E, Perdigón G. 2019. Beneficial effects of probiotic consumption on the immune system. *Ann. Nutr. Metab.* **74:** 115-124.
46. Link-Amster H, Rochat F, Saudan K, Mignot O, Aeschlimann J. 1994. Modulation of a specific humoral immune response and changes in intestinal flora mediated through fermented milk intake. *FEMS Immunol. Med. Microbiol.* **10:** 55-63.
47. Fang H, Elina T, Heikki A, Seppo S. 2000. Modulation of humoral immune response through probiotic intake. *FEMS Immunol. Med. Microbiol.* **29:** 47-52.
48. Sankaran-Walters S, Hart R, Dills C. 2017. Guardians of the gut: enteric defensins. *Front. Microbiol.* **8:** 647.
49. Cazorla SI, Maldonado-Galdeano C, Weill R, De Paula J, Perdigón GD. 2018. Oral administration of probiotics increases paneth cells and intestinal antimicrobial activity. *Front. Microbiol.* **9:** 736.
50. Pridgeon JW, Klesius PH. 2011. Development and efficacy of a novobiocin-resistant *Streptococcus iniae* as a novel vaccine in Nile tilapia (*Oreochromis niloticus*). *Vaccine* **29:** 5986-5993.
51. Rinkinen M, Jalava K, Westermarck E, Salminen S, Ouwehand AC. 2003. Interaction between probiotic lactic acid bacteria and canine enteric pathogens: a risk factor for intestinal *Enterococcus faecium* colonization? *Vet. Microbiol.* **92:** 111-119.
52. Abou-El-Atta ME, Abdel-Tawwab M, Abdel-Razek N, Abdelhakim TM. 2019. Effects of dietary probiotic *Lactobacillus plantarum* and whey protein concentrate on the productive parameters, immunity response and susceptibility of Nile tilapia, *Oreochromis niloticus* (L.), to *Aeromonas sobria* infection. *Aquac. Nutr.* **25:** 1367-1377.
53. Yu L, Zhai Q, Zhu J, Zhang C, Li T, Liu X, *et al.* 2017. Dietary *Lactobacillus plantarum* supplementation enhances growth performance and alleviates aluminum toxicity in tilapia. *Ecotoxicol. Environ. Safety* **143:** 307-314.
54. Zhai Q, Wang H, Tian F, Zhao J, Zhang H, Chen W. 2017. Dietary *Lactobacillus plantarum* supplementation decreases tissue lead accumulation and alleviates lead toxicity in Nile tilapia (*Oreochromis niloticus*). *Aquac. Res.* **48:** 5094-5103.
55. Van Doan H, Hoseinifar SH, Tapingkae W, Tongsiri S, Khamtavee P. 2016. Combined administration of low molecular weight sodium alginate boosted immunomodulatory, disease resistance and growth enhancing effects of *Lactobacillus plantarum* in Nile tilapia (*Oreochromis niloticus*). *Fish Shellfish Immunol.* **58:** 678-685.
56. Poolsawat L, Li X, He M, Ji D, Leng X. 2020. *Clostridium butyricum* as probiotic for promoting growth performance, feed utilization, gut health and microbiota community of tilapia (*Oreochromis niloticus*× *O. aureus*). *Aquac. Nutr.* **26:** 657-670.
57. Li H, Zhou Y, Ling H, Luo L, Qi D, Feng L. 2019. The effect of dietary supplementation with *Clostridium butyricum* on the growth performance, immunity, intestinal microbiota and disease resistance of tilapia (*Oreochromis niloticus*). *PLoS One* **14:** e0223428.
58. Liu H, Wang S, Cai Y, Guo X, Cao Z, Zhang Y, *et al.* 2017. Dietary administration of *Bacillus subtilis* HAINUP40 enhances growth, digestive enzyme activities, innate immune responses and disease resistance of tilapia, *Oreochromis niloticus*. *Fish Shellfish Immunol.* **60:** 326-333.
59. Gobi N, Vaseeharan B, Chen J-C, Rekha R, Vijayakumar S, Anjugam M, *et al.* 2018. Dietary supplementation of probiotic *Bacillus licheniformis* Dahb1 improves growth performance, mucus and serum immune parameters, antioxidant enzyme activity as well as resistance against *Aeromonas hydrophila* in tilapia *Oreochromis mossambicus. Fish Shellfish Immunol.* **74:** 501-508.
