Use of probiotics in aquaculture of China—a review of the past decade

Anran Wang, Chao Ran, Yanbo Wang, Zhen Zhang, Qianwen Ding, Yalin Yang,
Rolf Erik Olsen, Einar Ringø, Jérôme Bindelle, Zhigang Zhou

[a] *Liege University, Gembloux Agro-Bio Tech, AgroBioChem/TERRA, Precision Livestock and Nutrition Unit/AgricultureIsLife, Passage des Deportes, 2, 5030, Gembloux, Belgium*

[b] *Sino-Norway Fish Gastrointestinal Microbiota Joint Lab, Feed Research Institute, Chinese Academy of Agricultural Sciences, Beijing, 100081, PR China*

[c] *Marine Resource & Nutritional Biology, Food Quality and Safety Department, Zhejiang Gongshang University, Hangzhou, China*

[d] *Norway-China Fish Gastrointestinal Microbiota Joint Lab, Institute of Biology, Norwegian University of Science and Technology, Trondheim, Norway*

[e] *Norway-China Fish Gastrointestinal Microbiota Joint Lab, Faculty of Biosciences, Fisheries and Economics, UiT the Arctic University of Norway, Tromsø, Norway*

ABSTRACT

China is the largest aquaculture producer in the world. Antibiotics were extensively used to ensure the devel-opment of the intensive aquaculture; however, the use of antibiotics causes safety- and environment-associated problems. As an alternative strategy to antibiotics, aquatic probiotics have attracted attention. The microbial organisms used as probiotics or tested as potential probiotics in Chinese aquaculture belong to various taxo-nomic divisions, including Actinobacteria, Bacteroidetes, Firmicutes, Proteobacteria and yeast. Moreover, the mixture of probiotic strains and synbiotics are also widely used. Studies on the mode of action of aquatic pro-biotics have extended our understanding of the probiotic effects, and novel mechanisms have been discovered, such as interference of quorum sensing. However, use of probiotics in Chinese aquaculture is still at an initial stage, and there are potential risks for some probiotic applications in aquaculture. Further regulation and management are required to normalize the production and usage of aquatic probiotics. In this review, we discuss species, effects, and mode of actions of probiotics in Chinese aquaculture since 2008. Challenges and future directions for research are also discussed.

1. Introduction

Aquaculture has a long history and started in China more than 2000 years ago [1]. It is a fast-growing and rapidly expanding industry, and it is reported that food fish provides an average of one-fifth of the total animal protein intake of the world population [2,3]. Aquaculture pro-duction in China accounts for nearly 70% of world aquaculture pro-duction, and the total production rose from 2.33 million tons in 1978 to 51.42 million tons in 2016, making China the only country in the world where aquaculture production exceeds the wild catch (FAO 2015). However, the intensive aquaculture enhanced the incidence of disease outbreaks in the farmed species, leading to massive mortalities and economic loss. For many cultured aquatic species in China, vaccines are not available. Moreover, vaccines will hardly be available in the near future due to the limitations in fish vaccine development [4]. For these species the only treatment of diseases has been through extensive use of chemical additives and veterinary medicines, especially antibiotics [5].

However, the abuse of antibiotics is linked to many secondary com-plications like modulation of the "*normal*" microbiota in the culture environment, antibiotic accumulation in edible products, and the con-tinuously rising cost for disease treatment [6–8]. In addition, there is a general concern over the increased numbers of antibiotic resistant strains of bacteria in our environment [9]. To reduce the abuse of an-tibiotics in aquaculture, many alternative solutions have been sug-gested particularly when vaccines are not available. These include an-timicrobial peptide, herb extracts, pro-, pre- and synbiotics, and among them, probiotics have received particular attention due to the high abundance, low cost and convenience in application [3].

The Food and Agricultural Organization (FAO) and World Health Organization (WHO) define probiotics as "*live microorganisms which when administered in adequate amounts confer a health benefit on the host*" [10]. However, the probiotics for aquatic usage are different from probiotics for terrestrial animals and human. The key factor that con-tributes to this difference is the intricate relationship aquatic animals

have with the ambient environment. Therefore, it is accepted that we must have a distinctive definition for aquatic probiotics as opposed to that for terrestrial animals. Many authors proposed definitions for probiotics in aquaculture [11–14]. The definitions were similar while each has its own specificity. Verschuere et al. suggested the definition of probiotics for aquatic animals as "a live microbial adjunct which has a beneficial effect on the host by modifying the host-associated or ambient microbial community, by ensuring improved use of the feed or enhancing its nutritional value, by enhancing the host response towards disease, or by improving the quality of its ambient environment" [12]. In this review, we would adhere to this definition, and will summarize live microbial adjuncts applied by dietary supplementation or as water additives in this review. Notably, some scientists define aquatic probiotics as an entire or component(s) of a microorganism [15,16]. While the functional components of probiotics are very important, it is more appropriate to define them as "probiotic effectors", which cannot be considered as probiotics.

During the last decade, several reviews have summarized the use and beneficial effects of probiotics in aquaculture [17–20]. In particular, Qi et al. reviewed probiotic studies in Chinese aquaculture from 1988 to 2008 [18]. However, as numerous studies have been published on probiotics in Chinese aquaculture since 2008, an update is needed. Therefore, the current paper addressed the use of probiotics in Chinese aquaculture from 2008 and until today. Furthermore, issues associated with probiotics in Chinese aquaculture that merit further investigations are also discussed.

2. The microorganisms applied as probiotics in aquaculture of China

Probiotics used in Chinese aquaculture have a diverse origin. Most of them are either derived from the intestines of the host animals [21–24], or isolated from the environments [25–29]. When discussing probiotics, it is of interest to notice that some of the probiotic bacteria have been developed into commercial products [30–33] (Table 1). The microbial organisms used as probiotics or tested as potential probiotics in Chinese aquaculture belong to various taxonomic divisions, including Actinobacteria, Bacteroidetes, Firmicutes, Proteobacteria and yeast.

2.1. Actinobacteria

2.1.1. Arthrobacter

Arthrobacter is a genus of Gram-negative, obligate aerobe rods or cocci, and they have been identified successfully from the gastrointestinal (GI) tract of several finfish species [34–36]. However, less information is available on probiotic *Arthrobacter*. In an early study with white shrimp (*Penaeus chinensis*) by Li et al. [37], an *Arthrobacter* XE-7 isolated from white shrimp showing antagonisms towards *Vibrio parahaemolyticus*, *Vibrio anguillarum* and *Vibrio nereis* was added to the rearing water. As this treatment revealed protection of shrimp post larvae against pathogenic vibrios, the authors suggested that *Arthrobacter* XE-7 could be probiotic in shrimp larvae culture. Furthermore, *Arthrobacter* sp. CW9 isolated from the gut of white shrimp (*Penaeus vannamei*) improved survival and growth rates, phenoloxidase activity, phagocytic activity and clearance efficiency of haemocytes of white shrimp when added to the rearing water during a breeding experiment [38].

2.2. Bacteroidetes

2.2.1. Flaviramulus

Flaviramulus ichthyoenteri Th78[T], a novel species in family Flavobacteriaceae, was isolated from flounder (*Paralichthys olivaceus*) and showed strong quorum quenching (QQ) ability [39,40]. The genome of strain Th78[T] has been sequenced and genome information

suggests production of QQ enzyme, utilization of various nutrients available in the intestine, as well as production of digestive enzymes and vitamins, which suggests the prospect of Th78[T] to be used as a probiotic in aquaculture [39,40].

2.2.2. Flavobacterium

Genus *Flavobacterium* is Gram-negative, rod-shaped, non-motile and motile bacteria, and they have been reported in the GI tract of several fish species [34,35,41–43], but several species are known to cause disease in fish [44,45]. *Flavobacterium sasangense* BA-3, an autochthonous intestinal strain isolated from common carp (*Cyprinus carpio*), has been suggested as probiotics [21]. In this study, dietary supplementation of bacterial cells or extracellular products of BA-3 positively influenced the innate immune parameters of carp (lysozyme, complement C3, total serum protein, albumin and globulin levels, respiratory burst activity, phagocytic activity by blood leucocytes and the expression of IL-1β, lysozyme-C, and TNF-α in blood). Moreover, both bacterial cells and extracellular products of *F. sasangense* BA-3 improved resistance of carp against *Aeromonas hydrophila* infection.

2.3. Firmicutes

2.3.1. Bacillus

Bacillus species are one of the most widely used probiotics in aquaculture [15,46]. According to Gatesoupe's study, *Bacillus* strains were introduced as probiotics in aquaculture in the 90ties [46]. They can exert *in vitro* antagonistic or inhibitory activities against a variety of bacterial and fungal pathogens, provide digestive enzymes, activate growth factors, and regulate the immunity of aquatic animals [47–51].

Numerous studies have revealed that supplementation of *Bacillus* to the diet improved growth performance, digestive enzyme activities, antioxidant function, immune responses, and disease resistance of fish [28,52–58]. The *Bacillus* species used include *Bacillus subtilis* [59–63], *Bacillus cereus* [51,64,65], *Bacillus amyloliquefaciens* [56], *Bacillus baekryungensis* [66], *Bacillus licheniformis* [27,28,67], *Bacillus pumilus* [22,52,68], *Bacillus clausii* [52,69], *Bacillus coagulans* [25,26,29,58,70], and *Bacillus velezensis* [71].

