Symbiosis (2019) 77:99–113
https://doi.org/10.1007/s13199-018-0580-1

Probiotics in aquaculture: a promising emerging alternative approach

Arun Chauhan[1] · Rahul Singh[1]

Received: 31 May 2018 / Accepted: 1 November 2018 / Published online: 10 November 2018

Abstract
Aquaculture is an important food producing sector to fulfill nutritional food demand of a continuously growing population. However, disease outbreak has become a major problem in aquaculture which cause huge economic loss to aquaculture industries. The use of expensive chemotherapeutic drugs for treatment have negative impacts on the aquatic environment. So there is a growing concern to find other safe, non-antibiotic based and eco-friendly alternative for the treatment of the diseases. The use of probiotics is a promising alternative approach for the control of infectious agents and treatment of diseases. The benefits of probiotic include stimulation of growth, improved digestion, enhanced immune response and recuperate the water quality as well. Probiotics concoct the fish to fight against various pathogens and improves the overall health as they show anti-bacterial, anti-fungal and anti-viral properties. The use of probiotics in aquaculture is a recent trend and its efficacy in aquatic environment has not been studied extensively. This review paper provides the current knowledge of the use of probiotics in aquaculture, selection criteria, types of probiotics used in aquaculture, their mode of action and administrative methods of probiotics in aquaculture.

Keywords Putative probiotics · Prebiotics · Synbiotics · Antibiotics · Carp · Quorum sensing

1 Introduction

Aquaculture is an important and rapidly growing sector as it plays an important role to achieve global protein food demand compared to capture fisheries and terrestrial farmed meat. The role of aquaculture to improve the socio-economic status of any region is highly appreciable because it is not only limited to the source of essential nutrients but it also generates various employment opportunities (Araujo et al. 2015; Handbook on Fisheries Statistics 2014). India ranks second in the world after China in fish production through aquaculture with a contribution of 6.3% of the global aqua production, which is very less as compared to that of China (60.5%) (Chavan 2018; Mo et al. 2018). Fishes are dominant in aqua products, and around 200 fish species are produced for their commercial value (Swapna et al. 2010).

With the increasing intensification and commercialization of aquaculture production, diseases have become a hurdle in the fish farming industry (Hai 2015). The most common disease causing bacterial pathogens among aquaculture are gram-negative such as, *Aeromonas*, *Flavobacterium*, *Pseudomonas*, *Vibrio* and *Yersinia species*. These pathogens are etiological agents of various diseases like, enteric red mouth disease, furunculosis, hemorrhage, septicemia, vibriosis and so on (Hamid et al. 2017; Cascales et al. 2016; Patra et al. 2016; Wiklund 2016; Ronneseth et al. 2017). The use of chemotherapeutic drugs has served as an option to cure common diseases prevailing in fish farming (Hambali and Akhmad 2000).

In aquaculture, chemotherapeutic agents like antibiotics and chemicals are the classical cure for microbial infection. However, the extensive usage of these chemotherapeutic drugs leads to their accumulation in aquatic habitat and results in harmful consequences such as emergence of antibiotic-resistant bacteria, accumulation of antibiotic residues in the flesh, kill the beneficial microbes of the gastrointestinal tract and alterations in microbiota (effect on non-target microbes) of the aquatic environment (Munoz-Atienzal et al. 2013; Azevedo et al. 2015). Therefore, the use of antibiotics as chemotherapeutic drugs in aquaculture has become risky (Balcazar et al. 2008; Mancuso et al. 2015; Balcazar et al. 2006a, b). The quest for better alternatives to prevent infection and replace the antibiotics has been a major concern now-a-days.

A promising emerging alternative approach to prevent fish diseases is the use of probiotics, which helps fishes to fight against pathogens by various mechanisms. The importance of probiotics used in aquaculture is not only limited to gastrointestinal tract, but it also plays a major role in the improvement

✉ Rahul Singh
rahulsingh.mlkzoology@gmail.com

[1] Department of Zoology, School of Bioengineering & Biosciences, Lovely Professional University, Phagwara, Punjab 144411, India

of overall health of an organism (Mehrabi et al. 2018) such as: it acts as growth promoter (Gobi et al. 2018), prevents the diseases (Meidong et al. 2018), enhances the immune response (Havenaar and Marteau 2018; Ramesh and Souissi 2018) and improves the water quality by modifying microbial community of water and sediments (Verschuere et al. 2000; Deng et al. 2018). In ponds, nitrogenous contaminants like ammonia and nitrate have become a serious concern. Previous reports show that the use of *Lactobacillus* species as probiotics removes the nitrogenous waste from the ponds and use of *Bacillus* species improves the water quality by converting organic carbon to slime (Ma et al. 2009; Verschuere et al. 2000; Kolndadacha et al. 2011). Khattab et al. 2005 have reported the use of *Micrococcus luteus* as probiotics which resulted in increased growth performance and improved feed conversion ratio (FCR) in Tilapia (*Oreochromis niloticus*). Sakata 1990 and Ringo et al. 1995 have demonstrated the role of *Bacteroides* species, *Clostridium* species, *Agrobacterium* species, *Brevibacterium* species and *Microbacterium* species as nutritional sources to the host by supplying fatty acids and vitamins.

This review aims to provide useful knowledge about the use of probiotics in aquaculture, selection criteria, most commonly used probiotic strains, their possible mode of action and administrative methods in aquaculture.

1.1 Definition and brief history of probiotics

In 1907, Elie Metchnikoff, a Russian analyst observed that Bulgarian workers had a long life as they consumed fermented milk products. Later in 1965, Lilly and Stillwell explained the concept of probiotics, as a substance which accelerates the growth of good microbes. Parker (1974) gave the definition of probiotics as "organisms and substances, which add to intestinal balance". Fuller (1992) refined the definition as, "A live microbial feed supplement that beneficially affects the host by improving its intestinal microbial balance". This definition signifies that the living bacterial cells are an imperative part of potential probiotics and also clarifies the confusion created by the use of term "substance". WHO (2001) has termed probiotics as live microbes, which when administered in sufficient amount, confer a health benefit to the host.

Probiotics protect the host organism from pathogenic bacteria by liberating metabolites like bacteriocins and different organic acids. These metabolites hinder the adhesion of different pathogens and also inhibit them by limiting the available resources such as nutrients and space (Servin and Coconnier 2003; Vine et al. 2004). Probiotics have the potential to improve the host's defenses, including the innate and acquired immunity system. This is important for the prevention and treatment of infectious diseases and also to cure inflammation in the digestive tract. Probiotics also have a direct influence on other microbes, either commensal or pathogenic, which is very important for the prevention, treatment and restoration of the bacterial equilibrium inside the gut of the host (Oelschlaeger 2010). The use of probiotics in humans, pigs, steers and poultry has already been studied, but the use of probiotics in aquaculture is relatively a new concept (Daniel 2017; Chua et al. 2017; Jiang et al. 2017; Harimurti and Hadisaputro 2015; Uyeno et al. 2015).

2 Selection criteria for probiotics

The main purpose of probiotics is to establish or to maintain a relationship between beneficial and harmful bacteria which is usually present in the intestine or gut of fish (Thirumurugan and Vignesh 2015; Olsson et al. 1992). Effective probiotics should possess certain qualities which are specified underneath: (Olsson et al. 1992; Merrifield et al. 2010; Pandya 2016; Gatesoupe 1999; Ouwehand et al. 1999a; Ouwehand et al. 1999b; Holzapfel and Schillinger 2002; Fuller 1989).

1. The probiotics should have a beneficial effect on the growth, development and protection of fish against various pathogenic bacteria.
2. The probiotic bacteria should not have any harmful effect on the host.
3. The probiotics should not have the ability of drug resistance, they should have the ability to keep up the hereditary traits.
4. For the utilization of probiotics as an efficient feed, they should exhibit following properties:
   - Acid and bile tolerance
   - Resistance to gastric juices
   - Adherence to digestive system surface
   - Antagonism towards pathogens
   - Stimulation of the immunity
   - Increase in the gut motility
   - Survival in mucous
   - Production of enzymes and vitamins
5. They should have good sensorial properties, fermentative action, tolerance towards freeze-drying and viability in feed during packaging and storing process.

Bacteria isolated from different sources are subjected to screening through multiple steps in order to assess their potential as ideal probiotics. The screening process involves gram staining, indexing, in-vitro evaluation of antagonistic properties, acid tolerance, bile tolerance, susceptibility to drugs and biofilm formation. Figure 1 shows the sequential screening process for the selection of isolated bacteria as probiotics. Successful fulfillment of all criteria qualify them as potential probiotic fit for use in the aquaculture.

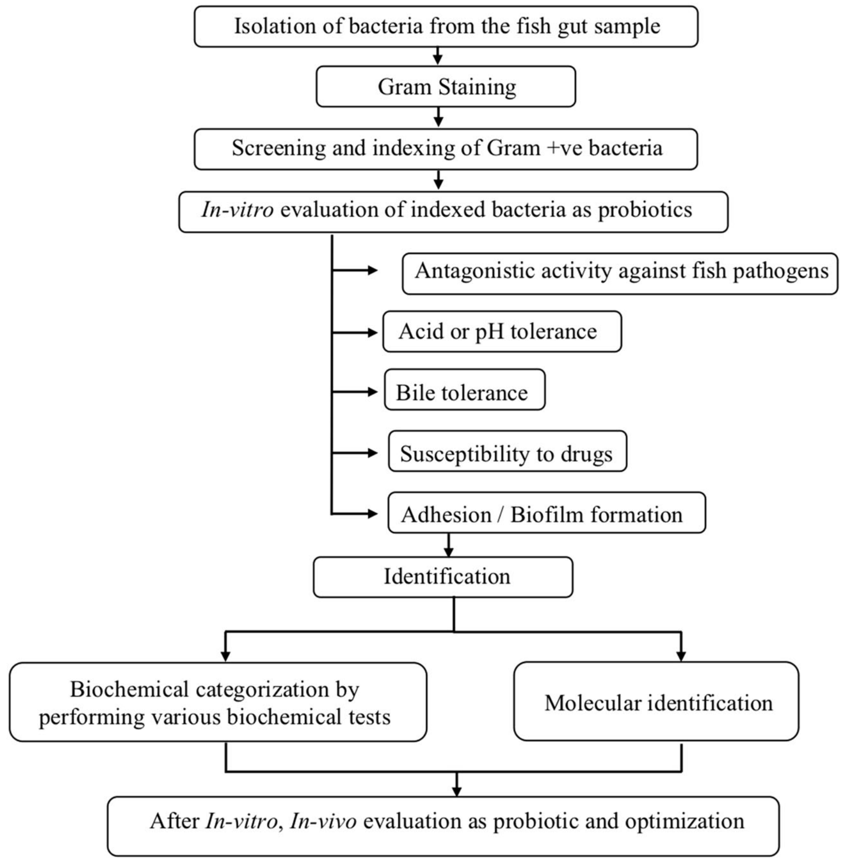

Fig. 1 Schematic representation of the screening process for the selection of isolated bacteria as ideal probiotics

3 Probiotics & aquaculture

Usually the aquatic probiotics are commercially available in two major forms- dry and liquid. Dry forms have higher shelf life and are mixed with water or feed which is given to the host. On the other hand, the liquid form of probiotics, usually preferred in egg hatcheries is directly blended with the feed or added to the tanks (Decamp and Moriarty 2007). The liquid forms of probiotics are reported to show better and positive results due to their lower density than spore and dry form probiotics (Nageswara and Babu 2006).

