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REVIEW ARTICLE

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Prospects of Probiotics and Fish Growth-promoting Bacteria in Aquaculture: A Review

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ABSTRACT

Modern aquaculture faces significant obstacles including a deficiency in sources of protein in the feed, vulnerability to infections, and quality degradation during growing and storage, despite being the sector with the highest growth rate. Beneficial bacterial species shield aquatic animals from infection or stop product deterioration, and bacterial biomass is thought to be a potential source of protein for animal feed. This review focuses on the nutritional, anti-pathogenic, and immunoregulatory functions of these bacteria in relation to aquatic products. Additionally, we examine the connection between host immunity, beneficial bacteria, and gut microbiota, along with recent advances in our understanding of host immunity and microbial mutualism. This analysis emphasizes specific microbial metabolites, bacterial components, and the immune system. The actions of probiotics in aquatic animals have garnered significant research attention in recent years. Various findings, with the potential to be both academically innovative and practically helpful, have emerged. The positive effects of beneficial bacteria on aquatic organisms have sparked extensive research, wide-ranging use in aquaculture, and innovative applications. Future improvements to current practices will require the development of novel applications and related mechanistic research.

Keywords: Probiotics, Growth-promotion, Fish, Vaccine, Immunoregulation.

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INTRODUCTION

The aquaculture industry was developed and is currently the fastest-growing to meet the increasing demand for fish protein and represents one-third of world fisheries production (FAO, 2020). With the increasing population, the demand for aquatic food has also increased, and this can be fulfilled by the multibillion-dollar, rapidly expanding aquaculture industry. Of the total production, 63 percent (112 million metric tons) was harvested in marine waters (70 percent from capture fisheries and 30 percent from aquaculture) and 37 percent (66 million metric tons) in inland waters (83 percent from aquaculture and 17 percent from capture fisheries) (FAO, 2022). All over the world, per year, the fish production industry has been gradually growing at a standard compounded rate of 9.2% since 1970 (El-Saadony et al., 2021). The aquaculture industry has partly compensated for the reduction of capture fisheries, and many reports show that it will be the future weapon for getting rid of this problem (El-Saadony et al., 2021). By 2050, aquaculture production is anticipated to double, allowing it to meet demand while relieving the strain on wild fishing (Yukgehnaish et al., 2020). According to projections by the United Nations Food and Agriculture Organization, farm-raised fish will contribute two-thirds of the world's consumption of seafood by the year 2030 (Thorpe and Castillo, 2018).

The major constraint is the presence of pathogenic microorganisms. Disease caused by this harmful microbiota creates challenges for farmers and finally impacts net production. Although various kinds of vaccines are being developed by experts, they are not the universal solution. Therefore, the management of disease in aquaculture became a very crucial problem for farmers. Later, to solve this problem, antibiotics are used as a traditional strategy for a long period of time. According to many scientific reports, antibiotics antibiotic are able to control many disease-causing bacteria and can improve fish health in aquaculture practices (El-Saadony et al., 2021). But, as we know, each coin has two sides. Likewise, everything has two effects. Antibiotics kill some beneficial bacteria, which are inhabitants of the fish gastrointestinal tract. However, it also caused fish products to acquire antibiotic residues that are unsafe for human consumption (WHO, 2006). These concerns, along with the detrimental impact of products and residual antibiotics on human health, led the European Union and the United States to impose prohibitions on the use of antibiotics (Kesarcodi-Watson et al., 2008).

With the ban on antibiotics, there was a need for a new management strategy for fish health. To fulfill this need, fishery scientists have conducted much research and they came to an unbeatable conclusion on the use of probiotics. Later, this new idea has received much more attention and has been recognized as a natural disease controller and a good growth -promoting agent for fish in aquaculture

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practice. The Greek words "pro" and "bios" gave rise to the phrase "probiotic," which means "for life" (Dailey et al*.*, 2019). The term "probiotic" refers to a material that can promote the growth of other organisms (Thatcher et al*.*, 2022).

Antimicrobial drugs and growth promoters are being replaced by these beneficial microorganisms. Fish pathogenic bacteria and probiotic bacteria compete for nutrients and sites of attachment in the stomach, adhering there to prevent pathogen growth, as some candidate probiotics have been shown to produce antibacterial substances that inhibit the growth of harmful microbes and maintain intestinal microecological balance (Xu et al*.*, 2014). Thus, several probiotics used in aquaculture have been documented to exert direct antibacterial activities against known pathogens. Several experiments concluded that beneficial bacteria could enhance aquaculture production along with the disease-causing bacteria in aquaculture (Allameh et al*.*, 2017).

Lactic acid bacteria (LAB) are the major group of microorganisms used as probiotics for animals. In the fish production industry, LABs enhance resistance to pathogens, survivability, feed conversion efficiency, protein efficiency ratio, and digestibility. They also prevent intestinal disorders and can neutralize the anti-nutritional factors present in feedstuffs. In addition, LABs improve the fish immune system. LABs are those that can improve bacterial growth and monitoring when used in aquaculture (Allameh et al*.*, 2017). Probiotic-fortified meal increases the metabolic process of the fish body and helps it grow in size.