Bacillus strains have also been used as probiotics for invertebrate aquatic species [26,60,72]. Four studies on sea cucumber (*Apostichopus japonicus*) revealed that *B. subtilis* T13, *B. baekryungensis* YD13, *B. cereus* G19, *B. cereus* BC-01, and *B. cereus* EN25 significantly enhanced growth performance, immunity and disease resistance of sea cucumber against *Vibrio splendidus* [61,64–66]. The commercial probiotic product BZT®, containing *B. subtilis* YB-1 (50%) and *B. cereus* YB-2 (50%), stimulated non-specific immune responses and enhanced growth performance of sea cucumbers, and was effective in controlling infection caused by *V. alginolyticus* [30]. Some studies using *B. subtilis* S12 and *Bacillus* PC465 revealed improved growth performance, non-specific immunity and disease-resistance of Pacific white shrimp (*Litopenaeus vannamei*) [73,74]. Two strains, *B. subtilis* DCU and *B. pumilus* BP, were reported to have potential application by controlling pathogenic vibriosis in mud crab (*Scylla paramamosain*) aquaculture [22].

Use of heat-inactivated bacilli has been investigated in two recent studies. Yan et al. demonstrated that heat-inactivated *B. pumilus* SE5 could effectively improve growth performance and remarkably up-regulated expression of TLR2 and pro-inflammatory cytokines (IL-8 and IL-1β) in head kidney of grouper (*Epinephelus coioides*) [68]. More recently, Wang et al. revealed that heat-inactivated *B. clausii* DE5 improved feed utilization and the expression of TLR5, pro-inflammatory cytokines (IL-8 and IL-1) and TGF-1 in the head kidney and intestine of grouper [69].

Some *Bacillus* strains applied as water additives showed similar beneficial effects to the aquatic animsls as those supplemented in the diet. Zhou et al. reported that probiotic, *B. coagulans* SC8168, supplemented as water additive at a certain concentration, could significantly increase survival rate and the activity of some digestive enzymes of

Table 1

Bibliographic review of research published in the last 10 years (2008–2018) on the use of probiotics in aquaculture of China.

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects			Improvement of aquaculture environment	Reference
					Disease resistance including immune improvements	Nutritional modulation	Productive effects and others	Water	
Gram-negative bacteria									
Aeromonas									
A. *veronii* BA-1(from intestinal tract of the common carp)	Proteobacteria	Diets 10^8 cell g^{-1} (live)	Common carp (*Cyprinus carpio*)	28 days	Serum protein, albumin, globulin ↑ Phagocytic capacity ↑ Transcriptional expression of IL-1β, TNF-α, lysozyme-C ↑ Mortality ↓ (80–66.66%) after A. *hydrophila* challenge ↓				[21]
A. *veronii* A-7 (from the intestinal tract of the healthy grass carp)	Proteobacteria	Diets 10^8 cell g^{-1} (live)	Grass carp (*Ctenopharyngodon idella*)	14 days	Respiratory burst, phagocytic and lysozyme activities ↑ Serum complement C3, total serum protein, albumin, globulin ↑ Transcriptional expression of IL-8, IL-1, lysozyme-C, TNF-α ↑ Mortality ↓ (80–26.67%) after A. *hydrophila* challenge.		Potential pathogen bacteria ↓ Potential probiotics ↑ Cellulose-degrading intestinal bacteria ↑		[23,154]
A. *bivalvium* D15 (from the gut of healthy Pacific white shrimp)	Proteobacteria	Diets 10^7 cell g^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	28 days	Respiratory burst and SOD activities ↑ Transcriptional expression ofprophenoloxidase, β-1, 3-glucan-binding protein (LGBP) ↑ Mortality ↓ (43.33%–13.33%) after V. *harveyi* challenge.		Growth ↑		[72]
Bdellovibrio									
BALO strain BDH12 (from sediment of Daya Bay in China)		Add to water at dose of 1×10^5 PFU ml^{-1} (live)	Abalone (*Haliotis discus hannai* Ino)	90 days			Growth ↑	Total cultivable Vibrio counts (TCVC) and bacterial counts (TCBC) ↓	[119]
B. *bacteriovorus* Bdm4 (from the sediment of fish ponds)	Proteobacteria	Add to water at dose of 10^7 PFU ml^{-1} (live)	Grass carp (*Ctenopharyngodon idellus*)	17 days				Chemical oxygen demand (COD) ↓, NH_3-N ↓, sulphide ↓, DO ↑	[120]
B. *bacteriovorus* (commercial product)	Proteobacteria	Add to water at dose 5×10^7 PFU m^{-3} (unidentified)	Tilapia (*Oreochromis nilotica*)	126 days	The death number of Tilapia caused by bacteriosis ↓			The general bacterial population ↓ The number of coli group ↓	[125]
B. *bacteriovorus*	Proteobacteria	Add to water with a final concentration of 5×10^6 PFU ml^{-1}	White leg shrimp (*Penaeus vannamei*)	7 days	Control of shrimp pathogen V. *cholerae*				[127]
Ectothiorhodospira									

Table 1 (continued)

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment	Reference
					Disease resistance including immune improvements			Water	
E. shaposhnikovii WF(from marine shrimp pond)	Proteobacteria	Immersion twice at 10^6 CFU ml^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	10 days			Mortality ↓ (46%–74%) Growth ↑	Ammonia, nitrite, COD ↓	[129]
Flavobacterium									
Flavobacterium sasangense BA-3 (from the intestinal tract of the common carp)	Proteobacteria	Diets 1×10^8 cell g^{-1}	Common carp (*Cyprinus carpio*)	28 days	Lysozyme, complement C3, total serum protein, albumin and globulin, Respiratory burst and phagocytic activities↑ Transcriptional expression of IL-1, lysozyme-C, and TNF-α ↑ Mortality rate ↓ (80%–66.66%) after *A. hydrophila* challenge.				[21]
Halomonas									
Halomonas sp. B12 (from the intestine of *Fenneropenaeus chinensis*)	Proteobacteria	Diets 3.68×10^7 or 7.18×10^{10} CFU g^{-1} (live)	Chinese whiter shrimp (*Fenneropenaeus chinensis*)	6 weeks	Hemocyte counts ↑, phenoloxidase activity ↑ Mortality after white spot syndrome virus challenge test ↓				[132]
Rhodopseudomonas									
R. pdustris G06 (from a carp pond in Haining, China)	Proteobacteria	Immersion at 1×10^7 CFU ml^{-1} (live)	Tilapia (*Oreochromis niloticus*)	40 days	SOD and catalase (CAT) activities ↑		Growth ↑		[25]
R. pdustris (from a pond of grass carp)	Proteobacteria	Incubation 1×10^{11} CFU m^{-3} (live)	Grass carp (*Ctenopharyngodon idella*)	15 days				Ammonia ↓, nitrite ↓, COD↓, nitrogen →	[149]
Shewanella									
S. colwelliana WA64 *S. olleyana* WA65 (from GI tract of abalone)	Proteobacteria	Diets 10^9 cell g^{-1} (live)	Abalone (*Haliotis discus hannai* Ino),	4 weeks	Haemocytes, respiratory burst activity, serum lysozyme activity, and total protein levels ↑ Mortality↓ after *V. harveyi* challenge.				[153]
S. japonica HS7 (from the intestines of healthy sea cucumbers)	Proteobacteria	Diets 10^9 cell g^{-1} (unidentified)	Sea cucumber (*Apostichopus japonicus*)	28 days	Total coelomocytes counts, respiratory burst activity, lysozyme, ACP, and phagocytic activities ↑		Mortality ↓ (97.6%–90.71%)		[140]
S. xiamenensis A-1 *S. xiamenensis* A-2 (from the intestines of grass carp)	Proteobacteria	Diets 10^8 cells g^{-1} of *S. xiamenensis* A-1(live)	Grass carp (*Ctenopharyngodon idella*)	14 days	Respiratory burst, phagocytic and lysozyme activities ↑ Complement C3, total serum proteins, albumin and globulin↑ Transcriptional expression of IL-8, IL-1, lysozyme-C, and TNF – α ↑ Mortality ↓ (80%–46.67%, 80%–33.33%) after *A. hydrophila* challenge.		The abundance of the potential pathogenic bacteria ↓ (e.g., *Pseudomonas* and *Flavobacterium* genus), reproduction of potential probiotics↓ (e.g., *Vibrio*, *Streptococcus*, and *Enterococcus* genus) and impact the abundance of cellulose-degrading bacteria ↑ (e.g., *Citrobacter*		[23]

Table 1 (*continued*)