The aquatic probiotics can be further categorized into two classes based on their mode of administration. First one involves the mixing of probiotic bacteria with feed supplement for the enhancement of useful bacteria inside the gut. Second class involves the addition of probiotic directly to the water so that they can consume nutrients available in the water and inhibit the proliferation of pathogens. These two categories of probiotics were used in finfish and shrimp aquaculture (Nageswara and Babu 2006; Sahu et al. 2008).

The probiotics isolated from different natural sources such as gastrointestinal tract (GIT), stomach, gill, kidney, gonads and other internal organs are called putative probiotics. In contrast, the commercial sources (non-putative) comprise of those which are already synthesized and commercially available in the market. The most frequently used probiotic microorganisms belong to *Bacillus*, *Lactobacillus* and *Bifidobacterium* genus (Nwanna 2015). Various species of *Lactobacillus*, *Bifidobacterium* and *Streptococcus* reported for use in aquaculture as probiotics, include *L. acidophilus, L. casei, L. fermentum, L. gasseri, L. plantarum, L. salivarius, L. rhamnosus, L. johnsonii, L. paracasei, L. reuteri, L. helveticus, L. bugaricus*, *Bifidobacterium bifidum, Bifidobacterium breve, Bifidobacterium lactis, Bifidobacterium longum, Saccharromyces species, Saccharromyces boulardii, S. thermophiles* and *S. cremoris* (Nwanna 2015).

Various aquatic probiotics have been reported which show activity not only against bacterial pathogen, but also against fungus and virus to improve growth and immunity of the host.

3.1 Antibacterial activity

Many probiotics used in aquaculture are well-known for their antibacterial property against known pathogens. *Lactococcus lactis* RQ516 probiotic shows inhibitory action against *Aeromonas hydrophila* when given to Tilapia (*Oreochromis niloticus*) (Zhou et al. 2010). Also *L. lactis* probiotic has antibacterial activity against two pathogens-*Yersinia rukeri* and *Aeromonas salmonicida* that affects the fish growth (Balcazar et al. 2007a, b). *Leuconostoc mesenteroides* has the potential to inhibit the fish pathogens found in Nile tilapia (*O. niloticus*) (Zapata and Lara-Flores 2012). According to reports, *Bacillus subtilis* considerably reduces the motile *Aeromonads*, total *Coliforms* and *Pseudomonads* found in ornamental fishes (Ghosh et al. 2008; Newaj-Fyzul and Austin 2015). Lactic acid bacteria such as *Lactobacillus acidophilus, Lactobacillus buchneri*, *Lactobacillus fermentum, Lactococcus lactis*, and *Sterptococcus salivarius* were isolated from Spanish mackerel (*Scomberomorus commerson*) intestine and were capable to inhibit the *Listeria innocua* growth (Moosavi-Nasab et al. 2014). Many *Lactobacilli* species isolated from the intestine of *Anguilla* species, *Clarias orientalis*, *Labeo rohita*, *Oreochromis* species and *Puntius carnaticus* showed significant antimicrobial activity against *Aeromonas* and *Vibrio* species (Dhanasekaran et al. 2008).

3.2 Antiviral activity

In recent years, the antiviral activity of probiotics has gained attention (Lakshmi et al. 2013), but the exact mechanism of action through which probiotic bacteria show antiviral effects is still unknown. However the in-vitro analysis reveals that the inhibition of viruses can occur by secretion of extracellular enzymes produced by the bacteria. For example, *Aeromonas* species, *Corynebacterium*, *Pseudomonas* and *Vibrio* species show the antiviral activity against the IHNV (Infectious hematopoietic necrosis virus) (Kamei et al. 1988; Zorriehzahra et al. 2016). Feeding of probiotic strain *Bacillus megaterium* has increased the resistance against WSSV (white-spot syndrome virus) in the shrimp, *Litopenaeus vannamei* (Li et al. 2009). The research has reported that probiotics strains *Bacillus* and *Vibrio* species are effective against WSSV and efficiently protect *Litopenaeus vannamei* (Balcazar 2003). Application of *Lactobacillus* as probiotic, either as a single strain or as a mixture with Sporolac resulted in better resistance against lymphocystis viral disease which is found in *Paralichthys olivaceus* (olive flounder) (Harikrishnan et al. 2010).

3.3 Antifungal activity

Only few studies have been reported about the antifungal activity of probiotics. *Aeromonas* strain A199 from *Anguilla australis* (eel) culture water, had high inhibitory property against *Saprolegnia* species (Lategan et al. 2004). In another study, *Pseudomonas* species M162, *Pseudomonas* species M174 and *Janthinobacterium* species M169 have increased the immunity against saprolegniasis in *Oncorhynchus mykiss* (rainbow trout) (Zorriehzahra et al. 2016). In 2012, Nurhajati et al. demonstrated that *Lactobacillus plantarum* FNCC 226 showed inhibitory potential in catfish (*Pangasius hypophthalamus*) against *Saprolegnia parasitica* A3 (Nurhajati et al. 2012).

The reported probiotic strains used in aquaculture can either be obtained commercially or isolated from different fish species. A detailed summary of different probiotics, their sources and the beneficial effects on the host are given in Table 1.

4 Mode of action

Probiotics have a special mode of action to protect the host from intestinal issues. The probiotic microorganisms hinder the establishment of different pathogenic bacteria by a process called colonization resistance. Probiotic microorganisms secrete a variety of inhibitory substances which inhibit Gram +ve and Gram –ve microscopic organisms. Principally, these inhibitory secretions are acetic acid, lactic acid, H_2O_2, bacteriocins and so on. These secretions decrease the number of pathogens by inhibiting the formation of virulence substances (Nwanna 2015). Oelschlaeger (2010) explained the mode of action of probiotics in a simple way in which probiotics modulate the acquired immune system as well as innate immunity to prevent host gut from disease causing pathogens and to treat against various digestive tract inflammations. Next possible action is that, they directly affect the pathogenic bacteria present in the gut, thus, resulting in the restoration of the probiotics in the gut. Finally they target various toxins produced by the microbial population resulting in their detoxification and inactivation in the gut (Oelschlaeger 2010). Thus, all modes of action of probiotics are directly associated with gut microbiota (Wolf 2006; Pandiyan et al. 2013). Probiotic secrete antagonistic compounds which help to improve the immunity and enhance the growth of fish. It also helps to improve the water and soil quality. The mode of action of probiotics is shown in Fig. 2.

Some possible well-known mechanisms by which probiotic bacteria protect the host organism against intestinal disorders are as follows:

4.1 Competition for space / blocking of adhesion sites

The activity of probiotics is visualized by the aggressive hindrance for the attachment sites on intestinal epithelial layer (Nwanna 2015). The mechanism of action by which probiotic bacteria struggle for the adhesion site is called 'competitive inhibition'. The ability of bacteria to colonize the gut and adhere to the epithelial surface and subsequently inhibit the adhesion of pathogens is desirable criteria in the selection of probiotics (Balcazar et al. 2006a, b; Lazado et al. 2011). *Lactobacillus* prevent the adhesion of the pathogenic bacteria such as *Escherichia coli*, *Klebsiella* species and *Pseudomonas aeruginosa* on intestinal cells of the host (Nwanna 2015).

Table 1 Probiotic species used in aquaculture, source and beneficial effects to the host species

Probiotic species	Source of probionts	Beneficial effects	References
Lactobacillus acidophilus *Streptococcus faecium*	Commercial (All Tech, Nicholasville, KY)	Best growth performance and feed efficiency	Lara-Flores et al. (2003)
Bacillus subtilis *Lactobacillus acidophilus*	Commercial	Enhanced the non-specific immune parameters and enhance the challenge against *Edwardsiella tarda* infection	Tovar-Ramırez et al. (2004)
Bacillus cereus *Paenibacillus polymyxa*	Seawater, sediment and gut of healthy fish (*Lates calcarifer*)	Improved resistance against pathogenic *Vibrio* spp.	Ravi et al. (2007)
Lactococcus lactis CLFP 101 *Lactobacillus plantarum* CLFP 238 *Lactobacillus fermentum* CLFP 242	*Oncorhynchus mykiss* (Rainbow trout)	Reduce the adhesion of pathogens i.e. *Aeromonas salmonicida*, *Aeromonas hydrophila*, *Yersinia ruckeri* and *Vibrio anguillarum* to intestinal mucus and shows antibacterial activity against these fish pathogens.	Balcazar et al. (2008)
Lactobacillus plantarum *Bacillus subtilis*	*Labeo rohita*	Shows antagonistic activity against *Aeromonas hydrophila*	Giri et al. (2011)
Bacillus coagulans *Bacillus mesentericus* *Bifidobacterium infantis*	*Puntius conchonius*	Probiotic bacteria significantly established in gut of *P. conchonius* and significant effects on the pathogenic gut inhabitants of the fish.	Divya et al. (2012)
Bacillus subtilis	*Cyprinus carpio* (Common carp)	Inhibit the growth of *Aeromonas hydrophila*	Al-Faragi and Alsaphar (2012)
Bacillus subtilis	*Cyprinus carpio* (Common carp)	Growth promoting probiotic, enhance growth at the rate of 4×10^8 cells per 100 g of feed. Shows better growth, feed conversion ratio (FCR), specific growth rate (SGR) and feed conversion efficiency (FCE)	Bisht et al. (2012)
Nitrosomonas species *Nitrobacter species*	Commercial	Improves water quality and lowers the pathogenic (*Pseudomonas* species) bacterial loads in fish ponds.	Padmavathi et al. (2012)
Lactococcus lactis (D1813)	*Marsupenaeus japonicas*	Exhibit highest amount of IFN-γ production and bactericidal activity. Inhibit the infection caused by *Vibrio penaeicida*.	Maeda et al. (2014)
Enterobacter sp. strain C6–6	*Oncorhynchus mykiss* (Rainbow trout)	Protects the fish against *Flavobacterium psychrophilum* infection, reduce the mortality and enhance the immunity of fish.	LaPatra et al. (2014)
Bacillus subtilis	*Macrobrachium rosenbergii*	Increase in the growth, survival, improve food digestion, reduce the mortality caused by pathogenic bacteria (*Aeromonas hydrophila*)	Ramzani et al. (2014)
Bacillus cereus	*Cirrhinus mrigala*	Shows high growth performance like specific growth rate, body weight and also shows inhibition against the pathogenic strain (*Aeromonas hydrophila*)	Bhatnagar and Lamba (2015)
Bacillus subtilis *Bacillus aerophilus* *Bacillus firmus*	*Labeo rohita*	Improves digestion and fight against the fish pathogens such as *Providencia rettgeri* and *Aeromonas* species.	Thankappan et al. (2015)
Lactococcus lactic *Lactobacillus plantarum*	Bean sprouts *Paralichthys olivaceus*	Show improve phagocytic activity of innate immune cells, skin mucus lysozyme activity and improves host innate immunity, weight gain and survival rate following *Streptococcus iniae* challenge.	Beck et al. (2015)
Bacillus subtilis *Pediococcus acidilactici* *Enterococcus faecium* *Lactobacillus reuteri*	Commercial	Increase growth performance, health status and also modulate intestinal microbial community.	Giannenas et al. (2015)
Bacillus subtilis *Lactococcus lactis* *Saccharomyces cerevisiae*	*Labeo rohita*	Strains are more efficient in converting organic matter, adhere to the intestine, enhance the growth and survival of *L. rohita*.	Abareethan and Amsath (2015)
Bacillus licheniformis	Commercial	Increase the growth, immune response and disease resistance of juvenile tilapia against *Streptococcus iniae*.	Han et al. (2015)