60. Abarike ED, Jian J, Tang J, Cai J, Yu H, Lihua C, *et al.* 2018. Influence of traditional Chinese medicine and *Bacillus* species (TCMBS) on growth, immune response and disease resistance in Nile tilapia, *Oreochromis niloticus*. *Aquac. Res.* **49:** 2366-2375.

61. Samson JS, Choresca CH, Quiazon KMA. 2022. Probiotic effect of *Bacillus* spp. isolated from African nightcrawler (*Eudrilus eugeniae*) on the performance of Nile Tilapia (*Oreochromis niloticus* L.). *Arch. Microbiol.* **204:** 235.
62. Wang M, Liu G, Lu M, Ke X, Liu Z, Gao F, *et al.* 2017. Effect of *Bacillus cereus* as a water or feed additive on the gut microbiota and immunological parameters of Nile tilapia. *Aquac. Res.* **48:** 3163-3173.
63. Ramos MA, Goncalves JF, Costas B, Batista S, Lochmann R, Pires MA, *et al.* 2017. Commercial *Bacillus* probiotic supplementation of rainbow trout (*Oncorhynchys mykiss*) and brown trout (*Salmo trutta*): growth, immune responses and intestinal morphology. *Aquac. Res.* **48:** 2538-2549.
64. Docando F, Nuñez-Ortiz N, Serra C, Arense P, Enes P, Oliva-Teles A, *et al.* 2022. Mucosal and systemic immune effects of *Bacillus* subtilis in rainbow trout (*Oncorhynchus mykiss*). *Fish Shellfish Immunol.* **124**: 142-155.
65. Chen S-W, Liu C-H, Hu S-Y. 2019. Dietary administration of probiotic *Paenibacillus ehimensis* NPUST1 with bacteriocin-like activity improves growth performance and immunity against *Aeromonas hydrophila* and *Streptococcus iniae* in Nile tilapia (*Oreochromis niloticus*). *Fish Shellfish Immunol.* **84:** 695-703.
66. Dawood MA, Moustafa EM, Gewaily MS, Abdo SE, AbdEl-Kader MF, SaadAllah MS, *et al.* 2020b. Ameliorative effects of *Lactobacillus plantarum* L-137 on Nile tilapia (*Oreochromis niloticus*) exposed to deltamethrin toxicity in rearing water. *Aquat. Toxicol.* **219:** 105377.
67. Tan HY, Chen S-W, Hu S-Y. 2019. Improvements in the growth performance, immunity, disease resistance, and gut microbiota by the probiotic *Rummeliibacillus stabekisii* in Nile tilapia (*Oreochromis niloticus*). *Fish Shellfish Immunol.* **92:** 265-275.
68. Makled SO, Hamdan AM, El-Sayed A-FM, Hafez EE. 2017. Evaluation of marine psychrophile, *Psychrobacter namhaensis* SO89, as a probiotic in Nile tilapia (*Oreochromis niloticus*) diets. *Fish Shellfish Immunol.* **61:** 194-200.
69. Maas RM, Verdegem MC, Debnath S, Marchal L, Schrama JW. 2021. Effect of enzymes (phytase and xylanase), probiotics (*B. amyloliquefaciens*) and their combination on growth performance and nutrient utilisation in Nile tilapia. *Aquaculture* **533:** 736226.
70. Kuebutornye FK, Wang Z, Lu Y, Abarike ED, Sakyi ME, Li Y, *et al.* 2020. Effects of three host-associated *Bacillus* species on mucosal immunity and gut health of Nile tilapia, *Oreochromis niloticus* and its resistance against *Aeromonas hydrophila* infection. *Fish Shellfish Immunol.* **97:** 83-95.
71. Sookchaiyaporn N, Srisapoome P, Unajak S, Areechon N. 2020. Efficacy of *Bacillus* spp. isolated from Nile tilapia *Oreochromis niloticus* Linn. on its growth and immunity, and control of pathogenic bacteria. *Fish. Sci.* **86:** 353-365.
72. Won S, Hamidoghli A, Choi W, Park Y, Jang WJ, Kong I-S, *et al.* 2020. Effects of *Bacillus subtilis* WB60 and *Lactococcus lactis* on growth, immune responses, histology and gene expression in Nile tilapia, *Oreochromis niloticus. Microorganisms* **8:** doi: 10.3390/microorganisms8010067.
73. Dawood MA, Moustafa EM, Gewaily MS, Abdo SE, AbdEl-Kader MF, SaadAllah MS, *et al.* 2020c. Ameliorative effects of *Lactobacillus plantarum* L-137 on Nile tilapia (*Oreochromis niloticus*) exposed to deltamethrin toxicity in rearing water. *Aquat. Toxicol.* **219:** 105377.