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects — Disease resistance including immune improvements	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment — Water	Reference
S. haliotis D4 (from the gut of shrimp)	Proteobacteria	Diets 10^7 cell g^{-1} (live)	Pacific white white shrimp (*Litopenaeus vannamei*)	28 days	Respiratory burst and SOD activities ↑ Expression of prophenoloxidase, LPS- and LGBP protein ↑ Mortality ↓ (43.33%–33.33%) after *V. harveyi* challenge.		genus) in the grass carp intestine. Growth ↑		[72]
Vibrio									
V. tasmaniensis HS10 (from the intestine of sea cucumber)	Proteobacteria	Diets 10^9 cell g^{-1} (unidentified)	Sea cucumber (*Apostichopus japonicus*)	28 days	Total coelomocytes counts, respiratory burst, lysozyme, ACP, and phagocytic activities ↑.		Survival rate ↑ (87.60%–97.97%).		[140]
Gram-positive bacteria									
Arthrobacter									
Arthrobacter sp. CW9 (from guts of white shrimp)	Actinobacteria	Added to the saline rearing water at 0, 10^5, 10^6 and 10^7 CFU ml^{-1} every 5 days during the 24-day breeding experiment (unidentified)	Pacific white shrimp (*Penaeus vannamei*)	24 days	Phenoloxidase, phagocytic and clearance efficiency ↑		Survival rate ↑ Mean shrimp weights ↑		[38]
Bacillus									
Bacillus PC465 (from the intestine of a healthy *Fenneropenaeus chinensis*)	Firmicutes	Diets 10^7 and 10^9 CFU g^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	30 days	Transcriptional expression of Pen-3a, peroxinectin, C-type lectin 3 (Lec-3), thioredoxin (Trx), prophenoloxidase (proPO) ↑ Survival rate ↑ (14.9%–45.2%, 50.7%) after white spot syndrome virus (WSSV) challenge.	Amylase and protease activities ↑	Growth ↑ Survival rate ↑ (35%–73.32%, 66.7%)		[74]
B. subtilis *B. amyloliquefaciens*	Firmicutes	Diets 10^5 CFU g^{-1} (live)	Grass carp (*Ctenopharyngodon idellus*)	52 days	IgM, complement C3 and AKP activities ↑ Serum glutathione (GSH), total antioxidant capacity (T-AOC), SOD and glutathione peroxidase (GSH-Px) activities ↑ Malondialdehyde (MDA) and anti-superoxide anion (anti-O$_2^-$) activity ↓				[56]
B. licheniformis B. subtilis (from the pond of grass carp)	Firmicutes	Group 1: added *Bacillus* preparation no. 1 with 10^8 CFU m^{-3} per 7 days in culture water (live) Group 2: diet mixed with 0.5% *Bacillus* preparation no. 2, and the culture water	Grass carp (*Ctenopharyngodon*)	4 weeks	Globulin, IgM, myeloperoxidase and C3 activities ↑ T-AOC, anti-superoxide anion free radical (ASAFR) and GSH ↑				[28]

Table 1 (continued)

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects — Disease resistance including immune improvements	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment (Water)	Reference
Probiotics product containing *B. subtilis* YB-1 (50%) and *B. cereus* YB-2 (50%)	Firmicutes	was added 10^8 CFU m^{-3} *Bacillus* preparation no. 1 per 7 days (live)							
	Firmicutes	Diets 10^{10} CFU g^{-1} (live)	Sea cucumbers (*Apostichopus japonicus*)	32 days	Phagocytic activity ↑, superoxide anion production ↑, lysozyme, catalase and phenoloxidase activities ↑ The cumulative mortality ↓ (100%–47%) after *V. alginolyticus* challenge.		Growth ↑		[30]
B. pumilus *B. clausii* (from the gut of grouper *E. coioides*)	Firmicutes	Diets 1×10^8 cell g^{-1} (live)	Grouper (*Epinephelus coioides*)	60 days	Phagocytic activity and phagocytic index, serum lysozyme, complement C3, IgM and SOD activities ↑		Feed conversion ratio (FCR) ↑		[52]
B. subtilis DCU *B. pumilus* BP (from the intestine of mud crabs)	Firmicutes	Diets 1×10^5 cell g^{-1}	Juvenile mud crabs (*Scylla paramamosain*)	30 days	Expression levels of CAT, proPO and SOD genes ↑ Respiratory burst activity↑ Final survival rates ↑ (54.88%–76.67%, 78.33%) after *V. parahaemolyticus* challenge.				[22]
B. baekryungensis YD13 (from sea cucumber culturing ponds)	Firmicutes	Diets 1×10^6 CFU g^{-1} (live)	Sea cucumber (*Apostichopus japonicus*)	60 days	Lysozyme, ACP, AKP, SOD, CAT activities ↑				[66]
B. cereus G19 *B. cereus* BC-01 (from the intestine of the sea cucumber)	Firmicutes	Diets 1×10^9 CFU kg^{-1} (live)	Sea cucumber (*Apostichopus japonicus* Selenka)	60 days	Phagocytic, respiratory burst and AKP activites ↑ Transcriptional expression of Aj-p50, Aj-rel↑		Growth ↑		[64]
B. cereus EN25 (from mud of sea cucumber culturing water bodies)	Firmicutes	Diets 1×10^7 CFU g^{-1} (live)	Juvenile sea cucumbers (*Apostichopus japonicus*)	30 days	Phagocytosis, respiratory burst activity and total nitric oxide synthase activity ↑ The cumulative mortality ↓ (64.2%–33.3%) after *V. splendidus* challenge.				[65]
B. cereus (from the intestinal contents of tilapia)	Firmicutes	Added to the water (1×10^4 CFU mL^{-1} and 1×10^5 CFU mL^{-1}) or feed (1×10^7 cell g^{-1} and 1×10^8 cell g^{-1})	Tilapia (*Oreochromisniloticus*)	42 days	Serum lysozyme, peroxidase, AKP and total superoxide dismutase (TSOD) activities ↑		Affect the gut microbiota of tilapia and stimulated various potentially beneficial bacteria		[51]
B. clausii DE5 (from the gut of juvenile *Epinephelu coioides*)	Firmicutes	Diets supplemented with viable (T1) and heat-inactivated (T2) *B. clausii* DE5 at dose of 1×10^8 cell g^{-1}	Grouper (*Epinephelus coioide*)	60 days	Serum lysozyme activity and complement C3 ↑ Transcriptional expression of TLR5, pro-inflammatory cytokines (IL-8, IL-1β) and TGF-β1↑ in head kidney and intestine.		Feed intake ↓ FCR- ↓		[69]
B. coagulans (from the shrimp *Penaeus vannamei* ponds)	Firmicutes	Diets viable (T-1) and dead (T-2) *B. coagulans* at dose of 1×10^7 cell g^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	50 days		Protease, amylase, and lipase↑	Growth ↓ Survival rate↓		[26]

Table 1 (*continued*)

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment	Reference
					Disease resistance including immune improvements			Water	
B. coagulans (from common carp aquaculture ponds)	Firmicutes	Diets 1×10^7 cell g^{-1}, 2×10^7 cell g^{-1}, 4×10^7 cell g^{-1} (live)	Common carp (*Cyprinus carpio*)	45 days	Lysozyme, myeloperoxidase, and respiratory burst activities ↑	Contents of crude fat, inosine, and inosinic acid↑	Growth ↑		[29]
B. coagulans, (from a commercial product provided by Suwei Microbial Research Co., Ltd (Jiangsu, China) that contained *B. coagulans* 2×10^{10} CFUg^{-1}).	Firmicutes	Diets 125, 250, 500, and 1000 mg kg^{-1} (live)	Juvenile gibel carp (*Carassius auratus gibelio*)	8 weeks	Plasma lysozyme activity, superoxide dismutase, and superoxide anion radical scavenging activity ↑ Transcriptional expression of heat shock protein 70 (HSP70)↑ The cumulative mortality↓ after *A. hydrophila* challenge.	The activities of protease↑, lipase↑ and amylase ↑	Growth ↑ FCR↓		[58]
B. coagulans SC8168 (from the pond sediment of shrimp)	Firmicutes	Diets supplemente 1×10^6 CFU ml^{-1} (live)	Larvae shrimp (*Penaeus vannamei*)	ontogenetic stages		Protease, amylase activity and lipase activity ↑	Survival rate ↑ (generally by 7.00–13.10%) over the controls.		[70]
B. coagulans B16 (from a carp *Cyprinus carpio* pond)	Firmicutes	Added to the water of tanks at final concentration of 1×10^7 CFU ml^{-1} every 2 days	Tilapia (*Oreochromis niloticus*)	40 days	SOD, CAT and respiratory burst activities ↑ Concentrations of serum protein and globulin ↑		Growth ↑		[25]
B. licheniformis BSK-4 (from a grass carp culture pond)	Firmicutes	Diets 3×10^8 CFU m^{-3} (live)	Grass carp (*Ctenopharyngodon idellus*)	18 days				Nitrite, nitrate and total nitrogen levels ↓, ammonia level ↑ Alterations of the microbial composition in grass carp water.	[27]
B. licheniformis (commercial product, AlCare*, Zoetis, Shanghai, China)	Firmicutes	Diets 4.4×10^6 CFU g^{-1} (live)	Juvenile Tilapia (*Oreochromis niloticus*)	10 weeks	Complement C3 ↑ Survival rate ↑		Growth ↑		[67]
B. pumilus SE5 (from the gut of juvenile grouper *Epinephelu coioides*)	Firmicutes	Diets live and heat-inactivated *B. pumilus* SE5 at dose of 1×10^8 CFU g^{-1}	Grouper (*Epinephelus coioides*)	60 days	Phagocytic activity, serum complement C3 and IgM levels, SOD activity ↑ Transcriptional expression of TLR2 and pro-inflammatory cytokines (IL-8 and IL-1β) ↑		Growth ↑		[68]
B. subtilis (from the gut contents of farm-reared shrimp)	Firmicutes	Diets *B. subtilis* at dose of 5×10^4 CFU g^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	40 days	Phenoloxidase and lysozyme activities ↑ Total antioxidant capacity, SOD, GSH-Px activity and superoxide anion activity ↑		Growth ↑		[60]
B. subtilis T13 (from intestine of healthy sea cucumbers)	Firmicutes	Diets 1×10^9 CFU g^{-1} (live)	Juvenile sea cucumbers (*Apostichopus japonicus*)	30 days	Phagocytosis, respiratory burst activity and total nitric oxide synthase (T-NOS) activities ↑ The cumulative mortality ↓ (56.2%–20.0%) after *V. splendidus* challenge.		Growth ↑		[61]