Table 1 (continued)

Probiotic species	Source of probionts	Beneficial effects	References
Bacillus pumilus	*Labeo rohita*	*Bacillus pumilus* treated fish show maximum percentage of total erythrocyte count, haemoglobin concentration and haematocrit concentrations which improves survival and therefore establish better health conditions.	Rajikkannu et al. (2015)
Bacillus pumilus *Bacillus mojavensis*	*Oratosquilla oratoria* *Portunus trituberculatus*	Shows antagonism against *Vibrio parahaemolyticus*	Liu et al. (2015)
Lactobacillus gasseri TSU3 *Lactobacillus animalis TSU4*	*Catla catla*	Capable of adhering to epithelial cells and mucosal surfaces and exhibit strong anti-bacterial activity against all pathogens including *Aeromonas hydrophila*.	Sahoo et al. (2015)
Pseudomonas psychrotolerans *Vibrio ichthyoenteri* *Labrenzia sp.*	*Sparus aurata*	Enhance the immune defence of fish. Show antagonism against three fish pathogens: *Vibrio anguillarum*, *Photobacterium damselae* and *Pseudomonas anguilliseptica*.	Mancuso et al. (2015)
Bacillus amyloliquefaciens (KF623290) *Bacillus sonorensis (KF623291)*	*Cirrhinus mrigala*	Shows antagonistic activity against *Pseudomonas putida* and *Aeromonas salmonicida.*	Dutta and Ghosh (2015)
Lactobacillus plantarum	Sediments	Stimulates growth rate, feed efficiency, conferred the best performance and immune response of Nile tilapia challenged with *Aeromonas hydrophila*.	Hamdan et al. (2016)
Bacillus stratosphericus (KM277362) *Bacillus aerophilus (KM277363)* *Bacillus licheniformis (KM277364)* *Solibacillus silvestris (KM277365)*	*Cirrhinus mrigala*	Strains grow better in intestinal mucus and produce various cellular components which exhibit bactericidal activity against the fish pathogens.	Mukherjee et al. (2016)
Lactobacillus plantarum	Shellfish	Show inhibitory activity against pathogens including *S. aureus*, *S. typhimurium*, *S. enteritidis*, *E. coli* O157:H7, *V. ichthyoenteri*, *S. iniae*, and *V. parahaemolyticus*.	Kang et al. (2016)
Lactobacillus sp. *Lactococcus sp.*	*Alestes baremoze*	Suppress the pathogenic bacteria, *S. aureus*, *Streptococcus sp.*, *Proteus sp.*, *Pseudomonas sp.* and *E. coli*.	Kato et al. (2016)
Bacillus amyloliquefaciens	*Clupanodon punctatus* *Epinephelus coioides*	Improve the growth performance, enhance the immune parameters in turbot and also fight against *V. anguillarum* infection.	Chen et al. (2016)
Kocuria sp. *Rhodococcus sp.*	*Oncorhynchus mykiss* (Rainbow trout)	Produce extracellular enzymes (secondary metabolites) which is inhibitory to *Virbio anguillarum*, *V. ordalii*, *E. coli*, *Pseudomonas aeruginosa* and *Staphylococcus aureus*.	Sharifuzzaman et al. (2017)
Enterococcus hirae	*Catla catla*	Persist in simulated gastric conditions with the inhibition capability of various pathogens like *Staphylococcus aureus* (MTCC 3160), *Escherichia coli* (MTCC 40), *Pseudomonas aeruginosa* (MTCC 424) and *Salmonella typhi* (MTCC 3215).	Adnan et al. (2017)
Bacillus pumilus AQAHBS01	*Oreochromis niloticus*	Improves immunity of Nile tilapia and enhance disease resistance against *Streptococcus agalactiae*.	Srisapoome and Areechon (2017)
Lactobacillus farraginis *Pediococcus acidilactici* *Pediococcus pentosaceus*	*Salmo salar* (Atlantic salmon)	Produce antimicrobial compounds against fish pathogens, have good colonization capacity on gastrointestinal tract of salmon.	Amin et al. (2017)
Bacillus sp.	*Mystus vittatus*		Nandi et al. (2017)

Table 1 (continued)

Probiotic species	Source of probionts	Beneficial effects	References
		Shows antibacterial activity against four fish pathogens, *Aeromonas salmonicida, A. hydrophila, A. sobria* and *Pseudomonas fluorescens*	
Bacillus subtilis	*Labeo rohita*	Show inhibitory activity against four fish pathogens such as *Aeromonas hydrophila, Aeromonas salmonicida*, *Bacillus mycoides* and *Pseudomonas fluorescens*.	Banerjee et al. (2017)
Bacillus subtilis HAINUP40	Pond water	Enhance growth performance, immune response and disease resistance of Nile tilapia against *Streptococcus agalactiae.*	Liu et al. (2017)
Bacillus subtilis *Bacillus licheniformis*	Shrimp	Enhance non-specific immune responses, growth performance and disease resistance against *A. salmonicida* in juvenile rainbow trout.	Park et al. (2017)

Probiotic adhesion can be non-specific due to the presence of physiochemical agents or specific due to the adhesion of the probiotics either on the surface of adherent bacteria or the receptor molecules on the epithelial cells (Salminen et al. 1996; Lazado et al. 2015).

4.2 Production of inhibitory substances

The probiotic bacteria produce inhibitory substances which have bacteriostatic or bactericidal influences on pathogenic microbes (Servin 2004) like hydrogen peroxide, bacteriocins, lysozymes, siderophores, proteases, and many others (Panigrahi and Azad 2007; Tinh et al. 2008). Some bacteria produce volatile fatty acid (acetic, butyric, lactic and propionic acid) and organic acid, as a result of which there is a decrease in pH of gastrointestinal tract. Hence, it inhibits the proliferation of opportunistic pathogens (Tinh et al. 2008). A compound named indole (2,3-benzopyrrole) has inhibitory potential against various pathogens i.e. *Vibrio anguillarum*, *Aeromonas salmonicida*, *Edwaedsiella tarda* and *Yersinia ruckeri* (Gibson 1998; Lategan et al. 2006; Abbass et al. 2010).

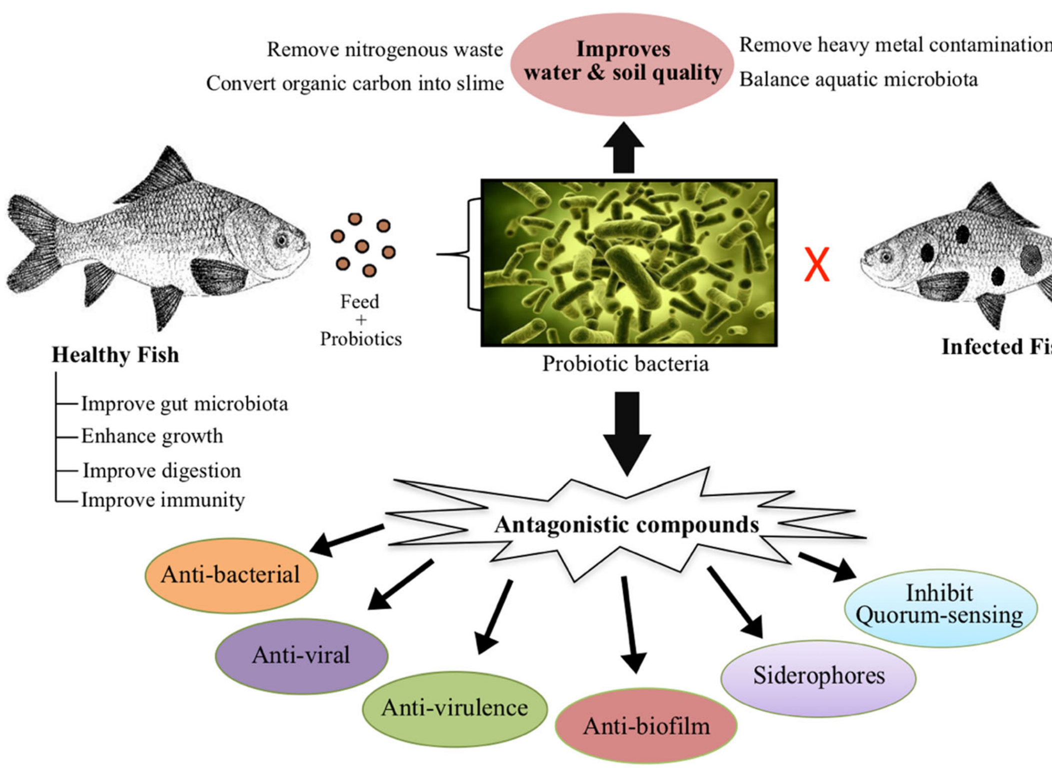

Fig. 2 Mode of action of probiotics. Modified from Chauhan and Singh (2018)

4.3 Competition for nutrients

The survival of any microbial population depends on its ability to compete for nutrients and available energy with other microbes in the same environment (Verschuere et al. 2000). While struggling for nutrients, probiotics can out-contend the pathogens by utilizing all the available nutrients that would have been consumed by pathogenic microorganisms. This mechanism would restrict the pathogen's presence in the intestinal tract because without nutrients the bacteria cannot survive (Nwanna 2015). For example, siderophores are low-molecular-weight iron-chelating agents that dissolve precipitated iron or extract it from the iron complexes, thus making it available for bacterial growth (Neilands 1981). Siderophore-producing bacteria can be used as probiotics because they can sequester ferric iron in an iron-low environment, hence, making it unavailable for the growth of pathogenic bacteria (Tinh et al. 2008). A culture supernatant of *Pseudomonas fluorescens* which was grown in iron-limited conditions inhibits the growth of *Vibrio anguillarum*. It has been shown that *P. fluorescens* can competitively inhibit the growth of fish pathogen *Aeromonas salmonicida* by competing for the available free iron (Gram et al. 1999; Smith and Davey 1993).