74. Foysal MJ, Alam M, Kawser AR, Hasan F, Rahman MM, Tay C-Y, *et al.* 2020. Meta-omics technologies reveals beneficiary effects of *Lactobacillus plantarum* as dietary supplements on gut microbiota, immune response and disease resistance of Nile tilapia (*Oreochromis niloticus*). *Aquaculture* **520:** 734974.
75. Dowidar M, Abd ElAzeem S, Khater A, Awad Somayah M, Metwally S. 2018. Improvement of growth performance, immunity and disease resistance in Nile tilapia, *Oreochromis niloticus*, by using dietary probiotics supplementation. *J. Anim. Sci. Vet. Med.* **3:** 35-46.
76. El-Kady AA, Magouz FI, Mahmoud SA, Abdel-Rahim MM. 2022. The effects of some commercial probiotics as water additive on water quality, fish performance, blood biochemical parameters, expression of growth and immune-related genes, and histology of Nile tilapia (*Oreochromis niloticus*). *Aquaculture* **546:** 737249.
77. Han B, Long W-Q, He J-Y, Liu Y-J, Si Y-Q, Tian L-X. 2015. Effects of dietary *Bacillus licheniformis* on growth performance, immunological parameters, intestinal morphology and resistance of juvenile Nile tilapia (*Oreochromis niloticus*) to challenge infections. *Fish Shellfish Immunol.* **46:** 225-231.
78. He S, Zhou Z, Liu Y, Shi P, Yao B, Ringø E, *et al.* 2009. Effects of dietary *Saccharomyces cerevisiae* fermentation product (DVAQUA®) on growth performance, intestinal autochthonous bacterial community and non-specific immunity of hybrid tilapia (*Oreochromis niloticus*♀ × *O. aureus*♂) cultured in cages. *Aquaculture* **294:** 99-107.
79. Aly SM, Mohamed MF, John G. 2008. Effect of probiotics on the survival, growth and challenge infection in Tilapia nilotica (*Oreochromis niloticus*). *Aquac. Res.* **39:** 647-656.
80. Wang C, Liu Y, Sun G, Li X, Liu Z. 2019. Growth, immune response, antioxidant capability, and disease resistance of juvenile Atlantic salmon (*Salmo salar* L.) fed *Bacillus velezensis* V4 and *Rhodotorula mucilaginosa* compound. *Aquaculture* **500:** 65-74.
81. Jaramillo-Torres A, Rawling MD, Rodiles A, Mikalsen HE, Johansen L-H, Tinsley J, *et al.* 2019. Influence of dietary supplementation of probiotic *Pediococcus acidilactici* MA18/5M during the transition from freshwater to seawater on intestinal health and microbiota of Atlantic salmon (*Salmo salar* L.). *Front. Microbiol.* doi.org/10.3389/fmicb.2019.02243.
82. Kiron V, Kulkarni A, Dahle D, Lokesh J, Kitani Y. 2015. A microbial feed additive abates intestinal inflammation in Atlantic salmon. *Front. Immunol.* **6:** 409.
83. Gupta S, Fečkaninová A, Lokesh J, Koščová J, Sørensen M, Fernandes J, *et al.* 2019. *Lactobacillus* dominate in the intestine of Atlantic salmon fed dietary probiotics. *Front. Microbiol.* **9:** 3247.
84. Nimalan N, Sørensen SL, Fečkaninová A, Koščová J, Mudroňová D, Gancarčíková S, *et al.* 2022. Mucosal barrier status in Atlantic salmon fed marine or plant-based diets supplemented with probiotics. *Aquaculture* **547:** 737516.
85. Salinas I, Myklebust R, Esteban MA, Olsen RE, Meseguer J, Ringø E. 2008. In vitro studies of *Lactobacillus delbrueckii* subsp. *lactis* in Atlantic salmon (*Salmo salar* L.) foregut: tissue responses and evidence of protection against *Aeromonas salmonicida* subsp. *salmonicida* epithelial damage. *Vet. Microbiol.* **128:** 167-177.
86. Kristiansen M, Ringø E. 2011. Evaluation of prebiotic and probiotic effects on the intestinal gut microbiota and histology of Atlantic salmon (*Salmo salar* L.). *J. Aquac. Res. Development* **S1:** 009.