Mechanism of Action of Bacteria for Fish Growth Promotion

Microorganisms inhabiting fish internal tissues play a variety of crucial roles, including digestion, immunity, defense against harmful bacteria, and other developments. Govindaraj et al*.* (2021) isolated 120 beneficial probiotics from the intestines of freshwater fishes: *Cirrhinus mrigala*, *Puntius filamentosus*, Channa *striata*, *Rasbora daniconius* and *Oreochromis mossambicus*. Among these, seven probiotics have been found to have strong antagonistic activity against several fish pathogens. They concluded that *Lactococcus fermentum* has high probiotic potential and is an effective dietary supplement for modern freshwater aquaculture. In their study, *L. fermentum isolated from C. mrigala showed* different extracellular enzyme secretions activity like amylase, lipase, and protease. Moreover, *in vitro evaluations of* intestinal mucus indicate that *L. fermentum* displayed potential adherence capacity and an increased survival rate after being inoculated with *Artemia nauplii.*

Banerjee et al*.* (2013) investigated enzyme-producing bacteria that had been isolated from the stinging catfish (*Heteropneustes fossilis) and* the murrel (*Channa punctata).* All tested bacterial strains belonged to the *Bacillus species*. The isolated bacteria could thrive in a wide temperature range, from 20 to 11.0. In their study, among eight isolated bacterial strains, Bacillus sp*.* (HFH4) was found to have the highest cellulolytic activity, followed by *Bacillus sp.* (CPF3) and *Bacillus licheniformis* (CPH6). The highest proteolytic activity was estimated from *B. licheniformis* (CPF4), taken out of murrel. They concluded that the production of proteolytic, cellulolytic, and amylolytic enzymes by bacteria isolated from the gastrointestinal systems of these two Indian air-breathing fish led researchers to hypothesize that these microorganisms are advantageous to the fish's extracellular digestion processes.

The role of two helpful bacteria isolated from the gastrointestinal tract of Atlantic Cod was described by Butt et al. (2021). They studied the role of *Pseudomonas sp.* (GP21) and *Psychrobacter psychrobacter Sp.* (GP12) and concluded that these two bacteria have an immunomodulatory effect in Cod. They are able to trigger an immunological response in the skin and intestine of cod, which are mucosal surfaces. On the other hand, Caipang et al*.* (2010) studied about four other bacterial species of occupants of the same fish's intestinal tract. The probiotics *Photobacterium sp*. (GP31), *Shewanella sp*. (GS11), *Psychrobacter sp*. (GP11), and *Vibrio* Sp. were associated with the differential expression of an immune gene connected to bacterial defense and kidney (GV11).

Numerous advantageous outcomes of probiotics have been identified, including the reduction of immune reactions and the prevention of degenerative diseases (Azad et al*.*, 2018). Different routes of application of probiotics in aquaculture and their effects are shown in Fig.1. Different probiotic bacteria, with their source and growth-promoting role, have been presented in Table 1 and Fig. 2.

Bacteria-Derived Fertilizers for Aquaculture

For the last two centuries, the aquaculture industry has been growing rapidly and has become a major contributor to global food production. Aquaculture produces a lot of waste, including metabolic byproducts, leftover food, feces, and leftover prophylactic and therapeutic inputs, which degrades water quality and causes disease outbreaks. To improve water quality in aquaculture, a very popular modern approach is the application of beneficial microbes and enzymes to the ponds, known as bioremediation.

According to Wang et al. (2008), to raise the water quality standards in the *Penaeus monodon* culture pond in China Bacillus sp. was used, which in turn enhanced the fish's overall growth. Similarly, to improve the water quality, *Bacillus* NL 110 and *Vibrio* sp. NE 17 were added to the *Macrobrachium rosenbergii* culture pond (Mujeeb et al*.* 2010). Dohail et al. (2009) studied *Lactobacillus acidophilus* growth performance, hematology parameters, and immunoglobulin concentration in African catfish (*Clarias gariepinus*, Burchell 1822) fingerlings. *B. coagulans* SC8168 has the ability to enhance the growth of *Pennaeus vannamei* in aquaculture by improving the water quality parameter (Zhou et al*.*, 2009).

Bacteria are considered to be very good biological transformers. Excess nitrogen application in the aquaculture pond could lead to the accumulation of nitrogenous compounds such as ammonia and nitrite. The waste products of the farmed fish additionally add nitrogenous substances to the pond. By doing nitrification, bacterial microbiota makes ammonia nitrate from ammonia (Kaiser et al*.*, 2013). In the culture pond, two bacterial genera predominantly mediate the process. Nitrosomonas and Nitrobacter both participate in the oxidation of ammonia and nitrite, respectively. By doing this, bacterial species make pond water suitable for fish growth.

Frequent applications of phosphate fertilizer are required to increase fish productivity in the aquaculture pond. It is estimated that about 10% of the fertilizer applied causes an increase in soluble phosphate in the water phase, which is absorbed by the phytoplankton within a few minutes of fertilizer application, whereas the rest is rapidly precipitated, settled at the bottom, and converted into insoluble compounds. (Jana, 2007). Phosphorus is mobilized from organic phosphate esters and inorganic salts, respectively, by enzymes and chelating agents that are extracellular products of the microbial population (organic acids). In a system controlled by humans, the ability of bacteria to dissolve insoluble inorganic phosphate is critical. Numerous phosphate-solubilizing microorganisms, such as bacteria, fungi, and cyanobacteria, can assimilate insoluble inorganic phosphates such as hydroxyapatite, tricalcium phosphate, and rock phosphate and make a significant

Table 1: List of different probiotic bacteria with their source and growth-promoting role