4.4 Improving water quality

According to the studies, use of Gram +ve bacteria (*Bacillus* species) as probiotics to improve the water quality has been reported**.** It was concluded that the Gram positive bacteria, especially *Bacillus* species are more efficient in conversion of organic matter into CO_2, slime or bacterial biomass. The studies suggest better performance of Gram positive bacteria over Gram negative bacteria. It is also suggested that the farmers can control the accumulation of dissolved and particulate organic carbon during the growing season by maintaining high level of probiotics in the production pond (Balcazar et al. 2006a, b; Mohapatra et al. 2013). The probiotic bacteria possess significant algicidal activity and affects several species of microalgae (Fukami et al. 1997). The nitrifying probiotic bacteria are beneficial as they increase the number of microbial species in water and improve the water quality by eliminating ammonia and nitrate toxicity (Zorriehzahra et al. 2016; Mohapatra et al. 2013). Also, after the use of probiotics, other parameters like temperature, pH, dissolved oxygen, ammonia and hydrogen sulfide in rearing water were found to be of better quality. Thus, probiotics maintain a positive and healthy environment for shrimp and prawn larval culture in aquatic system (Aguirre-Guzman et al. 2012; Banerjee et al. 2010).

4.5 Disruption of quorum sensing

Quorum Sensing (QS) is a bacterial regulatory mechanism, which is responsible to control the expression of various biological macromolecules such as, the virulence factors in a cell density-dependent manner. In this mechanism, bacteria regulate the gene expressions by producing, releasing and recognizing small signal molecules called auto-inducers (Chu et al. 2014). Many bacteria are using this system to communicate and regulate a diverse array of physiological activities (Miller and Bassler 2001). Disruption of the QS system of pathogens has been proposed as a new anti-infective strategy in aquaculture (Defoirdt et al. 2004; Zorriehzahra et al. 2016).

Since N-Acyl homoserine lactones (AHLs) are the main family of QS auto-inducers used in Gram negative bacteria, their Biodegradation prove to be an efficient way to interrupt QS,. *Bacillus* sp. QSI-1 is an efficient quorum quencher on virulence factors production and biofilm formation of fish pathogen *Aeromonas hydrophila* (Chu et al. 2014). *Bacillus* sp. QSI-1 reduced the accumulation of AHLs but did not affect the growth of *A. hydrophila* YJ-1. It has been found that the supernatant of QSI-1 showed significant inhibition of protease production (83.9%), hemolytic activity (77.6%) and biofilm formation (77.3%) in YJ-1. In biocontrol experiment, QSI-1 significantly reduced the pathogenicity of *A. hydrophila* strain YJ-1 in zebrafish (*Danio rerio*). The fish fed with QSI-1 were observed to have a relative percentage survival of 80.8%. The results indicated that AHLs degrading bacteria should be considered as an alternative for antibiotics in aquaculture for the bio-control of bacterial fish diseases (Chu et al. 2014). Probiotic bacteria such as *Lactobacillus*, *Bifidobacterium* and *Bacillus cereus* strains degrade the signal molecules of pathogenic bacteria by enzymatic secretion or production of auto-inducer antagonists (Brown 2011). Medellin-Pena et al. (2007) showed that *Lactobacillus acidophilus* secretes a molecule that inhibits the QS or interacts with bacterial transcription of *Escherichia coli* O157 gene.

5 Methods of administration of probiotics

Various methods have been put forth to regulate the use of probiotics in aquaculture. They can be added in feed, resulting in the colonization on the surface of intestinal tract. In prawns, the most common regulatory method for administration of probiotics is through water/oral routine (Huang et al. 2006). But most of the probiotics are designed in such a way that they can be mixed with the feed additives to show high efficiency against pathogens (Austin et al. 1992; Gildberg and Mikkelsen 1998; Hai et al. 2009; Gomes et al. 2009). The probiotics such as *Lactobacillus rhamnosus* were reported to improve the fecundity of *Danio rerio* (Gioacchini et al. 2010). Other methods such as addition of probiotics directly into water or in bacterial suspension were also reported (Queiroz and Boyd 1998; Gibson et al. 1998; Ringo and Vadstein 1998; Cha et al. 2013; Hansen and Olafsen 1989; Sung et al. 1994; Itami et al. 1998).

Probiotics can be used individually or in a combination of different strains (Havenaar et al. 1992; Salinas et al. 2005; Kesarcodi-Watson et al. 2008; Kesarcodi-Watson et al. 2012). Previous reviews on probiotics have focused on the utilization of sole culture species, and it is speculative whether combination two or more cultures of probiotic strains would be useful. Mixed probiotic strains are more efficient than probiotics based on a single strain (Verschuere et al. 2000; Hai et al. 2009). Multi-species and multi-strain probiotics enhance the defense mechanism against various infectious diseases (Kesarcodi-Watson et al. 2012; Timmerman et al. 2004). A recent study compared the activity of mixed strain of *Lactobacillus acidophilus* and *B. subtilis* in *Nile tilapia* in which serum bactericidal activity and hematocrit values were higher in comparison to sole strain (Aly et al. 2008a, b). Similar studies were conducted to modulate immunity against *Streptococcus iniae* by a mixture of *Lactobacillus plantarum* and *Lactococcus lactis* in Japanese flounder (Beck et al. 2015). In the growth and survival of *Labeo rohita*, multi strain probiotics have been efficiently used which enhanced fry and hatchling stages (Jha et al. 2015).

Synbiotics is the combination of probiotics with various plant products and prebiotics (Salminen et al. 1998; Van Hai and Fotedar 2009). It has been reported in many studies that synbiotics improves the microbial supplementation in the gastrointestinal tract of the host organism (Gibson and Roberfroid 1995). The feeding of synbiotic *Enterococcus faecalis* and mannan-oligosaccharide (MOS) showed better FCR (food conversion ratio) as compared to feeding of probiotic and prebiotic individually (Rodriguez-Estrada et al. 2009). The application of probiotics, prebiotics and synbiotics have improved the survival of aquatic organisms against pathogenic bacteria. The survivability were found to be maximum in the probiotic treatment followed by prebiotic and synbiotic (Daniels et al. 2013; Decamp and Moriarty 2007).

The enrichment of live feed with probiotics as encapsulation has developed into an interesting idea. In this technique, the probiotic bacteria can remain viable or even proliferate on the live feed. Therefore, probiotics can be delivered by the live feed to the host in a very efficient manner (Hai 2015). Various live feeds have been reported so far such as copepods (Sun et al. 2013), rotifer (Gatesoupe 1997) and *Artemia* species (Daniels et al. 2013; Gatesoupe 1994; Van Hai et al. 2010), in which probiotics were encapsulated. This approach of enrichment of live feed with probiotics has proved to be effective over other conventional methods. Van Hai et al. 2010 have reported an effective enrichment of *Artemia nauplii* using a combination of *Pseudomonas synxantha* and *Pseudomonas aeruginosa* for *Penaeus latisulcatus* (western king prawn). Similarly, Sun et al. 2013 have reported that the copepod (*Pseudodiaptomus annandalei*) is an appropriate vector of probiotic (*Bacillus* species) as live feed for *Epinephelus coioides* larvae.

The probiotics can be administered in either form- as live or dead strains. Various reports are available for the use of probiotics in either form. The comparison of live and dead forms reveals an interesting observation. Live probiotics provide immunity to the host in most of the cases and in a few cases certain inactivated probiotics also do the same. Hence, the use of probiotics in live or heat killed forms are case specific and cannot be generalized. For instance, Sharifuzzaman et al. 2011; Arijo et al. 2008; Panigrahi et al. 2011; Ramesh et al. 2015 have reported the use of viable probiotics with better results. Sharifuzzaman and Austin 2010; Arijo et al. 2008 have demonstrated the role of live probiotic cells Kocuria SM1 by production of cross-reactive antibodies in rainbow trout to protect against infections due to *Vibrio anguillarum*, *V. ordalii* and *V. harveyi*. Similarly, live cells of *Bacillus licheniformis* and *Bacillus pumilus* exhibited an enhanced expression of lysozyme activity and respiratory burst in rohu species (Ramesh et al. 2015). Panigrahi et al. 2011 states that higher expression of immune genes (TNF, TGF-b, IFN and Ig) is responsible for better immunity. The expression of these immune genes is induced using live probiotic cells (live-spray and freeze-dried) compared to the heat-killed ones. The phagocytic activity was found to be higher in rainbow trout, when they were fed with live cells of probiotic bacteria *Lactobacillus rhamnosus* JCM1136 as compared to heat-killed cells (Panigrahi et al. 2005).

Also, in some cases the supplementation of cell-free supernatant and heat-killed probiotics stimulated innate immunity of the fish (Irianto and Austin 2003). But they offer poor protection to rainbow trout and Chinese drum (*Miichthys miiuy*) against pathogens, *V. anguillarum*, *Streptococcus iniae*, *Aeromonas hydrophila* and *Lactococcus garvieae* (Brunt and Austin 2005; Pan et al. 2008). When Nile tilapia was nourished with both dead and live probiotics against *Edwardsiella tarda* disease, dead probiotics were found ineffective as compared to viable probiotics (Taoka et al. 2006).