87. Ringø E, Salinas I, Olsen R, Nyhaug A, Myklebust R, Mayhew T. 2007. Histological changes in intestine of Atlantic salmon (*Salmo salar* L.) following in vitro exposure to pathogenic and probiotic bacterial strains. *Cell Tissue Res.* **328:** 109-116.
88. Soltani M, Kane A, Taheri-Mirghaed A, Pakzad K, Hosseini-Shekarabi P. 2019a. Effect of the probiotic, *Lactobacillus plantarum* on growth performance and haematological indices of rainbow trout (*Oncorhynchus mykiss*) immunized with bivalent streptococcosis/lactococcosis vaccine. *Iran. J. Fish. Sci.* **18:** 283-295.
89. Soltani M, Pakzad K, Taheri-Mirghaed A, Mirzargar S, Shekarabi SPH, Yosefi P, *et al.* 2019b. Dietary application of the probiotic *Lactobacillus plantarum* 426951 enhances immune status and growth of rainbow trout (*Oncorhynchus mykiss*) vaccinated against Yersinia ruckeri. *Probiotics Antimicrob. Proteins* **11:** 207-219.
90. Panigrahi A, Kiron V, Satoh S, Watanabe T. 2010. Probiotic bacteria *Lactobacillus rhamnosus* influences the blood profile in rainbow trout *Oncorhynchus mykiss* (Walbaum). *Fish. Physiol. Biochem.* **36:** 969-977.
91. Vazirzadeh A, Roosta H, Masoumi H, Farhadi A, Jeffs A. 2020. Long-term effects of three probiotics, singular or combined, on serum innate immune parameters and expressions of cytokine genes in rainbow trout during grow-out. *Fish Shellfish Immunol.* **98:** 748-757.

92. Mohammadian T, Ghanei-Motlagh R, Jalali M, Nasirpour M, Mohtashamipour H, Osroush E*, et al.* 2022. Protective effects of non-encapsulated and microencapsulated *Lactobacillus delbrueckii* subsp. bulgaricus in rainbow trout (*Oncorhynchus mykiss*) exposed to lead (Pb) via diet. *Ann. Anim. Sci.* **22:** 325-348.
93. Mohammadian T, Nasirpour M, Tabandeh MR, Heidary AA, Ghanei-Motlagh R, Hosseini SS. 2019. Administrations of autochthonous probiotics altered juvenile rainbow trout *Oncorhynchus mykiss* health status, growth performance and resistance to *Lactococcus garvieae*, an experimental infection. *Fish Shellfish Immunol.* **86:** 269-279.
94. Pérez-Sánchez T, Balcázar JL, Merrifield DL, Carnevali O, Gioacchini G, de Blas I*, et al.* 2011. Expression of immune-related genes in rainbow trout (*Oncorhynchus mykiss*) induced by probiotic bacteria during *Lactococcus garvieae* infection. *Fish Shellfish Immunol.* **31:** 196-201.
95. Ramos M, Gonçalves J, Batista S, Costas B, Pires M, Rema P*, et al.* 2015. Growth, immune responses and intestinal morphology of rainbow trout (*Oncorhynchus mykiss*) supplemented with commercial probiotics. *Fish Shellfish Immunol.* **45:** 19-26.
96. Park Y, Lee S, Hong J, Kim D, Moniruzzaman M, Bai SC. 2017. Use of probiotics to enhance growth, stimulate immunity and confer disease resistance to *Aeromonas salmonicida* in rainbow trout (*Oncorhynchus mykiss*). *Aquac. Res.* **48:** 2672-2682.
97. Merrifield D, Bradley G, Baker R, Davies S. 2010b. Probiotic applications for rainbow trout (*Oncorhynchus mykiss* Walbaum) II. Effects on growth performance, feed utilization, intestinal microbiota and related health criteria postantibiotic treatment. *Aquac. Nutr.* **16:** 496-503.
98. Sharifuzzaman S, Austin B. 2010. Development of protection in rainbow trout (*Oncorhynchus mykiss, Walbaum*) to *Vibrio anguillarum f*ollowing use of the probiotic Kocuria SM1. *Fish Shellfish Immunol.* **29:** 212-216.
99. Capkin E, Altinok I. 2009. Effects of dietary probiotic supplementations on prevention/treatment of yersiniosis disease. *J. Appl. Microbiol.* **106:** 1147-1153.