Table 1 (*continued*)

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects — Disease resistance including immune improvements	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment — Water	Reference
B. subtilis SCO2 (from a pond containing grass carp)	Firmicutes	Diets 1×10^9 CFU m^{-3} per 7 days in culture water (live)	Grass carp (*Ctenopharyngodon idellus*)	15 days				Ammonia, nitrite and total nitrogen ↓	[62]
B. subtilis FY99-01 (commercial probiotic)	Firmicutes	Add to water with 5×10^4 CFU mL^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	56 days				Levels of pH, nitrite and soluble reactive phosphorus ↓	[32]
B. subtilis B2 (from sediment in healthy sea cucumber *A postichopus j aponicus* farm in Dalian)	Firmicutes	Diets supplemented according to the weight of sea cucumber by 0.1%, 0.2% and 0.3% (live)	Sea cucumbers (*Apostichopus japonicus*)	7 days	● AKP, TSOD and PO activities ↑	Activity of amylase and protease ↑			[59]
B. subtilis HAINUP40 (from natural pond water in Hainan University)	Firmicutes	Diets 10^8 CFU g^{-1} (live)	Tilapia (*Oreochromis nilotica*)	4 weeks	Respiratory bursts, serum lysozyme, T-AOC and SOD activities ↑	protease and amylase activities ↑ The relative percent survival (RPS%) ↓	Growth ↑		[63]
B. subtilis FY99-01 (from the gastrointestinal tract (GIT) of healthy grass carp)	Firmicutes	Diets 10^9 CFU g^{-1} (live)	Crucian (*Carassius auratus*)	4 weeks	Activities of ACP, AKP, and GSH-PX ↑ Transcriptional expression of IFN- γ, TNF-α, IL-1, IL-4, IL-10) ↑and IL-12↓ Survival rate ↑ (30%–80%) after A. hydrophila challenge.				[71]
Clostridium									
C. butyricum (from Miyarisan Pharmaceutical Co. Ltd, Tokyo, Japan)	Firmicutes	Diets 1.0×10^8 CFU g^{-1} (live)	Silver pomfret (*Pampus argenteus*)	60 days	Lysozyme activity, SOD activity and IgM concentrations ↑	Lipase, protease and Amylase activities ↑	Growth ↑		[31]
C. butyricum (from Zhongke Biotic Co., Ltd, China)	Firmicutes	Diets 1.0×10^9 CFU g^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	56 days	T-AOC, lysozyme activity, inducible nitric oxide synthase (iNOS) activity ↑ Transcriptional expression of heat shock protein 70 (HSP70), Toll and immune deficiency (Imd) ↑	Intestine SCFA content ↑ and body crude protein content ↑, modulated intestine digestive capacity ↑	Growth ↑ Intestine epithelium height ↑		[33]
C. butyricum (from healthy chicken intestine)	Firmicutes	Diets 1.0×10^3, 1.0×10^9 CFU g^{-1} (live)	*Miichthys miiuy*	8 weeks	Serum phenoloxidase and acid phosphatases activities ↑, immunoglobulin M ↑		Growth ↑		[85]
C. butyricum (from Zhongke Biotic Co., Ltd, China)	Firmicutes	Diets 5.0×10^9 CFU kg^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	56 days	Transcriptional expression of prophenoloxidase, lipopolysaccharide and β-1,3-glucan binding protein, lysozyme, crustin, and superoxide dismutase ↑	Transcriptional expression of α-amylase, lipase, trypsin, fatty acid-binding protein, and fatty acid synthase ↑			[87]
C. butyricum CBG01 (provided by the Microbial Culture Collection Center, Lab of Aquaculture Ecology,	Firmicutes	Diets 10^{11} and 10^{12} CFU g^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	42 days	AKP, ACP, lysozyme and total nitric oxide synthase (TNOS) activities ↑ The respiratory burst activity of hemolymph ↑				[88]

Table 1 (*continued*)

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects / Disease resistance including immune improvements	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment (Water)	Reference
Ocean University of China					Transcriptional expression of Toll, Imd and Relish ↑ The cumulative mortality ↓ after *V. parahaemolyticus* challenge.				
C. butyricum (from Zhongke Biotic Co., Ltd, China)	Firmicutes	Diets 1.0×10^9 CFU g^{-1} (live)	Kuruma shrimp (*Marsupenaeus japonicus*)	56 days	T-AOC, catalase, peroxidase activities ↑, MDA content ↑ Transcriptional expression of HSP70, ferritin and metallothionein↑				[89]
C. butyricum (from Zhongke Biotic Co., Ltd, China)	Firmicutes	Diets 10^8 CFU g^{-1} (live)	Kuruma shrimp (*Marsupenaeus japonicus*)	56 days		Amylase, lipase, alanine aminotransferase and aspartate aminotransferase activities ↑ Intestine SCFA and body crude protein content ↑			[90]
Enterococcus									
E. faecium MM4 (from the gut of healthy juvenile *Epinephlus coioides*)	Firmicutes	Diets 1.0×10^8 CFU g^{-1} (live)	Grouper (*Epinephlus coioides*)	60 days	Complement C3 levels ↑	Activity of hepatopancreatic protease, intestinal lipase ↑ and amylase ↑			[94]
E. faecalis LC3 (from intestine of marine animals)	Firmicutes	Diets 1.0×10^9 CFU g^{-1} (live)	Sea cucumber (*Apostichopus japonicus*)	30 days	AKP activity ↑ Transcriptional expression of NF-kappa-B transcription factor p65 (Rel), CASP2, HSP 90, HSP70↓at 15 d and ↑at 30 d. The survival rate ↑ (48.1%–61.1%) after *V. splendius* challenge.		Growth ↑		[98]
E. faecium NRW-2 (from the intestine of health *Acanthogobius hasta*)	Firmicutes	Diets 1.0×10^7 CFU g^{-1} (live)	White shrimp (*Penaeus vannamei*)	4 weeks		Activities of hepatopancreatic, intestinal lipase and amylase ↑			[96]
Lactobacillus									
L. pentosus HC-2 (from the intestine of health *Acanthogobius hasta*)	Firmicutes	Diets 1.0×10^7 CFU g^{-1} (live)	White shrimp (*Penaeus vannamei*)	4 weeks		Hepatopancreatic, intestinal lipase and amylase activities↑			[96]
L. plantarum L-137 (HK L-137) (from the Zhuanghe Jintuo Aquaculture Farming)	Firmicutes	Diets 0.05 g and 0.25 g HK L-137 kg^{-1} (heat-killed)	Sea cucumber (*Apostichopus japonicus*)	60 days	Lysozyme, phagocytic, SOD and AKP activities ↑		Growth ↑		[109]
L. plantarum CCFM639(from the Culture Collections	Firmicutes	Diets 10^8 CFU g^{-1} (live)	Tilapia (*Oreochromis nilotica*)	4 weeks			Growth ↑		[110]

Table 1 (*continued*)

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects — Disease resistance including immune improvements	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment — Water	Reference
of Food Microbiology, Jiangnan University)									
L. plantarum CCFM8661 (from the Culture Collections of Food Microbiology, Jiangnan University)	Firmicutes	Probiotic was administered at 10^8 CFU g^{-1} in fish diet twice daily (live)	Tilapia (*Oreochromis nilotica*)	4 weeks	Al-induced oxidative stress↓, recovered the activities of TAOC, SOD, CAT and GPx. Pb-induced oxidative stress↓, blood daminolevulinic acid dehydratase activity↑, reversed alterations in innate immune status ↑. The frequencies of the nuclear abnormalities↓ in peripheral blood erythrocytes.		Pb accumulation ↓		[111]
L. delbrueckii (from Angel Company, Wuhan, China)	Firmicutes	Diets 1.0×10^6 and 1.0×10^7 CFU g^{-1} (live)	Huanghe carp (*Cyprinus carpio* Huanghe var)	8 weeks	Transcriptional expression of TNF-α, IL-8, IL-1, NF-kβ p65, IL-10 and TGF-β↑ The antioxidant enzyme activities (SOD, CAT, GPX, T-AOC) ↑ The survival rate ↑ after *A. hydrophila* challenge.				[106]
L. plantarum (commercial probiotis)	Firmicutes	Cell-free extract of *L. plantarum* (dead)	Pacific white shrimp (*Litopenaeus vannamei*)	45 days	Significantly improved the resistance of *L. vannamei* against the stress of acute low salinity, as indicated by higher survival rate as well as higher transcript levels of ProPo, SOD and Lys gene.				
L. plantarum (provide by Xinhailisheng Biological Technology Co., Ltd., South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, China)	Firmicutes	Cell-free extract of *L. plantarum* (dead)	Pacific white shrimp (*Litopenaeus vannamei*)	15 days		Digestive enzyme (amylase, lipase, and pepsin) activity ↑	Growth ↑ FCR ↓		[107]
L. plantarum LL11 (from marine fish)	Firmicutes	Diets 1.0×10^9 CFU g^{-1} (live)	Sea cucumber (*Apostichopus japonicus*)	30 days	AKP, ACP and SOD activities ↑ Heat shock proteins (HSP60, HSP70 and HSP90) ↑ The survival rate ↑ (48.1%–66.7%) after *V. splendius* challenge.		Growth ↑		[98]
L. pentosus (from shrimp farming pond in Zhangpu, Fujian province, China)	Firmicutes	Diets 1.0×10^7 CFU g^{-1} (live)	Pacific white shrimp (*Litopenaeus vannamei*)	28 days	The cumulative mortality ↓ after *Vibrio* strains challenge.	protease, cellulose activities ↑	Growth ↑		[108]
L. plantarum (from shrimp farming pond in Zhangpu, Fujian province, China)	Firmicutes	Diets 10^3 CFU g^{-1} and 10^5 CFU g^{-1} (live)	Abalone (*Haliotis discus hannai* Ino),	8 weeks	The total number of blood lymphocytes, lysozyme				[112]