The administration duration of probiotic bacteria is also considered a very significant factor. According to research, the time-period for application of the potential probiotic can be as short as 6 days or as long as 5 months or even 8 months (Joborn et al. 1997; Aubin et al. 2005; Aly et al. 2008a, b). Prolonged administration of probiotics can induce immune-suppression of continuous responses of nonspecific immune systems (Sakai 1999). Supplementation of probiotic bacteria has demonstrated to give short-term benefits. However, they were not detected inside the gastrointestinal tract over a period of 1–3 weeks (Robertson et al. 2000; Kim and Austin 2006; Balcazar et al. 2007a, b). Short-term supplementation has turned out to be effective, while the data on long-term effectiveness is not available (Brunt et al. 2007; Newaj-Fyzul et al. 2007; Pieters et al. 2008; Wu et al. 2015; Skjermo et al. 2015). Feeding of probiotics (*Shewanella xiamenensis* and *Aeromonas veronii*) tograss carp for about 28 days reduced the cumulative mortality when challenged with *Aeromonas hydrophila* (Wu et al. 2015). Aubin et al. 2005 checked the recovered amount of probiotics over a time period and observed that recovery levels were found to be higher after 20 days than 5 months. The frequency of administration of probiotics also play a very important role in maintaining the effectiveness and function of probiotics,. A daily application of probiotics is better than thrice a week during the culture period (Guo et al. 2009).

6 Conclusion

In recent years, the use of probiotics as biological control agent has improved fish performance, water quality, prevention of diseases, enhancement of immune responses and so on. This review concludes that several probiotic strains are highly specific while others are quite selective. Efforts need to be made to streamline the whole range of probiotic strains and categorize them based on their action-specific mechanism. A simple step in this direction is going to make the use of probiotics very efficient, economical and eco-friendly. After proving the worth of probiotics, there is a need to look forward towards designing probiotic strains which are specific and can be used to target specific fish species. The evaluation of optimal conditions for probiotic interaction with the host also holds a lot of scope for further investigation. In the past, there have been instances of failure of in-vivo studies which were conducted based on the positive in-vitro results. We need to detail out the conditions in real samples which may affect their survival, colonization, proliferation and interaction with the host in a particular environment. This will help us to properly screen and test probiotics which will lead to no mismatch in in-vitro and in-vivo observations. Other important scope for future research is to study the fate of probiotics in host organism. The fate of live strains and durability of health effects of probiotics in host organism are uncertain and require further investigation.

After doing much study about the efficacy and action mechanism of probiotics, there are still many doubts which are unclear. Nevertheless, the future should focus on relevant research to develop innovative and suitable approach for administration of probiotic strains in foods and animals. Probiotic strains viability, functionality, host-microbe's interactions, antioxidant status, antagonistic and synergistic activity or probably side effects of probiotics should be the major concerns of study. In addition, advanced molecular level research is required on probiotic science for a better understanding of the molecular mechanisms and to decode the probiotic unique gene with novel applications.

Acknowledgements The authors would like to thank to Lovely Professional University, India to provide the database for writing this review and Dr. Rama Gaur Department of Chemistry, School of Chemical Engineering & Physical Sciences, Lovely Professional University, India for her help and guidance with this manuscript.

References

Abareethan M, Amsath A (2015) Characterization and evaluation of probiotic fish feed. Int J Pure Appl Zool 3:148–153

Abbass A, Sharifuzzaman SM, Austin B (2010) Cellular components of probiotics control *Yersinia ruckeri* infection in rainbow trout, *Oncorhynchus mykiss* (Walbaum). J Fish Dis 33:31–37

Adnan M, Patel M, Hadi S (2017) Functional and health promoting inherent attributes of *Enterococcus hirae* F2 as a novel probiotic isolated from the digestive tract of the freshwater fish *Catla catla*. PeerJ 5:e3085. https://doi.org/10.7717/peerj.3085

Aguirre-Guzman G, Lara-Flores M, Sanchez-Martinez JG, Campa-Cordova AI, Luna-Gonzalez A (2012) The use of probiotics in aquatic organisms: a review. Afr J Microbiol Res 6(23):4845–4857

Al-Faragi JK, Alsaphar SA (2012) Isolation and identification of *Bacillus subtilus* as (probiotic) from intestinal microflora of common carp *Cyprinus carpio L*. In Proceeding of the Eleventh Veterinary Scientific Conference 355:361

Aly SM, Ahmed YAG, Ghareeb AAA, Mohamed MF (2008a) Studies on *Bacillus subtilis* and *Lactobacillus acidophilus*, as potential probiotics, on the immune response and resistance of *Tilapia nilotica* (*Oreochromis niloticus*) to challenge infections. Fish Shellfish Immun 25(1):128–136

Aly SM, Mohamed MF, John G (2008b) Effect of probiotics on the survival, growth and challenge infection in *Tilapia nilotica* (*Oreochromis niloticus*). Aquac Res 39(6):647–656

Amin M, Adams M, Bolch CJ, Burke CM (2017) In vitro screening of lactic acid bacteria isolated from gastrointestinal tract of Atlantic Salmon (*Salmo salar*) as probiont candidates. Aquac Int 25(1): 485–498

Araujo C, Munoz-Atienza E, Nahuelquin Y, Poeta P, Igrejas G, Hernandez PE, Herranz C, Cintas LM (2015) Inhibition of fish pathogens by the microbiota from rainbow trout (*Oncorhynchus mykiss*, Walbaum) and rearing environment. Anaerobe 32:7–14

Arijo S, Brunt J, Chabrillon M, Diaz-Rosales P, Austin B (2008) Subcellular components of *Vibrio harveyi* and probiotics induce immune responses in rainbow trout, *Oncorhynchus mykiss* (Walbaum), against *V. harveyi*. J Fish Dis 31(8):579–590

Aubin J, Gatesoupe FJ, Labbe L, Lebrun L (2005) Trial of probiotics to prevent the vertebral column compression syndrome in rainbow trout (*Oncorhynchus mykiss Walbaum*). Aquac Res 36(8):758–767

Austin B, Baudet E, Stobie M (1992) Inhibition of bacterial fish pathogens by *Tetraselmis suecica*. J Fish Dis 15(1):55–61

Azevedo RVD, Fosse Filho JC, Cardoso LD, Mattos DDC, Junior V, Vazquez M, Andrade DRD (2015) Economic evaluation of prebiotics, probiotics and synbiotics in juvenile Nile tilapia. Rev Ciênc Agron 46(1):72–79

Balcazar JL (2003) Evaluation of probiotic bacterial strains in *Litopenaeus vannamei*. Final Report. National Center for Marine and Aquaculture Research Guayaquil Ecuador

Balcazar JL, De Blas I, Ruiz-Zarzuela I, Cunningham D, Vendrell D, Muzquiz JL (2006a) The role of probiotics in aquaculture. Vet Microbiol 114(3):173–186

Balcazar JL, Decamp O, Vendrell D, De Blas I, Ruiz-Zarzuela I (2006b) Health and nutritional properties of probiotics in fish and shellfish. Microb Ecol Health Dis 18(2):65–70

Balcazar JL, De Blas I, Ruiz-Zarzuela I, Vendrell D, Calvo AC, Marquez I, Girones O, Muzquiz JL (2007a) Changes in intestinal microbiota and humoral immune response following probiotic administration in brown trout (*Salmo trutta*). Br J Nutr 97(03):522–527

Balcazar JL, Vendrell D, De Blas I, Ruiz-Zarzuela I, Girones O, Muzquiz JL (2007b) In vitro competitive adhesion and production of antagonistic compounds by lactic acid bacteria against fish pathogens. Vet Microbiol 122(3):373–380

Balcazar JL, Vendrell D, de Blas I, Ruiz-Zarzuela I, Muzquiz JL, Girones O (2008) Characterization of probiotic properties of lactic acid bacteria isolated from intestinal microbiota of fish. Aquaculture 278(1): 188–191

Banerjee S, Khatoon H, Shariff M, Yusoff FM (2010) Enhancement of *Penaeus monodon* shrimp postlarvae growth and survival without water exchange using marine *Bacillus pumilus* and periphytic microalgae. Fish Sci 76(3):481–487

Banerjee G, Nandi A, Ray AK (2017) Assessment of hemolytic activity, enzyme production and bacteriocin characterization of *Bacillus subtilis* LR1 isolated from the gastrointestinal tract of fish. Arch Microbiol 199(1):115–124

Beck BR, Kim D, Jeon J, Lee SM, Kim HK, Kim OJ, Holzapfel WH (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(1):177–183

Bhatnagar A, Lamba R (2015) Antimicrobial ability and growth promoting effects of feed supplemented with probiotic bacterium isolated from gut microflora of *Cirrhinus mrigala*. J Integr Agric 14(3):583–592

Bisht GP, Singh UP, Pandey DCFR (2012) *Bacillus subtilis* as a potent probiotic for enhancing growth in fingerlings of common carp (*Cyprinus carpio L.*). Indian J Fish 59(3):103–107

Brown M (2011) Modes of action of probiotics: recent developments. J Anim Vet Adv 10(14):1895–1900

Brunt J, Austin B (2005) Use of a probiotic to control *lactococcosis* and *streptococcosis* in rainbow trout, *Oncorhynchus mykiss* (Walbaum). J Fish Dis 28(12):693–701

Brunt J, Newaj-Fyzul A, Austin B (2007) The development of probiotics for the control of multiple bacterial diseases of rainbow trout, *Oncorhynchus mykiss* (Walbaum). J Fish Dis 30(10):573–579

Cascales D, Guijarro JA, Reimundo P, Garcia-Torrico AI, Mendez J (2016) Genome sequence of the fish pathogen *Yersinia ruckeri* strain 150, isolated from diseased rainbow trout. Genome Announc. https://doi.org/10.1128/genomeA.01331-16

Cha JH, Rahimnejad S, Yang SY, Kim KW, Lee KJ (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

Chauhan A, Singh R (2018) Probiotics and their applications in aquaculture. In: Sharma D, Saharan BS (eds) Microbial cell factories, 1edn. Taylor & Francis, New York, pp 321–338

Chavan S (2018) Statistical modeling and forecasting of Total fish production of India: a time series perspective. Int J Curr Microbiol App Sci 7(3):1698–1707

Chen Y, Li J, Xiao P, Li GY, Yue S, Huang J, Mo ZL (2016) Isolation and characterization of *Bacillus* spp. M001 for potential application in turbot (*Scophthalmus maximus L.*) against *Vibrio anguillarum*. Aquac Nutr 22(2):374–381

Chu W, Zhou S, Zhu W, Zhuang X (2014) Quorum quenching bacteria *Bacillus* sp. QSI-1 protect zebrafish (*Danio rerio*) from *Aeromonas hydrophila* infection. Sci Rep 4:5446