100. Safari R, Adel M, Lazado CC, Caipang CMA, Dadar M. 2016. Host-derived probiotics *Enterococcus casseliflavus* improves resistance against *Streptococcus iniae* infection in rainbow trout (*Oncorhynchus mykiss*) via immunomodulation. *Fish Shellfish Immunol.* **52:** 198-205.
101. Sahandi J, Jafaryan H, Soltani M, Ebrahimi P. 2019. The use of two *Bifidobacterium* strains enhanced growth performance and nutrient utilization of Rainbow Trout (*Oncorhynchus mykiss*) fry. *Probiotics Antimicrob. Proteins* **11:** 966-972.
102. Adel M, Lazado CC, Safari R, Yeganeh S, Zorriehzahra MJ. 2017. Aqualase®, a yeast-based in-feed probiotic, modulates intestinal microbiota, immunity and growth of rainbow trout *Oncorhynchus mykiss*. *Aquac. Res.* **48:** 1815-1826.
103. Kurdomanov A, Sirakov I, Stoyanova S, Velichkova K, Nedeva I, Staykov Y. 2019. The effect of diet supplemented with Proviotic® on growth, blood biochemical parameters and meat quality in rainbow trout (*Oncorhynchus mykiss*) cultivated in recirculation system. *Aquaculture, Aquarium, Conservation Legislation* **12:** 404-412.
104. Zhang C, Zhang J, Fan W, Huang M, Liu M. 2019. Effects of dietary *Lactobacillus delbrueckii* on growth performance, body composition, digestive and absorptive capacity, and gene expression of common carp (*Cyprinus carpio* Huanghe var). *Aquac. Nutr.* **25:** 166-175.
105. Zhang C-N, Zhang J-L, Guan W-C, Zhang X-F, Guan S-H, Zeng Q-H*, et al.* 2017. Effects of *Lactobacillus delbrueckii* on immune response, disease resistance against *Aeromonas hydrophila*, antioxidant capability and growth performance of Cyprinus carpio Huanghe var. *Fish Shellfish Immunol.* **68:** 84-91.
106. Yanuhar U, Caesar NR, Junirahma NS, Soelistyoadi RN. 2022. Immunomolecular response of CD4+, CD8+, TNF-α and IFN-γ in Myxobolus-infected koi (*Cyprinus carpio*) treated with probiotics. *Aquac. Fish.* doi.org/10.1016/j.aaf.2022.01.004.
107. Valiallahi J, Pourabasali M, Janalizadeh E, Bucio A. 2018. Use of *Lactobacillus* for improved growth and enhanced biochemical, hematological, and digestive enzyme activity in common carp at Mazandaran, Iran. *North Am. J. Aquac.* **80:** 206-215.
108. Kazuń B, Małaczewska J, Kazuń K, Żylińska-Urban J, Siwicki AK. 2018. Immune-enhancing activity of potential probiotic strains of *Lactobacillus plantarum* in the common carp (*Cyprinus carpio*) fingerling. *J. Vet. Res.* **62:** 485.
109. Xu Y, Wang Y, Lin J. 2014. Use of *Bacillus coagulans* as a dietary probiotic for the common carp, *Cyprinus carpio. J. World Aquac. Soc.* **45:** 403-411.
110. Gupta A, Gupta P, Dhawan A. 2014. Dietary supplementation of probiotics affects growth, immune response and disease resistance of *Cyprinus carpio* fry. *Fish Shellfish Immunol.* **41:** 113-119.
111. Rostika R, Azhima MF, Ihsan YN, Andriani Y, Suryadi IBB, Dewanti LP. 2020. The use of solid probiotics in feed to growth and survival rate of mantap common carp (*Cyprinus carpio*). *Aquac. Aquar. Conserv. Legis.* **13:** 199-206.
112. Hoseinifar SH, Hosseini M, Paknejad H, Safari R, Jafar A, Yousefi M*, et al.* 2019. Enhanced mucosal immune responses, immune related genes and growth performance in common carp (*Cyprinus carpio*) juveniles fed dietary *Pediococcus acidilactici* MA18/5M and raffinose. *Dev. Comp. Immunol.* **94:** 59-65.
113. Ahmadifar E, Sadegh TH, Dawood MA, Dadar M, Sheikhzadeh N. 2020. The effects of dietary *Pediococcus pentosaceus* on growth performance, hemato-immunological parameters and digestive enzyme activities of common carp (*Cyprinus carpio*). *Aquaculture* **516:** 734656.