Table 1 (*continued*)

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects — Disease resistance including immune improvements	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment — Water	Reference
L. pentosus (from the intestinal tracts of healthy abalone)					activity, acid phosphatase, and SOD↑. Expression levels of peroxidase (TPx) ↑, MDA content ↓ The cumulative mortality rate ↓		Survival rate, Shell length-specific growth rate, and FCR ↑		
Lactococcus									
L. lactis MM1 (from the gut of juvenile grouper *Epinephelus Coioides*)	Firmicutes	Diets 1.0 × 10^8 CFU g^{-1} (live)	Juvenile grouper (*Epinephelus coioides*)	60 days	Serum complement component 3 (C3) level and lysozyme activity ↑	Hepatopancreatic protease activities ↑	Feed utilization ↑		[95]
L. lactis RQ516 (from fresh milk)	Firmicutes	Add to water at final concentration of 1 × 10^7 CFU ml^{-1} every 2 days (live)	Tilapia (*Oreochromis niloticus*)	40 days	Concentrations of serum protein and globulin ↑ Respiratory burst activity ↑ lysozyme content (LC) ↑, myeloperoxidase (MPO) ↑and SOD activities ↑		Growth ↑		[114]
L. lactis LH8 (from marine fish)	Firmicutes	Diets 1.0 × 10^9 CFU g^{-1} (live)	Sea cucumber (*Apostichopus japonicus*)	30 days	The Rel, HSP90 and HSP60 were down-regulated firstly at 15 d and up-regulated at 30 d, and only CASP2 showed up-regulation at both timepoints with 5.86 fold at 15 d and 10.29 fold at 30 d. The survival rate (48.1%–64.8%) ↑ after of *V. splendidus* challenge.		Growth ↑		[98]
Paracoccus									
P-. marcusii DB11	Proteobacteria	Diets 1.0 × 10^8 CFU g^{-1} (live)	Juvenile sea cucumber (*Apostichopus japonicus*)	60 days	SOD, CAT, lysozyme, ACP, and alkaline phosphatase (ALP) activities ↑ The cumulative mortality ↓ (40%–0%) after *V. splendidus* challenge.				[64,134]
Pseudomonas									
P. stutzeri SC221-M (from a grass carp pond)	Proteobacteria	Diets 3.0 × 10^9 CFU g^{-1} (live)	Grass carp (*Ctenopharyngodon idellus*)	6 days				Improve both the water quality and microbial community structure in experimental aquaculture system.	[136]
P. stutzeri F11 (from a grass carp pond)	Proteobacteria	Add to water at dose of 1 × 10^5 CFU ml^{-1} (dead)	Grass carp (*Ctenopharyngodon idellus*)					Ammonia-N↓, nitrite-N↓, and total N levels↓ and alter the microbial community	[137]

Table 1 (*continued*)

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects — Disease resistance including immune improvements	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment — Water	Reference
Pseudoalteromonas									
P. monas sp. BC228 (from healthy *A. japonicas*)	Proteobacteria	Diets 10^5, 10^7 and 10^9 CFU g^{-1} (live)	Juvenile sea cucumber (*Apostichopus japonicus*)	45 days	Lysozyme and phenoloxidase activities ↑ Mortality↓	Intestinal trypsin and lipase activities ↑			[141]
P. piscicida SW-1 (from seawater from a clam farm)	Proteobacteria	Add to water at 10^7, 10^8, or 10^9 CFU ml^{-1} (live)	Clams	15 days	The mortality ↓ (100%–11%) after *V. alginolyticus* challenge.				[142]
Psychrobacter									
Psychrobacter sp. (from the gut of *Epinephelus coioides*)	Proteobacteria	Diets 1.0×10^8 CFU g^{-1} (live)	Grouper (*Epinephelus coioides*)	60 days	Phagocytic activity and phagocytic index ↑	Hepatopancreatic protease and lipase activities ↑ Intestinal amylase activity ↑	FCR ↑		[144]
Weissella									
Weissella confusa LS13	Firmicutes	Diets 1.0×10^9 CFU g^{-1} (live)	Sea cucumber (*Apostichopus japonicus*)	30 days	ACP activity, HSP60 and Rel ↑ Survival rate ↑ (48.1%–63.0%) after *V. splendidus* challenge.		Growth ↑		[98]
Yeast									
Hanseniaspora opuntiae C21 (from the intestine of healthy sea cucumber)	Ascomycota	Diets 1.0×10^4 CFU g^{-1} (live)	Juvenile sea cucumbers (*Apostichopus japonicus*)	50 days	Phagocytic, coelomocytes, lysozyme, phenoloxidase, T-NOS, SOD, AKP and ACP activities ↑ The cumulative mortality ↓ (50%–0%) after *V. splendidus* challenge.				[218]
Metschnikowia sp. C14 (from the intestine of sea cucumber *Apostichopus japonicus*)	Ascomycota	Diets 10^4, 10^5, 10^6 CFU g^{-1}	Sea cucumber (*Apostichopus japonicus*)	45 days	Phagocytic, lysozyme, phenoloxidase, T-NOS, SOD and AKP activities ↑. The cumulative mortality ↓ (30%–0%) after *V. splendidus* challenge.	Trypsin and lipase activities ↑	Growth ↑		[164]
Rhodotorula benthica D30 (from local sea mud)	Basidiomycota	Diets 1.0×10^6 and 1.0×10^7 CFU g^{-1} (live)	Juvenile sea cucumber (*Apostichopus japonicus*)		Lysozyme, phagocytic and total nitricoxide synthase activities ↑	Amylase, cellulase activity and alginase activities ↑	Growth ↑		[167]
Rhodotorula sp. C11 (from the intestine of healthy sea cucumbers collected from the waters around Bailanzi, Dalian, China)	Basidiomycota	Diets 1.0×10^4 CFU g-1 (live)	Sea cucumber (*Apostichopus japonicus*)		The cumulative prevalence and mortality of sea cucumbers fed diets supplemented with *Rhodotorula* sp. C11 were zero, which were lower than those of animals fed the control diet. In control animals, the prevalence of disease was 70% and the resulting mortality was 30%.		Growth ↑		[166]
	Basidiomycota			2 weeks			Growth ↑		[169]

| | | | | | | | | structure of the water. | |

Table 1 (*continued*)

A.

Strains (source)	Phylum	Effective does/mode of application	Target host	Duration	Probiotic effects — Disease resistance including immune improvements	Nutritional modulation	Productive effects and others	Improvement of aquaculture environment — Water	Reference
Rhodosporidium paludigenum (from coastal water at Zhanjiang, China)		Dry yeast at 1 g/100 g diet and (b) live yeast at 10^8 yeast cells (hemocytometer counts)/1 g diet	Pacific white shrimp (*Litopenaeus vannamei*)		Transcriptional expression of manganese superoxide dismutase (SODMn) and CAT actin ↑				
Rhodosporidium paludigenum (from coastal water at Zhanjiang, China r)	Basidiomycota	Diets dry yeast at 1 g/100 g diet and live yeast at 10^8 yeast cells (hemocytometer counts)/1 g diet	Pacific white shrimp (*Litopenaeus vannamei*)	6 weeks	T-AOC, CAT, SOD and GPX activities ↑		Growth ↑		[168]
Saccharomyces cerevisiae (obtain as commercial preparation, Actisaf (Lesaffre, France)	Ascomycota	Diet was incorporated with 1 g kg^{-1} of the yeast for a final concentration of 10^7 CFU g^{-1} of feeds (live)	Tilapia (*Oreochromis nilotica*)	8 weeks	Transcriptional expression of HSP70, TNFα and TNFβ ↓ AKP activity ↓.		Growth ↑		[159]

shrimp larvae [70]. Zhou et al. demonstrated that the superoxide dismutase (SOD) activity of tilapia (*Oreochromis mossambicus*) was increased significantly after treatment with *B. subtilis* B10 and *B. coagulans* B16 as water additives [25]. Furthermore, *Bacillus* has also been frequently reported to improve the water quality when applied as water additives. The *Bacillus* genus has nitrification and de-nitrification functions [75–77]. Liang et al. reported that supplementation of *B. licheniformis* BSK-4 removed nitrogen and modulated the microbial community in grass carp (*Ctenopharyngodon idellus*) pond water [27]. Wu et al. showed that *B. subtilis* FY99-01 improved the water quality by reducing the levels of pH, nitrite and soluble reactive phosphorus when added to the culture water of Pacific white shrimp. In addition, weekly addition of FY99-01 showed influence on the bacterial community of culture water. It increased the abundance of beneficial microalgae (Bacillariophyta and Chlorophyta), and decreased the abundance of Vibrionaceae on day 84 post initial addition [32].