Chua KJ, Kwok WC, Aggarwal N, Sun T, Chang MW (2017) Designer probiotics for the prevention and treatment of human diseases. Curr Opin Chem Biol 40:8–16

Daniel N (2017) Status of aquaculture with respect to nutrition and feed. Int J fish Aquat 5(1):333–345

Daniels CL, Merrifield DL, Ringo E, Davies SJ (2013) Probiotic, prebiotic and synbiotic applications for the improvement of larval European lobster (*Homarus gammarus*) culture. Aquaculture 416: 396–406

Decamp O, Moriarty D (2007) Aquaculture species profit from probiotics. Feed Mix 15(1):20

Defoirdt T, Boon N, Bossier P, Verstraete W (2004) Disruption of bacterial quorum sensing: an unexplored strategy to fight infections in aquaculture. Aquaculture 240(1):69–88

Deng M, Chen J, Gou J, Hou J, Li D, He X (2018) The effect of different carbon sources on water quality, microbial community and structure of biofloc systems. Aquaculture 482:103–110

Dhanasekaran D, Saha S, Thajuddin N, Panneerselvam A (2008) Probiotic effect of *Lactobacillus* isolates against bacterial pathogens in *Clarias orientalis*. FU Med Biol 15(3):97–102

Divya KR, Isamma A, Ramasubramanian V, Sureshkumar S, Arunjith TS (2012) Colonization of probiotic bacteria and its impact on ornamental fish *Puntius conchonius*. J Environ Biol 33(3):551–555

Dutta D, Ghosh K (2015) Screening of extracellular enzyme-producing and pathogen inhibitory gut bacteria as putative probiotics in mrigal, *Cirrhinus mrigala* (Hamilton, 1822). Int J Fish Aquat 2(4):310–318

Fukami K, Nishijima T, Ishida Y (1997) Stimulative and inhibitory effects of bacteria on the growth of microalgae. Live food in aquaculture 185–191 Springer Netherlands

Fuller (1989) Probiotics in man and animals. J Appl Bacteriol 66(5):365–378

Fuller R (1992) History and development of probiotics. In: Fuller R (ed) Probiotics: the scientific basis. Chapman and Hall, London, pp 1–45

Gatesoupe FJ (1994) Lactic acid bacteria increase the resistance of turbot larvae, *Scophthalmus maximus*, against pathogenic vibrio. Aquat Living Resour 7(4):277–282

Gatesoupe FJ (1997) Siderophore production and probiotic effect of vibrio sp. associated with turbot larvae, *Scophthalmus maximus*. Aquat Living Resour 10(4):239–246

Gatesoupe FJ (1999) The use of probiotics in aquaculture. Aquaculture 180(1):147–165

Ghosh S, Sinha A, Sahu C (2008) Dietary probiotic supplementation in growth and health of live-bearing ornamental fishes. Aquac Nutr 14(4):289–299

Giannenas I, Karamaligas I, Margaroni M, Pappas I, Mayer E, Encarnacao P, Karagouni E (2015) Effect of dietary incorporation of a multi-strain probiotic on growth performance and health status in rainbow trout (*Oncorhynchus mykiss*). Fish Physiol Biochem 41(1):119–128

Gibson LF (1998) Bacteriocin activity and probiotic activity of *Aeromonas* media. J Appl Microbiol 85(S1):243S–248S

Gibson GR, Roberfroid MB (1995) Dietary modulation of the human colonic microbiota: introducing the concept of prebiotics. J Nutr 125(6):1401–1412

Gibson LF, Woodworth J, George AM (1998) Probiotic activity of *Aeromonas* media on the Pacific oyster, *Crassostrea gigas*, when challenged with *Vibrio tubiashii*. Aquaculture 169(1):111–120

Gildberg A, Mikkelsen H (1998) Effects of supplementing the feed to Atlantic cod (*Gadus morhua*) fry with lactic acid bacteria and immuno-stimulating peptides during a challenge trial with *Vibrio anguillarum*. Aquaculture 167(1):103–113

Gioacchini G, Maradonna F, Lombardo F, Bizzaro D, Olivotto I, Carnevali O (2010) Increase of fecundity by probiotic administration in zebrafish (*Danio rerio*). Reproduction 140(6):953–959

Giri SS, Sukumaran V, Sen SS, Vinumonia J, Banu BN, Jena PK (2011) Antagonistic activity of cellular components of potential probiotic bacteria, isolated from the gut of *Labeo rohita*, against *Aeromonas hydrophila*. Probiotics Antimicrob Proteins 3(3–4):214–222

Gobi N, Vaseeharan B, Chen JC, Rekha R, Vijayakumar S, Anjugam M, Iswarya A (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. https://doi.org/10.1016/j.fsi.2017.12.066

Gomes LC, Brinn RP, Marcon JL, Dantas LA, Brandao FR, De Abreu JS, Lemos PEM, McComb DM, Baldisserotto B (2009) Benefits of using the probiotic Efinol® L during transportation of cardinal tetra, *Paracheirodon axelrodi* (Schultz), in the Amazon. Aquac Res 40(2): 157–165

Gram L, Melchiorsen J, Spanggaard B, Huber I, Nielsen TF (1999) Inhibition of *Vibrio anguillarum* by *Pseudomonas fluorescens* AH2, a possible probiotic treatment of fish. Appl Environ Microbiol 65(3):969–973

Guo JJ, Liu KF, Cheng SH, Chang CI, Lay JJ, Hsu YO, Yang JY, Chen TI (2009) Selection of probiotic bacteria for use in shrimp larviculture. Aquac Res 40(5):609–618

Hai NV (2015) The use of probiotics in aquaculture. J Appl Microbiol 119(4):917–935

Hai NV, Buller N, Fotedar R (2009) Effects of probiotics (*Pseudomonas synxantha* and *Pseudomonas aeruginosa*) on the growth, survival and immune parameters of juvenile western king prawns (*Penaeus latisulcatus Kishinouye*, 1896). Aquac Res 40(5):590–602

Hambali S, Akhmad R (2000) The use of chemicals in aquaculture in Indonesia. In Use of Chemicals in Aquaculture in Asia: Proceedings of the Meeting on the Use of Chemicals in Aquaculture in Asia 20-22 May 1996, Tigbauan Iloilo, Philippines (pp. 113–118). SEAFDEC Aquaculture Department

Hamdan AM, El-Sayed AFM, Mahmoud MM (2016) Effects of a novel marine probiotic, *Lactobacillus plantarum* AH 78, on growth performance and immune response of Nile tilapia (*Oreochromis niloticus*). J Appl Microbiol 120(4):1061–1073

Hamid NH, Hassan MD, Sabri MM, Hasliza AH, Hamdan RH, Afifah MN, Raina MS, Nadia AB, Fuad MM (2017) Studies on pathogenicity effect of *Aeromonas hydrophila* infection in juvenile red hybrid tilapia *Oreochromis* sp. In Proceedings of International Seminar on Livestock Production and Veterinary Technology 532–539

Han B, Long WQ, He JY, Liu YJ, Si YQ, Tian LX (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(2):225–231

Handbook on Fisheries Statistics (2014) August 2014 Dept. of Animal Husbandry, Dairying & Fisheries, Ministry of Agriculture Govt. of India New Delhi

Hansen GH, Olafsen JA (1989) Bacterial colonization of cod (*Gadus morhua L.*) and halibut (*Hippoglossus hippoglossus*) eggs in marine aquaculture. Appl Environ Microbiol 55(6):1435–1446

Harikrishnan R, Balasundaram C, Heo MS (2010) Effect of probiotics enriched diet on *Paralichthys olivaceus* infected with lymphocystis disease virus (LCDV). Fish Shellfish Immunol 29(5):868–874

Harimurti S, Hadisaputro W (2015) Probiotics in poultry. In *Beneficial Microorganisms in Agriculture Aquaculture and Other Areas* (pp. 1–19) Springer International Publishing

Havenaar R, Marteau P (1994) Establishing a scientific basis for probiotic R&D. Trends Biotechnol 12(1):6–8

Havenaar R, Ten Brink B, Huis JH (1992) Selection of strains for probiotic use. In *Probiotics* (pp. 209–224) Springer Netherlands

Holzapfel WH, Schillinger U (2002) Introduction to pre-and probiotics. Food Res Int 35(2):109–116

Huang X, Zhou H, Zhang H (2006) The effect of *Sargassum fusiforme* polysaccharide extracts on vibriosis resistance and immune activity of the shrimp, *Fenneropenaeus chinensis*. Fish Shellfish Immunol 20(5):750–757

Irianto A, Austin B (2003) Use of dead probiotic cells to control furunculosis in rainbow trout, *Oncorhynchus mykiss* (Walbaum). J Fish Dis 26:59–62

Itami T, Asano M, Tokushige K, Kubono K, Nakagawa A, Takeno N, Nishimura H, Maeda M, Kondo M, Takahashi Y (1998) Enhancement of disease resistance of kuruma shrimp, *Penaeus japonicus*, after oral administration of peptidoglycan derived from *Bifidobacterium thermophilum*. Aquaculture 164(1):277–288

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

Jiang T, Li HS, Han GG, Singh B, Kang SK, Bok JD, Kim DD, Hong ZS, Choi YJ, Cho CS (2017) Oral delivery of probiotics in poultry using pH-sensitive tablets. J Microbiol Biotechnol 27(4):739–746

Joborn A, Olsson JC, Westerdahl A, Conway PL, Kjelleberg S (1997) Colonization in the fish intestinal tract and production of inhibitory substances in intestinal mucus and faecal extracts by *Carnobacterium* sp. strain K1. J Fish Dis 20(5):383–392

Kamei Y, Yoshimizu M, Ezura Y, Kimura T (1988) Screening of bacteria with antiviral activity from fresh water salmonid hatcheries. Microbiol Immunol 32(1):67–73

Kang CH, Shin Y, Kim Y, So JS (2016) Isolation of *Lactobacillus* strains from shellfish for their potential use as probiotics. Biotechnol Bioprocess Eng 21(1):46–52

Kato CD, Kahuma CE, Namulawa VT, Kasozi N (2016) Antibacterial activity of *Lactobacillus* spp and *Lactococcus* spp isolated from various parts of pebbly fish, Alestes baremoze. Br Microbiol Res J 17:1–7

Kesarcodi-Watson A, Kaspar H, Lategan MJ, Gibson L (2008) Probiotics in aquaculture: the need, principles and mechanisms of action and screening processes. Aquaculture 274(1):1–14