114. Ajdari A, Ghafarifarsani H, Hoseinifar SH, Javahery S, Narimanizad F, Gatphayak K*, et al.* 2022. Effects of dietary supplementation of primaLac, inulin, and biomin imbo on growth performance, antioxidant, and innate immune responses of common carp (*Cyprinus carpio*). *Aquac. Nutr.* doi.org/10.1155/2022/8297479.
115. Mehrabi F, Khalesi M, Hazaie K. 2018. Effects of pre-and probiotics on growth, survival, body composition, and hematology of common carp (*Cyprinus carpio* L.) fry from the Caspian Sea. *Turkish J. Fish. Aquat. Sci.* **18:** 597-602.
116. Lee JM, Jang WJ, Hasan MT, Lee B-J, Kim KW, Lim SG*, et al.* 2019. Characterization of a *Bacillus* sp. isolated from fermented food and its synbiotic effect with barley β-glucan as a biocontrol agent in the aquaculture industry. *Appl. Microbiol. Biotechnol.* **103:** 1429-1439.
117. Kim D, Beck BR, Lee SM, Jeon J, Lee DW, Lee JI*, et al.* 2016. Pellet feed adsorbed with the recombinant *Lactococcus lactis* BFE920 expressing SiMA antigen induced strong recall vaccine effects against *Streptococcus iniae* infection in olive flounder (*Paralichthys olivaceus*). *Fish Shellfish Immunol.* **55:** 374-383.
118. Beck BR, Lee SH, Kim D, Park JH, Lee HK, Kwon S-S*, et al.* 2017. A *Lactococcus lactis* BFE920 feed vaccine expressing a fusion protein composed of the OmpA and FlgD antigens from *Edwardsiella tarda* was significantly better at protecting olive flounder (*Paralichthys olivaceus*) from edwardsiellosis than single antigen vaccines. *Fish Shellfish Immunol.* **68:** 19-28.
119. Harikrishnan R, Kim M-C, Kim J-S, Balasundaram C, Heo M-S. 2011a. Probiotics and herbal mixtures enhance the growth, blood constituents, and nonspecific immune response in *Paralichthys olivaceus* against *Streptococcus parauberis. Fish Shellfish Immunol.* **31:** 310-317.
120. Harikrishnan R, Kim M-C, Kim J-S, Balasundaram C, Heo M-S. 2011b. Immunomodulatory effect of probiotics enriched diets on *Uronema marinum* infected olive flounder. *Fish Shellfish Immunol.* **30:** 964-971.
121. Kim J, Lee KW, Jeong HS, Ansary MWR, Kim HS, Kim T*, et al.* 2019. Oral administration effect of yacon, ginger and blueberry on the growth, body composition and plasma chemistry of juvenile olive flounder (*Paralichthys olivaceus*) and immunity test against *Streptococcus iniae* compared to a commercial probiotic, *Lactobacillus fermentum. Aquac. Rep.* **15:** 100212.
122. Jang WJ, Choi S-Y, Lee JM, Lee GH, Hasan MT, Kong I-S. 2019b. Viability of *Lactobacillus plantarum* encapsulated with poly-γ-glutamic acid produced by *Bacillus* sp. SJ-10 during freeze-drying and in an in vitro gastrointestinal model. *LWT* **112:** 108222.

123. Jang WJ, Lee JM, Kim Y-R, Hasan MT, Kong I-S. 2018. Complete genome sequence of *Bacillus* sp. SJ-10 (KCCM 90078) producing 400-kDa poly-γ-glutamic acid. *Curr. Microbiol.* **75:** 1378-1383.
124. Jang WJ, Lee JM, Hasan MT, Kong I-S. 2019c. Fusion of the N-terminal domain of *Pseudomonas* sp. phytase with *Bacillus* sp. phytase and its effects on optimal temperature and catalytic efficiency. *Enzyme Microb. Technol.* **126:** 69-76.
125. Hasan MT, Jang WJ, Lee B-J, Kim KW, Hur SW, Lim SG, *et al.* 2019b. Heat-killed *Bacillus* sp. SJ-10 probiotic acts as a growth and humoral innate immunity response enhancer in olive flounder (*Paralichthys olivaceus*). *Fish Shellfish Immunol.* **88:** 424-431.
126. Niu K-M, Khosravi S, Kothari D, Lee W-D, Lim J-M, Lee B-J, *et al.* 2019. Effects of dietary multi-strain probiotics supplementation in a low fishmeal diet on growth performance, nutrient utilization, proximate composition, immune parameters, and gut microbiota of juvenile olive flounder (*Paralichthys olivaceus*). *Fish Shellfish Immunol.* **93:** 258-268.