2.3.2. Clostridium butyricum

Clostridium butyricum is Gram-positive, obligate anaerobic and endospore-forming probiotic, which can provide short-chain fatty acids (SCFAs) especially butyric acid for the regeneration and repair of the intestinal epithelium, and regulation of intestine micro-ecological environment [78,79]. Besides, *C. butyricum* can also adapt to lower pH and higher temperatures and is resistant to many antibiotics [80,81]. *C. butyricum* has been used as probiotic for the prevention of human and veterinary intestinal diseases [82], as well as in some aquaculture studies [33,83–85]. *C. butyricum* and its culture supernatants have preventive and therapeutic effect on *Salmonella enteritidis* and *V. parahaemolyticus* infection in fish intestinal epithelial cells (FIECs) [83], and heat-killed *C. butyricum* retain interesting immunomodulating properties in *Miichthys miiuy* [86]. Furthermore, diets supplemented with *C. butyricum* improved growth performance, immune response, and digestive enzyme activity in silver pomfret (*Pampus argenteus*) [84]. Later, Duan et al. reported that dietary *C. butyricum* had beneficial effect on the intestine health of *L. vannamei*, and promoted growth, increased epithelial cells height and SCFA content, enhanced intestine immune function against ammonia stress in *L. vannamei* [33,87,88]. Furthermore, they also revealed that *C. butyricum* could improve the growth performance, increase intestine antioxidant capacity of *M. japonicus* against high temperature stress [89], and modulate intestine digestive and metabolic capacities, improve intestine SCFA content and body crude protein content in *M. japonicus* [90].

2.3.3. Enterococcus

Enterococcus faecium strain has been proposed as probiotics for human use due to the antagonistic effect on enteroaggregative *Escherichia coli* [91]. Sun et al. isolated an *E. faecium* MM4 from the whole intestinal tract of healthy juvenile grouper [92]. This strain exhibited *in vitro* antagonism against *Vibrio metschnikovi, Vibrio harveyi* and *Staphylococcus aureus*, and improved the feed efficiency and immune response of groupers when added in feed [93–95]. Sha et al. revealed that the amylase and lipase activities were significantly increased in the intestines and hepatopancreas of *L. vannamei* fed with *E. faecium* NRW-2 [96]. Cui et al. identified two strains, *E. faecalis* LS1-2 and *E. faecium* Z1-2, which showed significant antimicrobial activities against shrimp pathogens and were suggested to be good candidates of shrimp probiotics [97]. Recently, the probiotic strain *E. faecalis* LC3 isolated from marine fish significantly improved the alkaline phosphatase (AKP) activity and up-regulated transcriptionalexpression of Rel, CASP2, HSP 90, HSP70 of sea cucumber [98].

2.3.4. Lactic acid bacteria (LAB)

Bacteria belonging to LAB are classified in phylum Firmicutes, class Bacilli and order Latobacillales. They can be isolated from intestine of numerous fish species, and their potential as probiotics was recently discussed in the comprehensive review of Ringø et al. [99].

2.3.4.1. Lactobacillus *Lactobacillus* supplementation was shown to improve growth and disease resistance of tilapia, and was recommended for commercial aquaculture production systems [100]. Wang et al. indicated that adding *Lactobacillus* into basal diet promoted growth performance, increased digestive enzyme activities, and enhanced non-specific immunity in shrimp [101]. Huang et al. reported that dietary supplementation of *Lactobacillus* improved antioxidant activity, immune capacity (serum acid phosphatase and lysozyme activity) and resistance of tilapia against *A. hydrophila* in a challenge trial [102]. Dietary optimal levels of *Lactobacillus delbrueckii* at $10^6–10^7$ CFU g^{-1} could effectively enhanced immunity, disease resistance against *A. hydrophila* antioxidant capability and growth performance in *Cyprinus carpio* Huanghe var [103]. Qin et al. demonstrated that *Lactobacillus casei* BL23 significantly increased fecundity in zebrafish (*Danio erio*) [104]. The administration of *Lactobacillus plantarum* could effectively improve the growth performance and anti-stress capacity of Pacific white shrimp [105–107]. Zheng et al. also revealed that dietary addition of *Lactobacillus pentosus* AS13 effectively enhance the growth performance, feed utilization, digestive enzymes and disease resistance of Pacific white shrimp [108]. Dietary supplementation of heat-killed *L. plantarum* L-137 (HK L-137) and *L. plantarum* LL11 improved growth, digestive enzyme activities and non-specific immune parameters of sea cucumber [98,109]. Yu et al. reported that *L. plantarum* CCFM639 significantly enhanced feed utilization and growth performance, while alleviated aluminum toxicity in tilapia [110]. Moreover, Zhai et al. reported that dietary *L. plantarum* CCFM8661 alleviated Pb-induced toxicity in Nile tilapia (*Oreochromis niloticus*) [111]. Gao et al. showed that *L. pentosus* supplemented to diets enhanced food intake and growth of abalones (*Haliotis discus hannai*), and improved the non-specific immunity (total number of blood lymphocytes, lysozyme activity, acid phosphatase (ACP), superoxide dismutase and transcriptional expression of Mn-superoxide dismutase (Mn-SOD) and thioredoxin peroxidase (TPx) and resistance of abalones against *V. parahaemolyticus* infection [112]. Xie et al. reported that a *L. plantarum* screened from the aquaculture environment has high nitrite removal ability, and suggested that *L. plantarum* could be promising microorganism for water purification in aquaculture [113].

2.3.4.2. Lactococcus lactis. In a study with tilapia, Zhou et al. revealed that *Lactococcus lactis* RQ516 enhanced growth and protected the fish against *A. hydrophila* infection [114]. *L. lactis* MM1 exhibited *in vitro* antagonistic activity against fish pathogens, such as *S. aureus*, *V. parahaemolyticus*, *V. harveyi*, and *V. metschnikovi* [93,115], and improved the feed utilization and immune responses (serum complement component 3 (C3) level and serum lysozyme activity) of juvenile grouper [95]. *L. lactis* LH8, isolated from marine fish, showed positive effects on immune response in sea cucumber [98].

2.3.4.3. Leuconostoc lactis *Leuconostoc lactis* isolated from the intestinal tract of black porgy (*Sparus microcephalus*), was evaluated as a potential probiotic strain for aquaculture [116]. The results showed that *Leu. lactis* had high tolerance to bile, low pH, trypsinase and pepsin conditions. Moreover, *in vitro* studies revealed that it co-aggregates with some pathogens, such as *V. parahaemolyticus*, *Listeria monocytogenes*, *E. coli* O157, *Salmonella typhimurium*, *Shigella*, *S. aureus* and *Proteusbacillus vulgaris* Although the strain was not tested *in vivo*, the author speculated that *Leu. lactis* might be a putative probiotic strain in marine aquaculture.

2.3.5. Weissella confusa

Weissella confusa strain LS13 isolated from marine animals (no specification given) by Li et al. showed inhibitory effects against some fish pathogens (*Vibrio splendius*, *V. anguillarum*, *V. parahaemolyticus* and *S. aureus*), but dietary *W. confusa* (WC group) showed no effect on growth performance, AKP, lysozyme and SOD activities in sea

cucumber [98]. However, ACP activity was significantly higher in the WC group *vs*. control. In WC group, heat shock protein 60 (HSP60) was the most up-regulated gene at day 30, but first it was down regulated at day 15. Similar expression pattern was noticed for NF-kappa-B transcription factor p65 (Rel), in contrast to heat shock protein 90 (HSP90) and nitric oxide synthase (NOS), which were down regulated at all-time points.

2.4. Proteobacteria

2.4.1. Aeromonas

Although *Aeromonas* species have typically been considered as opportunistic pathogens in the aquatic environment, several *Aeromonas* species are also commensal members in fish intestinal microbiota [117], and some of *Aeromonas* strains have been tested as potential probiotics in aquaculture. Dietary supplemented *Aeromonas veronii* BA-1 enhanced cellular (respiratory burst activity, phagocytic capacity) and humoral immune responses (serum protein, albumin, globulin values and lysozyme activity) and disease resistance of common carp against *A. hydrophila* infection [21]. Part of the immunostimulatory activity of *Aeromonas* spp. seems to reside in their extracellular products [23,72].

2.4.2. Bdellovibrio

Bdellovibrio and like organisms (BALOs) are a group of motile and parasitic proteobacteria that prey on other Gram-negative bacteria for growth, reproduction, and survival [118]. *Bdellovibrio* was approved for animal use by the Chinese Ministry of Agriculture in 1994, and BALOs have been tested as probiotic/biocontrol agents in aquaculture for many years [119]. *Bdellovibrio* and BALOs are known to (i) reduce the total bacterial number and/or *Vibrio* population in the rearing water [119–125], (ii) improve water quality [120], (iii) reduce bacterial infection in fish [125–127], and (iv) promote survival and growth [119,123–125].

2.4.3. Ectothiorhodospira

Ectothiorhodospira is a genus of photosynthetic purple sulfur bacteria, spiral cells of red color, depositing sulfur globules outside the cells [128]. *Ectothiorhodospira shaposhnikovii* WF was isolated from a marine shrimp pond and act both as bioremediation agent and nutrient source and can benefit white shrimp larvae at an appropriate dose [129].

2.4.4. Halomonas

Halomonas species demonstrated to play an important ecological role because of their abundance in hypersaline environments [130], and they are also very interesting for biotechnological purposes for producing exoenzymes and other substances of commercial interest [130,131]. Zhang et al. isolated a *Halomonas* sp. B12 from the intestine of shrimp (*Fenneropenaeus chinensis*). Dietary inclusion of the strain improved the resistance of shrimp to white spot syndrome virus (WSSV) in a challenge trial [132].