Sl. No.	Bacteria	Source Organisms/Medium	Fish growth promoting Role	References
1	*Psychrobacter* spp.	digestive system of Turbot, wild (*Scophthalmus maximus*)	antagonistic activity towards pathogen *Tenacibaculum maritimum*	(Wanka et al., 2018)
2	*Bacillus* Sp.	Common carp, *Cyprinus carpio* ponds	Increase Survival rate Protease activity Lipase activity	(Yanbo and Zirong, 2006)
3	*Bacillus* spp.	Intestines of *Penaeus monodon* and shrimp pond sediment	Increase Growth and survival Beneficial microbial probiotics	(Nimrat et al., 2011)
4	*L. sakei*	Intestines of *Paralichthys olivaceus*	Macrophage phagocytic activity " Peroxidase activity	(Harikrishnan et al. 2010)
5	*Escherichia coli, Proteus vulgaris, Bacillus subtilis, Klebsiella pneumonia, Pseudomonas aeruginosa* and *Staphylococcus aureus*	Scomberomorus *guttatus*	-	(Karthiga et al., 2016)
6	*Bacillus* Sp. (HFH4, CPF3) *Bacillus licheniformis* (CPH6, CPF4)	The gastrointestinal tract of *Channa punctatus* and *Heteropneustes fossils*	Proteolytic, Cellulolytic, and amylolytic enzyme activity	(Banerjee *et al.*, 2013)
7	*Pseudomonas* Sp. (GP21) and *psychrobacter* Sp. (GP12)	The gastrointestinal tract of Atlantic Cod	Elicit the immune response, particularly in mucosal surfaces such as the skin and intestine.	(Butt, et al., 2021)
8	*Psychrobacter* Sp*.* (GP11), *Shewanella Sp.* (GS11), *Photobacterium* Sp. (GP31), and *Vibrio* Sp*.* (GV11),	Atlantic cod's intestine	Differential expression of an immune gene associated with bacterial defense and inflammation in the head kidney leukocytes.	(Caipang et al., 2010)
9	*Nitrosomonas* Sp. *Nitrobacters* Sp.	The gut of Catla (*Catla catla*), Rohu (*Labeo rohita*), and Grass carp (*Ctenopharyngodon idella)*	Block the pathogen entry in the culture pond and can raise the concentration of dissolved oxygen.	(Sunitha and Krishna, 2016)
10	*Bacillus* Sp.,	Added in rearing water	Increasing growth through improving the water quality in the *Penaeus monodon* culture pond	(Wang et al., 2008)
11	*Bacillus* NL 110, *Vibrio* Sp. NE 17	Added in rearing water	Enhancing water quality in the culture pond of *Macrobrachium rosenbergii*	(Mujeeb et al., 2010)
12	*Lactobacillus acidophilus*	Added in rearing water	Enhancing water quality in the culture pond of *Clarias gariepinus*	(Dohail et al., 2009)
13	*B. coagulans* SC8168	Added in rearing water	Enhancing water quality in the culture pond of *Penaeuss vannamei*	(Zhou et al., 2009)
14	*Nitrosomonas Nitrobacter*	Applied in culture pond	Promote growth by Oxidizing ammonia and nitrite in the cultured pond.	(Kaiser et al., 2013)
15	*Bacillus* spp.	Added in the surrounding water	Increase growth performance in cultured pond by phosphate solubilization and phosphate production	(Jana, 2007)
16	*Methylococcus capsulatus*	Added to the diet of Atlantic salmon *(Salmo salar)*	Enhance growth by supplying abundant protein to *Salmo salar*	(Romarheim et al., 2011)
17	*Clostridium butyricum*	kuruma shrimp (*Marsupenaeus japonicas*)	Increased the content of intestinal short-chain fatty acid along with propionic acid and butyric acid, and increased the levels of body crude protein.	(Duan et al., 2018)
18	Yeast *Debaryomyces hansenii* HF1	Supplemented to Sea bass larvae	Promote growth by secreting amylase and trypsin, enzymes that help in digestion	(Tovar et al., 2002)
19	*Bacillus cereus*	Added to the meal of Juvenile *Dentex dentex* L	Increases fish growth due to a greater food consumption capacity	(Merrifield et al., 2010)
20	*B. subtilis*, *B. licheniformis,* and *Enterococcus faecium*	Supplemented with a traditional meal of Rainbow trout	Enhance fish growth by increasing feed consumption efficiency	(Merrifield et al., 2010)
21	*Bacillus subtilis*	Gut of *Cirrhinus mrigala*	Increase the length and weight of guppies (*Poecilia reticulata*, *P. sphenops*), and swordtail (*Xiphophorus helleri*, *X. maculatus*), and increase the proteases and amylases activity in ornamental fish	(Ghosh et al., 2008)
22	*Carnobacterium* Sp.	Supplemented to salmon bowel	Promote growth by showing *in vitro* antagonism against known fish pathogens in rainbow trout and Atlantic salmon	(Robertson et al., 2000; Martinez et al., 2012)
23	*Bacillus cereus, Paenibacillus polymyxa,* and *Pseudomonas* Sp. PS-102	-	Act as the antagonist against various pathogens in shrimp	(Ravi et al., 2007; Vijayan et al., 2006)
24	*Lactobacillus rhamnosus*	Administrated to *Oreochromis niloticus*	Stimulate the phagocytic activity in Tilapia	(Cano-Lozano et al., 2022)
25	*Lactobacillus Plantarum* and *Pseudomonas fluorescent*	Added in pond water	Increase survival rate by 96.22% in *Clarias gariepinus*	(Omenwa et al., 2015)
26	*Lactobacillus acidophilus* (Fla) and *Saccharomyces boulardii* (FSB)	Supplemented with the diet of *Acipenser baerii*	Enhance growth, immunity, and survival rate	(Mocanu et al., 2022)