Kesarcodi-Watson A, Kaspar H, Lategan MJ, Gibson L (2012) Performance of single and multi-strain probiotics during hatchery production of Greenshell™ mussel larvae, *Perna canaliculus*. Aquaculture 354:56–63

Khattab YA, Shalaby AM, Abdel-Rhman A (2005) Use of probiotic bacteria as growth promoters, anti-bacterial and their effects on physiological parameters of *Oreochromis niloticus*. In Proceedings of international symposium on Nile Tilapia in aquaculture 7:156–165)

Kim DH, Austin B (2006) Innate immune responses in rainbow trout (*Oncorhynchus mykiss*, Walbaum) induced by probiotics. Fish Shellfish Immunol 21(5):513–524

Kolndadacha OD, Adikwu IA, Okaeme AN, Atiribom RY, Mohammed A, Musa YM (2011) The role of probiotics in aquaculture in Nigeria-a review. Cont J Fish Aquat Sci 5(1):8–15

Lakshmi B, Viswanath B, Sai Gopal DVR (2013) Probiotics as antiviral agents in shrimp aquaculture. J Pathogens. https://doi.org/10.1155/2013/424123

LaPatra SE, Fehringer TR, Cain KD (2014) A probiotic *Enterobacter* sp. provides significant protection against *Flavobacterium psychrophilum* in rainbow trout (*Oncorhynchus mykiss*) after injection by two different routes. Aquaculture 433:361–366

Lara-Flores M, Olvera-Novoa MA, Guzman-Mendez BE, Lopez-Madrid W (2003) Use of the bacteria *Streptococcus faecium* and *Lactobacillus acidophilus*, and the yeast *Saccharomyces cerevisiae* as growth promoters in Nile tilapia (*Oreochromis niloticus*). Aquaculture 216(1):193–201

Lategan MJ, Torpy FR, Gibson LF (2004) Control of saprolegniosis in the eel *Anguilla australis* Richardson, by *Aeromonas* media strain A199. Aquaculture 240(1):19–27

Lategan MJ, Booth W, Shimmon R, Gibson LF (2006) An inhibitory substance produced by *Aeromonas* media A199, an aquatic probiotic. Aquaculture 254(1):115–124

Lazado CC, Caipang CMA, Brinchmann MF, Kiron V (2011) In vitro adherence of two candidate probiotics from Atlantic cod and their interference with the adhesion of two pathogenic bacteria. Vet Microbiol 148(2):252–259

Lazado CC, Caipang CMA, Estante EG (2015) Prospects of host-associated microorganisms in fish and penaeids as probiotics with immunomodulatory functions. Fish Shellfish Immunol 45(1):2–12

Li J, Tan B, Mai K (2009) Dietary probiotic bacillus OJ and isomaltooligosaccharides influence the intestine microbial populations, immune responses and resistance to white spot syndrome virus in shrimp (*Litopenaeus vannamei*). Aquaculture 291(1):35–40

Lilly DM, Stillwell RH (1965) Probiotics: growth-promoting factors produced by microorganisms. Science147(3659):747–748

Liu XF, Li Y, Li JR, Cai LY, Li XX, Chen JR, Lyu SX (2015) Isolation and characterisation of *Bacillus* spp. antagonistic to *Vibrio parahaemolyticus* for use as probiotics in aquaculture. World J Microbiol Biotechnol 31(5):795–803

Liu H, Wang S, Cai Y, Guo X, Cao Z, Zhang Y, Xie Z (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

Ma CW, Cho YS, Oh KH (2009) Removal of pathogenic bacteria and nitrogens by *Lactobacillus* spp. JK-8 and JK-11. Aquaculture 287(3):266–270

Maeda M, Shibata A, Biswas G, Korenaga H, Kono T, Itami T, Sakai M (2014) Isolation of lactic acid bacteria from kuruma shrimp (*Marsupenaeus japonicus*) intestine and assessment of immunomodulatory role of a selected strain as probiotic. Mar Biotechnol 16(2):181–192

Mancuso M, Rappazzo AC, Genovese M, El Hady M, Ghonimy A, Ismail M, Reda R, Cappello S, Genovese L, Maricchiolo G (2015) In vitro selection of bacteria and isolation of Probionts from farmed *Sparus aurata* with potential for use as probiotics. Int J Animal Biol 1(4):93–98

Medellin-Pena MJ, Wang H, Johnson R, Anand S, Griffiths MW (2007) Probiotics affect virulence-related gene expression in *Escherichia coli* O157: H7. Appl Environ Microbiol 73(13):4259–4267

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. Turk J Fish Aquat Sci 18(4):597–602

Meidong R, Khotchanalekha K, Doolgindachbaporn S, Nagasawa T, Nakao M, Sakai K, Tongpim S (2018) Evaluation of probiotic *Bacillus aerius* B81e isolated from healthy hybrid catfish on growth, disease resistance and innate immunity of Pla-mong *Pangasius bocourti*. Fish Shellfish Immunol 73:1–10

Merrifield DL, Dimitroglou A, Foey A, Davies SJ, Baker RT, Bogwald J, Castex M, Ringo E (2010) The current status and future focus of probiotic and prebiotic applications for salmonids. Aquaculture 302: 1):1–1)18

Metchnikoff E (1907) The prolongation of life. Optimistic studies. William Heinemann, London

Miller MB, Bassler BL (2001) Quorum sensing in bacteria. Annu Rev Microbiol 55(1):165–199

Mo WY, Man YB, Wong MH (2018) Use of food waste, fish waste and food processing waste for China's aquaculture industry: needs and challenge. Sci Total Environ 613:635–643

Mohapatra S, Chakraborty T, Kumar V, DeBoeck G, Mohanta KN (2013) Aquaculture and stress management: a review of probiotic intervention. J Anim Physiol Anim Nutr 97(3):405–430

Moosavi-Nasab M, Abedi E, Moosavi-Nasab S, Eskandari MH (2014) Inhibitory effect of isolated lactic acid bacteria from *Scomberomorus commerson* intestines and their bacteriocin on *Listeria innocua*. Iran Agric Res 33(1):43–52

Mukherjee A, Dutta D, Banerjee S, Ringo E, Breines EM, Hareide E, Ghosh K (2016) Potential probiotics from Indian major carp, *Cirrhinus mrigala*. Characterization, pathogen inhibitory activity, partial characterization of bacteriocin and production of exoenzymes. Res Vet Sci 108:76–84

Munoz-Atienzal E, Gomez-Sala B, Araujo C, Campanerol C, del Campo R, Hernandez PE, Herranz C, Cintas LM (2013) Antibiotic susceptibility and virulence factors of lactic acid bacteria of aquatic origin intended for use as probiotics in aquaculture. BMC Microbiol 13(1):15

Nageswara PV, Babu DE (2006) Probiotics as an alternative therapy to minimize or avoid antibiotics use in aquaculture. Fishing Chimes 26(1):112–114

Nandi A, Dan SK, Banerjee G, Ghosh P, Ghosh K, Ringo E, Ray AK (2017) Probiotic potential of autochthonous bacteria isolated from the gastrointestinal tract of four freshwater teleost. Probiotics Antimicrob Proteins 9(1):12–21

Neilands JB (1981) Iron absorption and transport in microorganisms. Annu Rev Nutr 1(1):27–46

Newaj-Fyzul A, Austin B (2015) Probiotics, immunostimulants, plant products and oral vaccines, and their role as feed supplements in the control of bacterial fish diseases. J Fish Dis 38(11):937–955

Newaj-Fyzul A, Adesiyun AA, Mutani A, Ramsubhag A, Brunt J, Austin B (2007) *Bacillus subtilis* AB1 controls *Aeromonas* infection in rainbow trout (*Oncorhynchus mykiss*, Walbaum). J Appl Microbiol 103(5):1699–1706

Nurhajati J, Aryantha INP, Indah DG (2012) The curative action of *Lactobacillus plantarum* FNCC 226 to *Saprolegnia parasitica* A3 on catfish (*Pangasius hypophthalamus Sauvage*). Int Food Res J 19(4):1723–1727

Nwanna LC (2015) Use of probiotics in aquaculture. Appl Trop Agr J 15(2):76–83

Oelschlaeger TA (2010) Mechanisms of probiotic actions–a review. Int J Med Microbiol 300(1):57–62

Olsson JC, Westerdahl ALLAN, Conway PL, Kjelleberg STAFFAN (1992) Intestinal colonization potential of turbot (*Scophthalmus maximus*) and dab (*Limanda limanda*)-associated bacteria with inhibitory effects against *Vibrio anguillarum*. Appl Environ Microbiol 58(2):551–556

Ouwehand AC, Kirjavainen PV, Gronlund MM, Isolauri E, Salminen SJ (1999a) Adhesion of probiotic micro-organisms to intestinal mucus. Int Dairy J 9(9):623–630

Ouwehand AC, Kirjavainen PV, Shortt C, Salminen S (1999b) Probiotics: mechanisms and established effects. Int Dairy J 9(1):43–52

Padmavathi P, Sunitha K, Veeraiah K (2012) Efficacy of probiotics in improving water quality and bacterial flora in fish ponds. Afr J Microbiol Res 6(49):7471–7478

Pan X, Wu T, Song Z, Tang H, Zhao Z (2008) Immune responses and enhanced disease resistance in Chinese drum, *Miichthysmiiuy* (Basilewsky), after oral administration of live or dead cells of *Clostridiumbutyrium* CB2. J Fish Dis 31(9):679–686

Pandiyan P, Balaraman D, Thirunavukkarasu R, George EGJ, Subaramaniyan K, Manikkam S, Sadayappan B (2013) Probiotics in aquaculture. Drug invent 5(1):55–59

Pandya D (2016) Benefits of probiotics in Oral cavity–a detailed review. Ann Int Med Dental Res 2(5):1–17

Panigrahi A, Azad IS (2007) Microbial intervention for better fish health in aquaculture: the Indian scenario. Fish Physiol Biochem 33(4): 429–440

Panigrahi A, Kiron V, Puangkaew J, Kobayashi T, Satoh S, Sugita H (2005) The viability of probiotic bacteria as a factor influencing the immune response in rainbow trout *Oncorhynchus mykiss*. Aquaculture 243(1):241–254

Panigrahi A, Viswanath K, Satoh S (2011) Real-time quantification of the immune gene expression in rainbow trout fed different forms of probiotic bacteria *Lactobacillus rhamnosus*. Aquaculture Res 42(7):906–917

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*). Aquaculture Res 48(6):2672–2682

Parker RB (1974) Probiotics, the other half of the antibiotics story. Anim Nutr Health 29:4–8