127. FAO. 2020. Sustainability in action. State of World Fisheries and Aquaculture. Rome 200.
128. Qin L, Xiang J, Xiong F, Wang G, Zou H, Li W, *et al.* 2020. Effects of *Bacillus licheniformis* on the growth, antioxidant capacity, intestinal barrier and disease resistance of grass carp (*Ctenopharyngodon idella*). *Fish Shellfish Immunol.* **97:** 344-350.
129. Tang Y, Han L, Chen X, Xie M, Kong W, Wu Z. 2019. Dietary supplementation of probiotic *Bacillus subtilis* affects antioxidant defenses and immune response in grass carp under *Aeromonas hydrophila* challenge. *Probiotics Antimicrob. Proteins* **11:** 545-558.
130. Guo D, Xie M, Xiao H, Xu L, Zhang S, Chen X, *et al.* 2022. *Bacillus subtilis* supplementation in a high-fat diet modulates the gut microbiota and ameliorates hepatic lipid accumulation in grass carp (*Ctenopharyngodon idella*). *Fishes* **7:** 94.
131. Li Y, Luo L, Yang Q, Zhang W, Tang X, Yu X, *et al.* 2022. *Bacillus methylotrophicus* WM-1 enhances the immunity of grass carp against *Aeromonas hydrophila*. *Aquac. Res.* **53:** 2464-2471.
132. Li Y, Hu S, Gong L, Pan L, Li D, Cao L, *et al.* 2020. Isolating a new *Streptomyces amritsarensis* N1-32 against fish pathogens and determining its effects on disease resistance of grass carp. *Fish Shellfish Immunol.* **98:** 632-640.
133. Wu Z-Q, Jiang C, Ling F, Wang G-X. 2015. Effects of dietary supplementation of intestinal autochthonous bacteria on the innate immunity and disease resistance of grass carp (*Ctenopharyngodon idellus*). *Aquaculture* **438:** 105-114.
134. Hao K, Wu Z-Q, Li D-L, Yu X-B, Wang G-X, Ling F. 2017. Effects of dietary administration of *Shewanella xiamenensis* A-1, *Aeromonas veronii* A-7, and *Bacillus subtilis*, single or combined, on the grass carp (*Ctenopharyngodon idella*) intestinal microbiota. *Probiotics Antimicrob. Proteins* **9:** 386-396.
135. Fu L, Zhang X, Wang Y, Peng L, Li W. 2017. Nitrogen removal characteristics of *Pseudomonas stutzeri* F11 and its application in grass carp culture. *Fish. Sci.* **83:** 89-98.
136. Liang Q, Zhang X, Lee KH, Wang Y, Yu K, Shen W, *et al.* 2015. Nitrogen removal and water microbiota in grass carp culture following supplementation with *Bacillus licheniformis* BSK-4. *World J. Microbiol. Biotechnol.* **31:** 1711-1718.
137. Deng B, Fu L, Zhang X, Zheng J, Peng L, Sun J, *et al.* 2014. The denitrification characteristics of *Pseudomonas stutzeri* SC221-M and its application to water quality control in grass carp aquaculture. *PLoS One* **9:** e114886.
138. Amir I, Zuberi A, Imran M, Ullah S. 2018. Evaluation of yeast and bacterial based probiotics for early rearing of *Labeo rohita* (Hamilton, 1822). *Aquac. Res.* **49:** 3856-3863.
139. Hussain S, Afzal M, Salim M, Javid A, Khichi T, Hussain M, *et al.* 2011. Apparent digestibility of fish meal, blood meal and meat meal for *Labeo rohita* fingerlings. *J. Anim. Plant Sci.* **21:** 807-811.
140. Ibrar M, Zuberi A, Amir I, Imran M, Noor Z. 2017. Effect of probiotic *Geotrichum candidum* on early rearing of *Labeo rohita* (Hamilton, 1822). *Turkish J. Fish. Aquat. Sci.* **17:** 1263-1270.
141. Giri S, Sukumaran V, Sen S, Jena P. 2014. Effects of dietary supplementation of potential probiotic *Bacillus subtilis* VSG 1 singularly or in combination with *Lactobacillus plantarum* VSG 3 or/and *Pseudomonas aeruginosa* VSG 2 on the growth, immunity and disease resistance of *Labeo rohita*. *Aquac. Nutr.* **20:** 163-171.