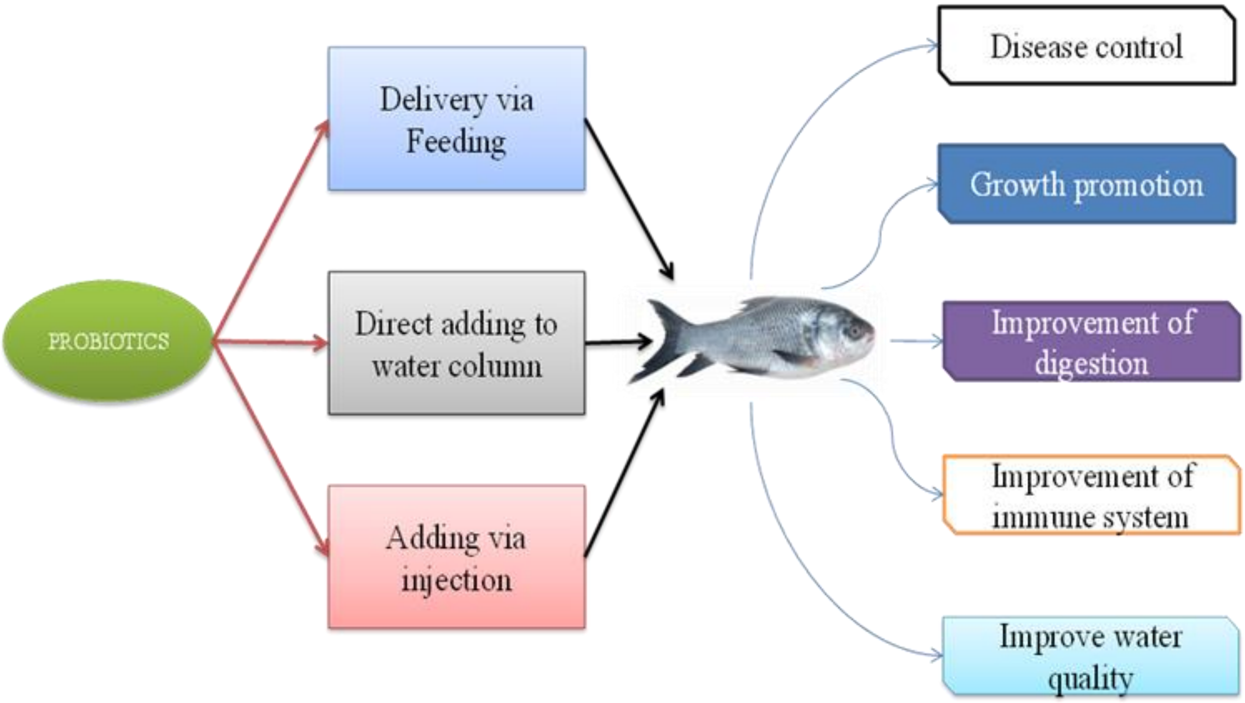

Fig. 1: Different routes of application of probiotics in aquaculture and their effect.

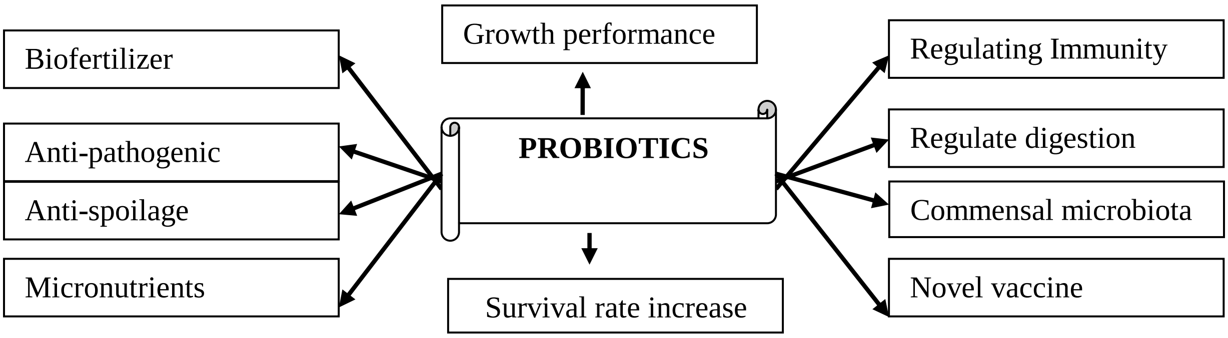

Fig. 2: Role of Fish Growth Promoting Bacteria.

portion of them soluble by producing organic and inorganic acids in the water and sediments of fishponds. Bacillus is the bacteria that produces the most phosphates and is the most effective at solubilizing phosphates, according to reports (Jana, 2007).

Bacteria as an Alternative Feed for Aquaculture

Fish are a good source of protein as well as vitamins, fatty acids, and minerals for human health. Aquaculture industries were developed to increase fish production as per the requirements of human health. For proper growth, strong immunity, stress tolerance, and good reproductive ability in the aquaculture industries, fish require an abundant proteinaceous diet rather than traditional fish meals. A wide range of bacteria rich in protein can make up 65% of total dry weight (Wang et al., 2020). Gamboa Delgado and Marquez (2018) that dietary supplementations of beneficial bacteria can be used for better growth, immunity, and stress response in aquatic animals and can also improve diet palatability.