2.4.5. Paracoccus

Paracoccus marcusii DB11 was isolated from healthy sea cucumber intestines and culture ponds [133]. It has been shown to effectively reduce the concentrations of COD, ammonia, and nitrite in sea cucumber feed leachate [133] and inhibit the growth of *V. splendidus*, which causes skin ulceration syndrome in sea cucumbers. *P. marcusii* DB11 stimulated the immune system of juvenile sea cucumber and enhanced their resistance against *V. splendidus* [134]. Moreover, *P. marcusii* DB11 supplementation showed a positive effect on the growth performance and immune response in coelomocytes and the intestine of sea cucumbers [64].

2.4.6. Pseudomonas

Pseudomonas stutzeri is distributed widely in the environment,

occupying diverse ecological niches, and has been proposed as a model organism for denitrification studies [135]. *P. stutzeri* strain SC221-M improved both water quality and microbial community structure in farmed carp system [136]. Fu et al. showed that the addition of *P. stutzeri* F11 to an experimental grass carp aquaculture system decreased nitrogen levels and modulated water microbial community [137]. Moreover, the natural compounds produced by *Pseudomonas aeruginosa* also showed antagonistic activities against *Vibrio* pathogens, suggesting the potential of *P. aeruginosa* strains as probiotics to treat vibriosis [138,139].

2.4.7. Pseudoalteromonas

Pseudoalteromonas is a genus of marine bacteria. In a study with sea cucumber, 224 bacterial strains were isolated from the intestine [140]. One of the strains, *Pseudoalteromona selya kovii* HS1, improved total coelomocytes counts, respiratory burst activity, lysozyme activity, ACP activity, and phagocytic activity of sea cucumber when supplemented to the basal diet. Ma et al. revealed that marine *Pseudoalteromonas* sp. BC228 improved the digestive enzyme activities (trypsin and lipase activities), immune response (phagocytic and lysozyme activities) and disease resistance of juvenile sea cucumber against *V. splendidus* infection in a challenge trial [141]. Furthermore, *P. piscicida* SW-1, isolated from seawater in a clam farm, was proved to protect clams from the infection of *V. alginolyticus* (V.-MP-1), indicating that SW-1 could be used as a probiotic to protect farmed clams [142].

2.4.8. Psychrobacter

Genus *Psychrobacter* belongs to the family Moraxellaceae and has been reported as commensal members in the GI tract of several fish species [36,92,143], and can inhibit *in vitro* growth of *Vibrio anguillarum* and *Aeromonas salmonicida* [143]. In an *in vitro* study, *Psychrobacter* sp. SE6, isolated from the gut of fast-growing grouper showed antagonistic activity against *V. harveyi*, *V. metschnikovi* and *Vibrio alginolyticus* [92]. In a subsequent 60-day feeding trial, dietary supplementation of *Psychrobacter* sp. SE6 significantly improved feed conversion ratio and complement 4 (C4) of juvenile grouper [144]. Further, Yang et al. evaluated the effect of dietary *Psychrobacter* sp. SE6 on the auto-chthonous (adherent) microbial diversity in fore-, mid- and hindgut of grouper, and revealed that samples from the probiotic group displayed different DGGE patterns compared with control group. Total number of bands and Shannon index of the fore-, mid- and hindgut samples in the probiotic group were significantly higher than those in the control group. Some potentially beneficial bacteria were stimulated, while some potentially harmful species, such as *Staphylococcus saprophyticus*, were suppressed [145]. Furthermore, Xia et al. showed that both the viable and heat-inactivated *Psychrobacter* sp. SE6 revealed positive effects on feed utilization and immunity in grouper [146].

2.4.9. Rhodopseudomonas

A photosynthetic purple non-sulfur bacterial strain, *Rhodopseudomonas palustris* G06, improved the growth performance of juvenile white shrimp when administered as a water additive [147]. *R. palustris* G06 furthermore increased growth and immune function of tilapia when added to the water [25]. Wang also reported that dietary supplemented *R. palustris* improved growth performance of grass carp fingerlings [148]. Moreover, Zhang et al. reported that adding *R. palustris* to grass carp water significantly reduced the nitrogen levels as it modulates the microbial community [149].

2.4.10. Shewanella

Shewanella species are facultatively anaerobic Gram-negative rods, most of which are found in extreme aquatic habitats [150]. *Shewanella* bacteria are a normal component of the surface and intestinal microbiota of fish, and are implicated in fish spoilage [151]. The use of *Shewanella* as probiotics has been reported in various aquatic species. Jiang et al. isolated *Shewanella colwelliana* WA64 and *Shewanella*

olleyana WA65 from the gut of abalone [152]. Dietary supplementation of WA64 and WA65 promoted growth, enhanced cellular and humoral immune responses of abalone, and decreased mortality of juvenile abalone after challenge with *V. harveyi* [153]. Similarly, *S. japonica* HS7 isolated from the intestine of healthy sea cucumber enhanced growth, survival, and cellular and humoral immune responses of sea cucumber when added in diet at 10^9 cell g^{-1} [140]. Hao et al. showed that *S. haliotis* D4 improved growth, innate immunity (respiratory burst, SOD and ACP activities; expression of prophenoloxidase and beta-1, 3-glucan-binding protein) and disease resistance of Pacific white shrimp [72]. The same authors further showed that dietary administration of *S. xiamenensis* A-1 and *S. xiamenensis* A-2 improved the composition of intestinal microbial community and enhanced the immunity in grass carp [23,154].

2.4.11. Vibrio

Although isolates of *Vibrio* spp. are commonly believed to be pathogenic for aquatic animals [155], some avirulent strains have been suggested to have probiotic properties [156,157]. It has been reported that *Vibrio* sp. V33 isolated from healthy sepia has strong antagonistic activity against pathogenic *V. splendidus* Vs [158]. Chi et al. isolated a *V. tasmaniensis* strain HS10 from the intestine of sea cucumber, and dietary supplementation of the strain improved the humoral and cellular immune response of sea cucumber [140].

2.5. Non-bacterial candidates

2.5.1. Yeast

2.5.1.1. Saccharomyces.
Saccharomyces cerevisiae is the most commonly used yeast probiotic in aquaculture. Ran et al. proved that live yeast, *Saccharomyces cerevisiae*, significantly increased gut microvilli length and trypsin activity, decreased intestinal *hsp70* expression, and enhanced resistance of tilapia (*Oreochromis mossambicus*) against *A. hydrophila* infection in a challenge trial. Apart from live yeast, the fermentation product of *S. cerevisiae* has also been widely used, and some have been developed as commercial products [159]. He et al. showed that supplementation of the *S. cerevisiae* fermentation product DVAQUA® improved the immunity of hybrid tilapia (*Oreochromis mossambicus*) [160]. In a study with common carp, Huang et al. reported that dietary supplementation of 1 g kg^{-1} Saccharoculture (a Korean-made *S. cerevisiae* culture product containing 10^7 CFU g^{-1} *B. amyloliquefaciens* spores) improved the posterior intestinal microvillus length and general welfare of the fish [161].

2.5.1.2. Marine yeasts.
A series of studies have used marine yeasts as probiotics in sea cucumber. Li et al. isolated *Hanseniaspora opuntiae* C21 from the intestine of healthy sea cucumber. The strain showed *in vitro* antagonism against the growth of the pathogen *Shewanella marisflavi* AP629 [162]. Diet supplementation with *H. opuntiae* C21 at 10^4 and 10^5 CFU g^{-1} improved growth, immunity, and resistance against *V. splendidus* in juvenile sea cucumber [163]. The marine yeast *Metschnikowia* sp. C14, isolated from the intestine of sea cucumber, stimulated the immune system of juvenile sea cucumber and enhanced resistance against *V. splendidus* infection [164]. Furthermore, *Metschnikowia* sp. C14 was also reported to improve the growth and activity of intestinal digestive enzymes (trypsin and lipase) of juvenile sea cucumber [165]. The marine yeast *Rhodotorula* sp. C11, isolated from the intestine of the sea cucumber, inhibited growth of the pathogen *V. splendidus* NB13 *in vitro* [166], and further use revealed that *Rhodotorula* sp. C11 effectively colonized the intestine of Japanese spiky sea cucumbers and improved growth and disease resistance against *V. splendidus* in a challenge trial. Similarly, Wang et al. used a *Rhodotorula benthica* D30 isolated from sea mud, and supplemented the strain in feed at 10^6 CFU g^{-1} and 10^7 CFU g^{-1}. Results showed that *R. benthica* D30 can increase growth, digestive enzymes activity, immunity, and disease resistance of sea cucumber against *V.*

splendidus infection [167].

Yang et al. (2010) isolated the marine red yeast *Rhodosporidium paludigenum* from coastal water in Zhejiang, China. Dietary inclusion of *R. paludigenum* at 10^8 CFU g^{-1} enhanced growth and antioxidant capacity (SOD, catalase, glutathione peroxidase, total antioxidant capacity) of Pacific white shrimp [168]. Later, the same authors studied the expression of genes related with antioxidant function in Pacific white shrimp fed dry or live *R. paludigenum,* and the results showed a significant up-regulation of genes coding for manganese superoxide dismutase (SODMn), catalase, glutathione peroxidase, and ferritin, which are all important elements of the antioxidant defense system [169].

2.6. Mixture of probiotic strains

In his review "*Probiotics in man and animals*", Fuller stated; "*Probiotic preparations may consist of single strains or may contain any number up to eight strains*" [170]. Most probiotic studies have used single administration in Chinese aquaculture, but inclusion of multiple probiotics have gained interest during the last decade [30,72,136,154,171–173]. The advantage by using multiple-strain preparations is that they may further improve the overall beneficial effect of the probiotic formulation and are active against wider range of conditions and species.