Patra A, Sarker S, Banerjee S, Adikesavalu H, Biswas D, Abraham TJ (2016) Rapid detection of *Flavobacterium columnare* infection in fish by species-specific polymerase chain reaction. J Aquac Res Dev 7:1–4

Pieters N, Brunt J, Austin B, Lyndon AR (2008) Efficacy of in-feed probiotics against *Aeromonas bestiarum* and *Ichthyophthirius multifiliis* skin infections in rainbow trout (*Oncorhynchus mykiss*, Walbaum). J Appl Microbiol 105(3):723–732

Queiroz JF, Boyd CE (1998) Effects of a bacterial inoculum in channel catfish ponds. J World Aquacult Soc 29(1):67–73

Rajikkannu M, Natarajan N, Santhanam P, Deivasigamani B, Ilamathi J, Janani S (2015) Effect of probiotics on the haematological parameters of Indian major carp (*Labeo rohita*). Int J Fish Aquat Stud 2(5): 105–109

Ramesh D, Souissi S (2018) Effects of potential probiotic *Bacillus subtilis* KADR1 and its subcellular components on immune responses and disease resistance in *Labeo rohita*. Aquaculture Res 49(1):367–377

Ramesh D, Vinothkanna A, Rai AK, Vignesh VS (2015) Isolation of potential probiotic *Bacillus* spp. and assessment of their subcellular components to induce immune responses in *Labeo rohita* against *Aeromonas hydrophila*. Fish Shellfish Immunol 45(2):268–276

Ramzani SR, Ismail MM, Daud HM, Abdurofi I (2014) Probiotic application in freshwater prawns; some implication on farm profitability. Ann Biol Res 5(5):64–76

Ravi AV, Musthafa KS, Jegathammbal G, Kathiresan K, Pandian SK (2007) Screening and evaluation of probiotics as a bio-control agent against pathogenic Vibrios in marine aquaculture. Lett Appl Microbiol 45(2):219–223

Ringo E, Vadstein O (1998) Colonization of *Vibrio pelagius* and *Aeromonascaviae* in early developing turbot (*Scophthalmus maximus L.*) larvae. J Appl Microbiol 84(2):227–233

Ringo E, Strom E, Tabachek JA (1995) Intestinal microflora of salmonids: a review. Aquaculture Res 26(10):773–789

Robertson PAW, O'Dowd C, Burrells C, Williams P, Austin B (2000) Use of *Carnobacterium* sp. as a probiotic for Atlantic salmon (*Salmo salar L.*) and rainbow trout (*Oncorhynchusmykiss*, Walbaum). Aquaculture 185(3):235–243

Rodriguez-Estrada U, Satoh S, Haga Y, Fushimi H, Sweetman J (2009) Effects of single and combined supplementation of *Enterococcus faecalis*, mannan oligosaccharide and polyhydroxybutyrate acid on growth performance and immune response of rainbow trout *Oncorhynchus mykiss*. Aquac Sci 57(4):609–617

Ronneseth A, Castillo D, D'Alvise P, Tonnesen O, Haugland G, Grotkjar T, Engell-Sorensen K, Norremark L, Bergh O, Wergeland HI, Gram L (2017) Comparative assessment of vibrio virulence in marine fish larvae. J Fish Dis 40(10):1373–1385

Sahoo TK, Jena PK, Nagar N, Patel AK, Seshadri S (2015) In vitro evaluation of probiotic properties of lactic acid bacteria from the gut of *Labeo rohita* and *Catlacatla*. Probiotics Antimicrob Proteins 7(2):126–136

Sahu MK, Swarnakumar NS, Sivakumar K, Thangaradjou T, Kannan L (2008) Probiotics in aquaculture: importance and future perspectives. Ind J Microbiol 48(3):299–308

Sakai M (1999) Current research status of fish immunostimulants. Aquaculture 172(1):63–92

Sakata T (1990) Microflora in the digestive tract of fish and shell-fish. Microbiol Poecilotherms:171–176

Salinas I, Cuesta A, Esteban MA, Meseguer J (2005) Dietary administration of *Lactobacillus delbrueckii* and *Bacillus subtilis*, single or combined, on gilthead sea bream cellular innate immune responses. Fish Shellfish Immunol 19(1):67–77

Salminen S, Isolauri E, Salminen E (1996) Clinical uses of probiotics for stabilizing the gut mucosal barrier: successful strains and future challenges. Antonie Van Leeuwenhoek 70(2):347–358

Salminen S, Ouwehand AC, Isolauri E (1998) Clinical applications of probiotic bacteria. Int Dairy J 8(5–6):563–572

Servin AL (2004) Antagonistic activities of lactobacilli and bifidobacteria against microbial pathogens. FEMS Microbiol Rev 28(4):405–440

Servin AL, Coconnier MH (2003) Adhesion of probiotic strains to the intestinal mucosa and interaction with pathogens. Best Pract Res Clin Gastroenterol 17(5):741–754

Sharifuzzaman SM, Austin B (2010) Kocuria SM1 controls vibriosis in rainbow trout (*Oncorhynchus mykiss*, Walbaum). J Appl Microbiol 108(6):2162–2170

Sharifuzzaman SM, Abbass A, Tinsley JW, Austin B (2011) Subcellular components of probiotics *Kocuria* SM1 and *Rhodococcus* SM2 induce protective immunity in rainbow trout (*Oncorhynchusmykiss*, Walbaum) against *Vibrioanguillarum*. Fish Shellfish Immunol 30(1):347–353

Sharifuzzaman SM, Rahman H, Austin DA, Austin B (2017) Properties of probiotics Kocuria SM1 and Rhodococcus SM2 isolated from fish guts. Probiotics Antimicrob Proteins:1–9

Skjermo J, Bakke I, Dahle SW, Vadstein O (2015) Probiotic strains introduced through live feed and rearing water have low colonizing success in developing Atlantic cod larvae. Aquaculture 438:17–23

Smith P, Davey S (1993) Evidence for the competitive exclusion of *Aeromonas salmonicida* from fish with stress-inducible furunculosis by a fluorescent pseudomonad. J Fish Dis 16(5):521–524

Srisapoome P, Areechon N (2017) Efficacy of viable *Bacillus pumilus* isolated from farmed fish on immune responses and increased disease resistance in Nile tilapia (*Oreochromis niloticus*): laboratory and on-farm trials. Fish Shellfish Immunol 67:199–210

Sun YZ, Yang HL, Huang KP, Ye JD, Zhang CX (2013) Application of autochthonous *Bacillus* bioencapsulated in copepod to grouper *Epinephelus coioides* larvae. Aquaculture 392:44–50

Sung HH, Kou GH, Song YL (1994) Vibriosis resistance induced by glucan treatment in tiger shrimp (*Penaeus monodon*). Fish Pathol 29(1):11–17

Swapna HC, Rai AK, Bhaskar N, Sachindra NM (2010) Lipid classes and fatty acid profile of selected Indian fresh water fishes. J Food Sci Technol 47(4):394–340

Taoka Y, Maeda H, Jo JY, Kim SM, Park SI, Yoshikawa T, Sakata T (2006) Use of live and dead probiotic cells in tilapia *Oreochromisniloticus*. Fish Sci 72(4):755–766

Thankappan B, Ramesh D, Ramkumar S, Natarajaseenivasan K, Anbarasu K (2015) Characterization of *Bacillus* spp. from the gastrointestinal tract of *Labeo rohita* towards to identify novel probiotics against fish pathogens. Appl Biochem Biotechnol 175(1):340–353

Thirumurugan R, Vignesh V (2015) Probiotics: live boon to aquaculture. In: Advances in marine and brackishwater aquaculture. Springer India, pp 51–61

Timmerman HM, Koning CJM, Mulder L, Rombouts FM, Beynen AC (2004) Monostrain, multistrain and multispecies probiotics– a comparison of functionality and efficacy. Int J Food Microbiol 96(3): 219–233

Tinh NTN, Dierckens K, Sorgeloos P, Bossier P (2008) A review of the functionality of probiotics in the larviculture food chain. Mar Biol 10(1):1–12

Tovar-Ramırez D, Infante JZ, Cahu C, Gatesoupe FJ, Vazquez-Juarez R (2004) Influence of dietary live yeast on European sea bass (*Dicentrarchus labrax*) larval development. Aquaculture 234(1): 415–427

Uyeno Y, Shigemori S, Shimosato T (2015) Effect of probiotics/prebiotics on cattle health and productivity. Microbes Environ 30(2):126–132

Van Hai N, Fotedar R (2009) Comparison of the effects of the prebiotics (Bio-Mos® and β-1, 3-D-glucan) and the customised probiotics (*Pseudomonas synxantha* and *P. aeruginosa*) on the culture of juvenile western king prawns *(Penaeus latisulcatus* Kishinouye, 1896). Aquaculture 289(3):310–316

Van Hai N, Buller N, Fotedar R (2010) Encapsulation capacity of *Artemia nauplii* with customized probiotics for use in the cultivation of western king prawns (*Penaeus latisulcatus* Kishinouye, 1896). Aquaculture Res 41(6):893–903

Verschuere L, Rombaut G, Sorgeloos P, Verstraete W (2000) Probiotic bacteria as biological control agents in aquaculture. Microbiol Mol Biol Rev 64(4):655–671

Vine NG, Leukes WD, Kaiser H (2004) In vitro growth characteristics of five candidate aquaculture probiotics and two fish pathogens grown in fish intestinal mucus. FEMS Microbiol Lett 231(1):145–152

WHO (2001) Health and nutritional properties of probiotics in food including powder milk with lactic acid bacteria. Medicine Rep 12(10): 328–330

Wiklund T (2016) *Pseudomonas anguilliseptica* infection as a threat to wild and farmed fish in the Baltic Sea. Microbiol Aust 37(3): 135–136

Wolf G (2006) Gut microbiota: a factor in energy regulation. Nutr Rev 64(1):47–50

Wu ZQ, Jiang C, Ling F, Wang GX (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

Zapata AA, Lara-Flores M (2012) Antimicrobial activities of lactic acid bacteria strains isolated from Nile tilapia intestine (*Oreochromis niloticus*). J Biol Life Sci 4(1):164–171

Zhou X, Wang Y, Yao J, Li W (2010) Inhibition ability of probiotic, *Lactococcus lactis*, against *A. hydrophila* and study of its immunostimulatory effect in tilapia (*Oreochromis niloticus*). Int J Eng Sci Technol 2(7):73–80

Zorriehzahra MJ, Delshad ST, Adel M, Tiwari R, Karthik K, Dhama K, Lazado CC (2016) Probiotics as beneficial microbes in aquaculture: an update on their multiple modes of action: a review. Vet Q 36(4): 228–241