142. Mohapatra S, Chakraborty T, Prusty AK, PaniPrasad K, Mohanta KN. 2014. Beneficial effects of dietary probiotics mixture on hemato-immunology and cell apoptosis of *Labeo rohita* fingerlings reared at higher water temperatures. *PLoS One* **9:** e100929.
143. Mukherjee A, Chandra G, Ghosh K. 2019. Single or conjoint application of autochthonous *Bacillus* strains as potential probiotics: Effects on growth, feed utilization, immunity and disease resistance in Rohu, *Labeo rohita* (Hamilton). *Aquaculture* **512:** 734302.
144. Nandi A, Banerjee G, Dan SK, Ghosh K, Ray AK. 2018. Evaluation of in vivo probiotic efficiency of *Bacillus amyloliquefaciens* in *Labeo rohita* challenged by pathogenic strain of *Aeromonas hydrophila* MTCC 1739. *Probiotics Antimicrob. Proteins* **10:** 391-398.
145. Khan MIR, Kamilya D, Choudhury TG, Rathore G. 2022. Dietary administration of a host-gut derived probiotic *Bacillus amyloliquefaciens* COFCAU_P1 modulates immune-biochemical response, immune-related gene expression, and resistance of *Labeo rohita* to *Aeromonas hydrophila* infection. *Aquaculture* **546:** 737390.
146. Ghori I, Tabassum M, Ahmad T, Zuberi A, Imran M. 2018. *Geotrichum candidum* enhanced the *Enterococcus faecium* impact in improving physiology, and health of *Labeo rohita* (Hamilton, 1822) by modulating gut microbiome under mimic aquaculture conditions. *Turkish J. Fish. Aquat. Sci.* **18:** 1255-1267.
147. Bandyopadhyay P, Mishra S, Sarkar B, Swain SK, Pal A, Tripathy PP, *et al.* 2015. Dietary *Saccharomyces cerevisiae* boosts growth and immunity of IMC *Labeo rohita* (Ham.) juveniles. *Indian J. Microbiol.* **55:** 81-87.
148. Brown C, Power D, Núñez J. 2010. Disorders of development in fish. *Fish diseases and disorders, Volume 2.* pp. 166-181.
149. Padeniya U, Larson ET, Septriani S, Pataueg A, Kafui AR, Hasan E, *et al.* 2022. Probiotic treatment enhances pre-feeding larval development and early survival in zebrafish *Danio rerio*. *J. Aquat. Anim. Health* **34:** 3-11.
150. Ozorio RO, Kopecka-Pilarczyk J, Peixoto MJ, Lochmann R, Santos RJ, Santos G, *et al.* 2016. Dietary probiotic supplementation in juvenile rainbow trout (*Oncorhynchus mykiss*) reared under cage culture production: effects on growth, fish welfare, flesh quality and intestinal microbiota. *Aquac. Res.* **47:** 2732-2747.
151. Bisht A, Singh UP, Pandey N. 2012. *Bacillus subtilis* as a potent probiotic for enhancing growth in fingerlings of common carp (*Cyprinus carpio* Linnaeus). *Ind. J. Fish.* **59:** 103-107.
152. Kim D, Beck BR, Heo S-B, Kim J, Kim HD, Lee S-M, *et al.* 2013. *Lactococcus lactis* BFE920 activates the innate immune system of olive flounder (*Paralichthys olivaceus*), resulting in protection against *Streptococcus iniae* infection and enhancing feed efficiency and weight gain in large-scale field studies. *Fish Shellfish Immunol.* **35:** 1585-1590.
153. Li Z, Chen Y, Zhang J, Zhu X, Zhang J, Chen D, *et al.* 2017. Effects of dietary *Bacillus natto* supplementation on growth performance and the growth-related gene/micro RNA expression in the skeletal muscle of grass carp (*Ctenopharyngodon idella*). *Aquac. Nutr.* **23:** 46-53.
154. Amir I, Zuberi A, Kamran M, Imran M. 2019. Evaluation of commercial application of dietary encapsulated probiotic (*Geotrichum candidum* QAUGC01): Effect on growth and immunological indices of rohu (*Labeo rohita*, Hamilton 1822) in semi-intensive culture system. *Fish Shellfish Immunol.* **95:** 464-472.
155. Jha DK, Bhujel RC, Anal AK. 2015. Dietary supplementation of probiotics improves survival and growth of Rohu (*Labeo rohita* Ham.) hatchlings and fry in outdoor tanks. *Aquaculture* **435:** 475-479.