It was discovered that methanotrophic bacteria, particularly *Methylococcus capsulatus*, when employed as a replacement for traditional fish meal in the case of Atlantic salmon (*Salmo salar)*, could be a substitute protein source for fish meal. According to Perera et al. (1995), when the traditional fish meal was replaced by the bacterial single-cell protein, it was noted that the growth rate, amount of feed consumed, and rate of absorption of rainbow trout were unchanged (*Oncorhynchus mykiss*). When beneficial bacteria were used as feed, the growth rate of black tiger prawns significantly changed from lower to higher (Glencross et al., 2014). In addition, when bacterial protein was added to the shrimp feed, improvements in growth were recorded (Arnold et al. 2016). According to De Schryver et al. (2008), probiotic bacteria have the capacity to enhance rearing water quality parameters by forming some flocculated materials, resulting in a higher breeding density in aquaculture. According to Dantas et al. (2016), when 20% of a fish diet is replaced with a prepared food, it may actually boost shrimp growth. A similar result was recorded by Chen et al. (2018) and Kim et al. (2018) in the case of flatfish (*Paralichthys olivaceus*) as well as sea cucumber (*Apostichopus japonicas*).

According to Perera et al. (1995), overuse of bacterial biomass showed a negative feedback mechanism, resulting in reduced growth and low digestibility of nutrients caused by the decrease in nitrogen (N) absorption and increase in urea excretion. According to Goodall et al. (2016), although domesticated broodstock's reproductive efficiency was unaffected, a higher amount of bacterial biomass highly affected the egg-hatching rate of *Penaeus monodon.*

Bacteria Generate Beneficial Micronutrients

Aquatic animals fulfill their basic nutrient requirements through feed intake. But micronutrients such as vitamins, fatty acids, and some essential amino acids that promote growth and normal physiological functions may not be sufficiently available in the feed provided (Fig. 2). Therefore, it is needed to supply it artificially. Recent studies have reported that a number of beneficial bacteria can produce some essential micronutrients. So probiotic-supplemented diets are now becoming a famous concept for aquaculture industries.

Cyanocobalamine, commonly known as vitamin B-12, is one of the essential cofactors for DNA synthesis and also plays a role in the metabolism of fats and amino acids, which are generated by some probiotic strains (Wang et al., 2020). Teshima and Kashiwada (1967) isolated some bacterial strains from the intestine of carp and demonstrated that these strains are capable of producing B-12 vitamins in a large percentage. Even in the absence of dietary B-12, these helpful bacteria may provide vitamin B-12 for the typical growth of aquatic species (Wang et al., 2020). Another report stated that the intestinal microbiota of channel catfish creates roughly 14 nanograms of cyanocobalamin per gram of body weight, which the host organism absorbs directly into its d. Because of this, a dietary supplement of B-12 is not necessary (Wang et al., 2020). According to LeBlanc et al*.* (2013) and (2017), various vitamins from the B family and vitamin K that are produced by the gut bacteria of humans have a similar impact on the host body.

However, plant protein, a substitute for fish meals, may also be deficient in several necessary amino acids, such as lysine, tryptophan, and sulfur-containing amino acids. As a result, shrimp development performance may be affected when using plant protein sources. To address this issue, Jannathulla et al*.* (2017) and associates employed bacterial, fungal, and yeast fermentation processes. They then measured the increase in critical amino acids, as expected. Trypsin inhibitors, phytic acid, saponin, tannin, glucosinolate, and guar gum, which are antinutrients found in plant protein sources, were also reduced after the fermentation process. Jannathulla et al*.* (2017) concluded from their study that plant protein sources fermented with beneficial microorganisms yield a higher growth ratio when fed to the aquatic fauna.

Probiotics create simple and short-chain fatty acids by fermenting some specific intestine-found fiber, according to LeBlanc et al*.* (2017). They also play a role in the host's energy metabolism. Duan et al*.* (2018) demonstrated that the probiotic *Clostridium butyricum,* when supplemented with the diet of *Marsupenaeus japonicas*, enhanced the short-chain fatty acid content of the intestine along with butyric acid and propionic acid, which can increase body crude protein and encourage kuruma shrimp growth. According to Hao et al*.* (2017), this kind of diet can alter the grass carp's hindgut microbiota, which is related to the concentrations of short-chain fatty acids.

Bacteria Regulate Digestion in the Host

According to Balcázar et al*.* (2006), beneficial microorganisms show a good effect on the metabolic process of cultured animals in aquaculture by synthesizing extracellular enzymes such as proteases, lipases, and amylases, along with providing some micronutrients like vitamins, amino acids, and fatty acids. Therefore, when probiotics are added to the diet, the nutrients are absorbed by the host organisms more effectively (El-Haroun et al., 2006). Probiotics can therefore be used to improve how well edible fish digest. According to a study by Tovar et al*.* (2002), *Debaryomyces hansenii* HF1, which is a yeast species, can produce the polyamines spermine and spermidine, which are crucial for the development of the mammalian gastrointestinal tract. Additionally, this yeast secretes trypsin and amylase, which help sea bass larvae digest their food. It has been reported that when the diet of juvenile *Dentex dentex* L. is supplemented with 0.5 g of *Bacillus cereus* strain Ekg^{-1} of food, it increases fish growth due to a greater food consumption capacity (Merrifield et al., 2010). When the diet of rainbow trout was supplemented with *B. subtilis*, *B. licheniformis,* and *Enterococcus faecium* for 10 weeks, similar results were found (Merrifield et al., 2010).

When diets of *Litopenaeus vannamei* (white shrimp) Boone and *Fenneropenaeus indicus* are treated with 50g of probiotics per kg of meal, the digestion of dry matter, crude protein, and phosphorus rises along with the larger body size. In order to create a consistent impact on the synthesis of enzymes involved in digestion, probiotic maintenance in all ontogenetic phases of shrimp has been explicitly highlighted in other studies (Martinez et al., 2012). When B. subtilis was taken out of the digestive tract of *C. mrigala* and supplemented with the diet of guppies (*Poecilia reticulata, P. sphenops)* and swordtails (*Xiphophorus helleri, X. maculatus*), these fish displayed a larger body weight and good length, along with the remarkable functions of enzyme proteases and amylases of the gut (Ghosh et al., 2008). A wide range of coenzymes is secreted by *Bacillus,* which in turn increases the enzymatic digestion of the fish bodies. Protease, cellulase, lipase, chitinase, and trypsin activity have also been demonstrated by these isolated beneficial bacteria from the digestive tract of aquatic animals (Vine et al., 2006).

Beneficial Bacteria have an Anti-Pathogen Action

In the past centuries, antibiotics have been used as potent anti-pathogenic drugs in aquaculture. Later, it was found that though antibiotics can prevent disease in aquatic crops, they have some negative impacts on cultured aquatic animals as well as on human health. Problems raised by the applications of antibiotics in aquaculture industries include an accumulation of antimicrobial drug residue in host tissue, the development of microbial defiant mechanisms, and the disbalance of beneficial gut fauna in cultured organisms, which further affects their physique (Nakano, 2007). Even antibiotic use in organisms intended for human consumption is governed by EU regulations. (Ronson and Medina, 2002). People are concerned about their health, and it has been seen that natural items without additions like antibiotics are always preferred. In addition, disease prevention is more common than disease treatment. Therefore, using probiotics to inhibit pathogens and reduce disease in aquaculture species is a viable alternative. (Martinez et al., 2012*)*.

Beneficial bacteria can stimulate innate and humoral immunity in fish to combat pathogenic microorganisms (Allameh et al., 2017). By secreting some chemical substances, probiotic bacteria can prevent the colonization by pathogens within the gut of the host organisms. The creation of antibiotics, bacteriocins, siderophores, digestive enzymes like lysozymes, proteases, and hydrogen peroxide, as well as the adjustment of the gut pH brought on by the formation of organic acids, are what give probiotics their antibacterial effects. (Verschuere et al., 2000).

Taoka and Maeda Jo (2006) demonstrated that live beneficial microorganism administration to tilapia, *Oreochromis niloticus*, enhanced innate immune response, which can be measured by lysozyme activity, neutrophile migration, and bactericidal activity, responsible for the improvement of the defense mechanism of fish against the infection caused by *Edwardsiella tarda*. Live Carnobacterium spp. were given to rainbow trout and Atlantic salmon by Robertson et al. (2000) and isolated from the salmon bowel, which demonstrated in vitro antagonistic activity against recognized fish pathogens like *Aeromonas hydrophila*, *A. salmonicida*, *Flavobacterium psychrophilum, Photobacterium damselae*, and *Vibrio spp.* There is proof that deceased probiotic cultures made up of a combination of *Aeromonas hydrophila A3-51*, *Carnobacterium BA211,* and *Vibrio fluvialis A3-47S* can help control furunculosis disease in rainbow trout (Martinez et al., 2012). Probiotics, including *Bacillus cereus, Paenibacillus polymyxa,* and *Pseudomonas spp.,* have been evaluated in studies. In the case of shrimp, PS-102 biocontrol drugs prevent a variety of Vibrio species (Ravi et al., 2007; Vijayan et al., 2006).

It has been observed that microbial strains that were taken out from the gastrointestinal mucosa of clownfish have the ability to generate antimicrobial metabolites in invivo conditions which were useful to deactivate some pathogenic bacteria such as *A. hydrophila* and *Vibrio alginolyticus* among others (Vine et al., 2004). According to Ghosh et al. (2008) probiotic bacteria with concentrations of 10^6 to 10^8 cellsg^{-1} enhanced the proliferation of beneficial microorganisms in the GI tract of ornamental fishes which belong to the genera *Poecilia* and *Xiphophorus*.

Regulation of Fish Immune Systems by Beneficial Microorganisms

Probiotics are now a crucial component of aquaculture methods that can help achieve high productivity. Commonly used beneficial microbes in aquaculture include Lactobacillus*, Lactococcus, Leuconostoc, Enterococcus, Carnobacterium, Shewanella, Bacillus, Aeromonas, Vibrio, Enterobacter, Pseudomonas, Clostridium,* and *Saccharomyces* species (Fernandes et al., 2021). Probiotics have been shown to have a variety of positive effects on fish, including stimulation of growth, improved nutrition, disease resistance, and other positive effects. But one of the most frequently cited effects is the modification of the immune system in aquatic organisms. Probiotic supplementation can elevate phagocytic, lysozyme, complement, and respiratory burst activity as well as the expression of various cytokines in fish. According to studies, microorganisms can enhance the number of immunoglobulin cells and acidophilic granulocytes in the fish gut immune system (Fernandes et al., 2021).

Pirarat et al. (2006) recorded stimulation of phagocytic activity in *Oreochromis niloticus* (Tilapia) when administrated with *Lactobacillus rhamnosus* for 2 weeks. The phagocytic activity of *O. mykiss* has also been shown to increase when *Clostridium butyricum* is fed to tilapia (Sharifuzzaman and Austin, 2009). Bacillus subtilis and some members of the LAB group have been shown to enhance respiratory burst activity in fish (Nikoskelainen et al., 2003; Salinas et al., 2005; Salinas et al., 2006; Zhou et al., 2009). Bacteria like *Lactobacillus rhamnosus, Carnobacterium maltaromaticum, and Carnobacterium divergens* enhance the lysozyme level in O. mykiss (Kim and Austin, 2006; Panigrahi et al., 2004). A study has shown that when *Ulva Sp.* was fed to Nile tilapia, it significantly enhanced the complement activity (i.e., alternative hemolytic complement activity (ACH_{50}), an essential component of the innate immunity system), while the muscle colour was modified, and the sour parameter of the fillets was decreased (Valente et al., 2016). *Pseudomonas aeruginosa*, according to Kanther et al. (2011), can also affect the immune system of larval zebrafish by promoting NF-B-dependent production of innate immunity genes, including complement factor b (cfb) and serum amyloid a (saa), which increase neutrophil infiltration. A study reveals that a unique protein, AimA, is secreted by *Aeromonas veronii* in the zebra fish intestine and is beneficial for both the host and microbes. It protects the host by preventing chemical and bacterially induced inflammation, and it protects *A. veronii* by helping in colonization and the host immune response (Rolig et al., 2018). According to Panigrahi et al. (2007), microbes like *L. rhamnosus, E. faecium,* and *B. subtilis* can increase the level of pro-inflammatory cytokines like IL-1b1 and TGFb in Tilapia's head, kidney, and spleen. Likewise, the anti-inflammatory response in Tilapia is also influenced by *C. maltaromaticum* and *C. divergens*, which can express IL-1b, IL-8, TNF-a, and TGF-b in the head and kidney of *O. mykiss* (Kim and Austin, 2006). Picchietti et al. (2009) recorded the enhancement of T-lymphocytes in the GI tract of *D. labra* when supplemented with L. *delbrueckii* sp. through artemia and rotifers.

Commensal Microbiota in Host Immune Homeostasis Maintenance

Healthy fish have various microbial communities in contrast to those that are ill, which provides clear evidence of the intimate relationship between commensal microbiota and bodily homeostasis. This remark is well demonstrated by the comparison of a healthy member of the same species with a crucian carp (*Carassius auratus*) that has red operculum disease and a varied microbial population. On the other hand, some species of microbes are found abundantly in diseased fish as good pathogens, and these include *Vibrio, Aeromonas, and Shewanella* (Li et al*.,* 2017). The same record was found in the case of *Coreius guichenoti* when infected by the bacterial pathogen *Aeromonas salmonicida,* resulting in furunculosis (Li et al*.,* 2016). According to Nie et al. (2017), when *Plecoglossus altivelis* was infected by *V. anguillarum,* it was demonstrated that the host's gut microbiota dynamics significantly decreased, along with the complexity, connectivity, and cooperativeness of gut bacterial interspecies interaction. This affects the host immunological response, which includes TNFa and IL-1b expression. According to the findings of this study, the host defense system and the inhabitants of the gut interact to prevent harmful microbes.

When antibiotics were used to treat various pathogenic microorganisms in the host, it was seen that they affected the commensal microbiota in the host intestine, which further affected the host immune response. Moreover, Limbu et al. (2018) observed human health risks. To overcome this problem, He et al. (2017) used olaquindox on zebrafish against the pathogen *A. hydrophil*a infection, and they found a compromised result, i.e., they recorded minimal changes in the intestinal microbiota and host immune response of zebrafish. They came to the conclusion that bacteria may have an impact on the host immune system.

Beneficial Bacteria Modulate Commensal Microbiota

The gut microbiota of fish is undoubtedly abundant and diverse and is capable of providing a potential barrier for foreign invaders such as pathogenic organisms like viruses, bacteria, protozoans, parasites, nematodes, etc. These intestinal microbiotas maintain a mutual relationship with the host for nutrition, defense, hormonal, neural, and metabolic activity. An imbalance in the intestinal microbiota of Pisces causes critical health conditions resulting in growth retardation, low immunity, various clinical conditions, and a higher mortality rate for the host. Several therapeutic strategies are applicable to overcoming this problem, and one of the most modern is the administration of probiotic bacteria to the fish.

Fish that have been treated with antibiotics may have a decline in their gut microbiota, but probiotics can help restore the balance (Yukgehnaish et al*.,* 2020). Probiotics, as stated by Reid et al*.* (2003), can influence the gut microbiota through mechanisms such as colonization of the intestine mucosa, competitive adherence and exclusion, and the production of beneficial substances and chemical signs for the host, which in turn influence the immune system to modulate and regulate allergic responses. Pathogen growth can be inhibited by the presence of chemicals in probiotics such as bacteriocins, enzymes, hydrogen peroxide, and organic acids (Alonso et al*.,* 2019). Tan et al*.* (2019) report that in the intestine of Tilapia*, R. stabekisii* stimulates the growth of other probiotic bacteria, specifically *Bacillus* and *Lactobacillus spp.*, while concurrently decreasing the number of harmful bacteria, such as *Streptococcus* and *Staphylococcus spp*. According to research published by Huyben et al*.* (2017), the yeast *Saccharomyces cerevisiae* can alter the composition of the gut microbiota of fish without causing any harm to the host. Yeast protein is a dietary supplement that has been shown to promote beneficial yeast species in fish. According to research by Huyben et al*. (*2018*),* supplementing a rainbow trout's diet with live yeast has been shown to increase the diversity of yeast species in the fish's digestive tract. When immersed in a solution containing 49 different strains of *Lactobacillus*, He et al*.* (2017) found that the zebrafish's intestines became gradually colonized and that the Lactobacillus was distributed dynamically along the length of the intestine.

Increase Survival Rate

Probiotics are live beneficial microorganisms that are capable of maintaining good health, desirable growth, strong immunity, and a higher survival rate in aquatic organisms in aquaculture practice. Probiotic supplementation with the fish diet for obtaining desirable growth and a higher survival rate is a famous approach in aquaculture. Definite probiotic doses in fish can enhance the gut microflora, inhibit pathogens, and increase immunity in the host.

Omenwa et al. (2015) also reported that the addition of *Lactobacillus plantarum* and *Pseudomonas fluorescent* in the pond water of *C. gariepinus* juveniles increases the survival rate by 96.22%. Likewise, Tarnecki et al. (2019) supplemented a mixture of *Bacillus* species (B. *licheniformis and B. amyloliquefaciens*) to the larval common snook (*Centropomus undecimalis*) in three different ways: 1) probiotic added to rearing water and live feed; 2) probiotic supplemented with rearing water only and 3) no probiotic control. After some days, they recorded the results of each treatment. From these two separate trial treatments, they discovered a 2.5-fold increase in snook survival after adding the probiotic. And a 20% increase in survival seven days after a transit event. Mocanu et al. (2022) showed how probiotics can increase the survival rate of aquatic organisms in a rearing pond. They carried out an experiment on Siberian sturgeon (*Acipenser baerii*) in a recirculating system. The diet of *A. baerii* is supplemented with *Saccharomyces boulardii* (FSB) and *L. acidophilus* (Fla) separately as well as combined. They feed 2000 fish with four different diets for 8 weeks: 1) a diet without probiotic addition; 2) a diet with *Lactobacillus acidophilus;* 3) a diet with *Saccharomyces boulardii* and 4) a diet with a mixture of both bacteria and yeast in equal proportion. The Fla+Fsb diet results in higher growth performance, a higher feed conversion ratio, strong immunity, and higher survival than the control diet in the *A.r. baerii*.

Application of Probiotics in Biofloc Technology

Biofloc technology is a fish farming system that recycles waste nutrients as fish food. By manipulating the water's carbon-nitrogen ratio, heterotrophic bacteria can be promoted to proliferate and utilized in situ by cultured animals or extracted and processed as feed ingredients.

Novel Vaccine

Another innovative application is the diverse synthesis of functional genes in bacteria and their application in aquaculture activities. Jia and colleagues engineered the heterocystous cyanobacterium *Anabaena Sp.* PCC 7120 to express the principal envelope protein (VP28) of the white spot syndrome virus for oral immunization (Jia et al*.,* 2016).

As previously mentioned, many bacterial strains have been demonstrated to be favorable to both aquatic creatures and humans. There is no information on whether an aquaculture strain will directly or indirectly enhance consumer health through aquatic products. Contrarily, there are currently relatively few practical applications despite the fact that numerous studies have shown that different bacterial strains have a positive impact on aquaculture growth. As a result, there are many opportunities for beneficial bacteria to increase the quantity and quality of aquaculture and to provide wholesome aquatic products. For this reason, the corresponding basic research and commercial trials are important.

Future Direction-Novel Applications of Beneficial Bacteria

The good effects of beneficial bacteria on aquatic organisms have led to significant research and widespread application of these microbes in aquaculture, as well as the development of several novel applications. The nutritional and healthcare applications of these interventions stand to benefit from the novel types, mechanisms, and applications that are currently under investigation. Related domains of microbiome-targeted therapies are growing, and the environment for implementation across regulatory, policy, prescriber, and consumer sectors is shifting, heralding a new era of profound transformation. Widespread improvements in data gathering and analytical methods allow for the discovery of novel candidates for probiotics and prebiotics and provide light on the complex relationships between these microbes and the hosts they inhabit. Increased focus is being placed on discovering novel uses for probiotics and prebiotics in a wide variety of medical contexts, anatomical locations, demographic groupings, and administration methods. The incorporation of probiotics and prebiotics into nutrition and healthcare is also influenced by the development of regulatory frameworks, clinical guidelines, and market tendencies. Future healthcare solutions may include the use of probiotics and prebiotics to combat microbial infections and other conditions. In order to treat and prevent COVID-19 infection, probiotics and prebiotics have been proposed as potential components of both preventative and acute care methods (Villena and Kitazawa, 2020).

Conclusion

The aquaculture business has experienced a remarkable expansion in recent years because of the rising demand for seafood and the advancement of cultural technologies. However, the contemporary aquaculture business, particularly high-density aquaculture, has a number of significant obstacles. These are the lack of a cheap and plentiful source of protein for feeding, the significant loss brought on by viral infection, and the quality loss during growth and storage. Bacteria can be employed as a potential remedy for these issues due to their inexpensive cost, high protein content, and variety of biological activities. Numerous beneficial bacterial species have been studied and utilized in aquaculture for a variety of purposes. However, fresh applications and pertinent mechanistic research will be required in the future to improve current procedures and avoid potential hazards.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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