A dietary commercial probiotic product (Qingdao Master Biotechnology Co. Ltd., Qingdao, China) containing *B. subtilis* 7.0×10^9 CFU g^{-1}, *B. licheniformis* 3.0×10^9 CFU g^{-1}, *Lactobacillus* spp. 5.0×10^8 CFU g^{-1} and *Arthrobacter* spp. 1.0×10^8 CFU g^{-1} significantly increased the specific growth rate (SGR), innate immunity, and resistance against *V. harveyi* in cobia (*Rachycentron canadum*) [171]. A mixed preparation of *B. cereus* BSC24 and *P. stutzeri* SC221-M was more efficient in removing nitrogen from grass carp culture water than supplementation of SC221-M or BSC24 alone, i.e., 53.9% for the mixture versus 24.5% and 26.6% for SC221-M and BSC24, respectively [136]. Hao et al. revealed that shrimps fed *S. haliotis* D4, *B. cereus* D7 and *Aeromonas bivalvium* D15 at a ratio of 2:1:1, dosed at 10^7 cell g^{-1}, showed better growth performance and disease resistance compared with those fed single probiotics [72]. Wu et al. demonstrated that dietary supplementation of a mixture of *S. xiamenensis* A-1, *S. xiamenensis* A-2, and *A. veronii* A-7 at 10^8 cell g^{-1}, at a ratio of 4:2:1, resulted in more improved innate immunity and disease resistance compared to single fed probiotics [154]. Li et al. reported that a dietary probiotics mixture of *B. subtilis* YB-1 and *B. cereus* YB-2 stimulated non-specific immune responses and enhanced the growth performance and resistance against *V. alginolyticus* infection *vs.* the control group [30]. Dietary combination of *B. cereus*, *L. acidophilus* and *C. butyricum* at 3.0×10^9 CFU kg^{-1} significantly improved final weight, SGR, food consumption, food conversion efficiency and apparent digestibility coefficient, and enhanced the activity of digestive enzymes (pepsin, trypsin, amylase and lipase), anti-oxidant enzymes (superoxide dismutase, catalase and glutathione peroxidase), and lysozyme of hybrid grouper (*Epinephelus lanceolatus* ♂ × *fuscoguttatus* ♀) compared to control [173]. Liu et al. proved that dietary supplementation with 3% complex-probiotics-preparation (BSCP, including *B. amyloliquefaciens* V4CGMCC 10149 and *Rhodotorula mucilaginosa* CGMCC 1013) improved the growth performance, enhanced the activities of some digestive enzymes, and promoted the nonspecific immunity of Atlantic salmon (*Salmo salar* L.) [174].

2.7. Synbiotics

Synbiotics refers to nutritional supplements combining a mixture of probiotics and prebiotics in a form of synergism. Gibson and Roberfroid defined synbiotics to '*characterize some colonic foods with interesting nutritional properties that make these compounds candidates for classification as health-enhancing functional ingredients*' [175]. In aquaculture the first finfish study on synbiotics was published by Rodriguez-Estrada et al. [176], and since then several studies have emerged [177–181].

In Chinese aquaculture several studies have used synbiotics. Zhang et al. revealed that dietary supplementation of *B. subtilis* (10^7 CFU g^{-1}) and 0.25% fructooligosaccharide (FOS) significantly increased SGR, total coelomocytes counts (TCC), phagocytosis, and disease resistance of sea cucumbers against *V. splendidus* infection [182]. Moreover, the counts of total viable bacteria were increased by supplementation of *B. subtilis* (10^7 CFU g^{-1}) and 0.25% FOS, whereas *Vibrio* counts were decreased. Dietary *B. licheniformis* (10^7 CFU g^{-1}) and 0.3% FOS significantly enhanced the innate immunity and antioxidant capability of triangular bream (*Megalobrama terminalis*), and improved its resistance against *A. hydrophila* in a challenge trial [183]. In a study with juvenile ovate pompano, Zhang et al. showed that dietary administration of *B. subtilis* (10^7 CFU g^{-1}) and FOS (0.2% and 0.4%) had significant interaction on enhancing SGR, respiratory burst activity, lysozyme activity and disease resistance against *V. vulnificus* compared to control. Supplementation with *B. licheniformis* and xylo-oligosaccharide at 0.1% of diet increased weight gain by 20.9% with a 8.9% lower food conversion ratio in grass carp juveniles compared to controls [184]. The synbiotics fed fish also revealed higher intestinal activity of trypsin (18.8%), amylase (36.8%) and lipase (19.8%) activities. Zhang et al. showed significant improvement of finial weight, WG, SGR, survival rate as well as protease and Na$^+$, K$^+$-ATPase activities of triangular bream (*Megalobrama terminalis*) fed *B. licheniformis* and FOS *vs.* control fed fish [185].

Zhang et al. revealed that a mixture of 10^8 CFU g^{-1} *B. licheniformis*, *B. subtilis* and 0.2% isomaltooligosaccharide (IMO) improved immune activities (phenoloxidase, lysozyme, NOS activity, superoxide dismutase activities) and disease resistance against *V. alginolyticus* infection of shrimp (*Penaeus japonicus*) compared to the control group [186]. Hu et al. showed that combined use of *Bacillus* and molasses increased the diversity of the microbial community, and promoted the formation and development of a beneficial microbial community structure and inhibited pathogens in Pacific white shrimp [187]. Dietary *B. coagulans* (10^9 CFU g^{-1}) and 0.2% chitosan oligosaccharides (COS) had a synergistic effect in enhancing immunity (total leukocyte count, respiratory burst activity, phagocytic activity, lysozyme, SOD) and disease resistance against *A. veronii* infection of common carp (*Cyprinus carpio* koi) [188]. Feeding sea cucumber *B. lincheniformis* WS-2 (10^9 CFU g^{-1}) and alginate oligosaccharides (AOS) improved growth, activity of digestive enzymes (amylase, protease and alginate lyase), non-specific immune response, intestinal *Bacillus* and *Lactococcus* levels, and resistance against *V. splendidus* infection [189]. Ye et al. revealed that diets supplemented with FOS, Maltooligosaccharide (MOS) and *B. clausii* (10^7 cell g^{-1}) improved growth performance and health benefits of the Japanese flounder (*Paralichthys olivaceus*) compared to the control [190]. Geng et al. demonstrated that combination of 1.0 g *B. subtilis* kg^{-1} and 6.0 g chitosan kg^{-1} is the optimal inclusion level of cobia (*Rachycentron canadum*) for growth, innate immunity (lysozyme, ACP, phagocytosis and respiratory burst), and resistance against *V. harveyi* infection [191].

3. Mode of action

3.1. Production of digestive enzymes

Higher enzyme activities in the digestive tract enhance digestive capabilities and growth performance of the host. It is widely accepted that the activity of digestive enzymes is a useful comparative indicator for food utilization, digestive capacity, and growth performance of the host [177]. Gao et al. demonstrated a likely correlation between higher growth rate and higher intestinal digestive enzyme activity in probiotic fed silver pomfret (*Pampas argenteus*). They suggested the main cause was better utilization and digestion of the diets [31]. Previous studies have shown that many *Bacillus* spp. with exo-enzyme activities can significantly improve the host's growth performance [63,67,192,193], which may be attributed to the production of digestive enzymes.

A. Wang et al.

3.2. Production of antibacterial substances

In vitro antagonism against aquatic pathogens has been an important selection criterion for candidate probiotics for aquaculture use. The nature of antimicrobial compounds that are responsible for the antagonistic activity of probiotics have been investigated in several studies in the past decade. Yang et al. reported that two strains of LAB (*Lactococcus lactis* MM1 and MM4) can secrete hydrogen peroxide and bacteriocin-like substances, which have strongly inhibitory activities against pathogens, i.e., *V. metschnikovi*, *V. harveyi* and *S. aureus* that infects orange-spotted grouper [115]. Xu et al. purified lipopetides N3 produced by *B. amyloliquefaciens* M1, whish displayed strong anti-*Vibrio* action on the whole cells and cell membrane. Further, this antibacterial actions of lipopeptide N3 could be a consequence of its ability to form ion-conducting channels in bacterial cell membranes by exploiting its detergent-like action on cell membranes, also called membrane active properties [194]. In recent study, Gao et al. revealed that *B. pumilus* H2 had considerable anti-*Vibrio* activity and the major mechanism appeared to involve disruption of cell membranes and consequent cell lysis relating to an anti-*Vibrio* substance named amicoumacin A [195]. Gao et al. also identified several anti-*A. salmonicida* compounds belonging to the iturin, macrolactin, and difficidin groups from cell-free supernatant of *B. velezensis* V4. These compounds contributed collaboratively to *in vitro* growth inhibition of *A. salmonicida*. The diversity of the compounds was related to the versatility of their mode of action, especially the membrane disruptive effect of iturin group members [196]. *C. butyricum* and its spent culture supernatants inhibited growth and adherence to fish intestine epithelial cells (FIECs) of *Salmonella enteritidis* and *V. parahaemolyticus*. It was hypothesized that these antibacterial functions were related to the organic acids produced by *C. butyricum* which lowered the pH in the intestine [83].

3.3. Immune stimulation

Numerous publications have shown that probiotics stimulate the immune system [99,197]. However, the mechanisms underlying the immune stimulation effect of probiotics have been less investigated. Sun et al. showed that feeding viable and heat-inactivated *Psychrobacter* sp. SE6 to grouper had interesting effects on the intestinal immune responses. The expression of TLR2 and TLR5, adaptor MyD88 and cytokines (IL-1β, IL-8 and TGF-β1) was upregulated when fed the viable SE6. In fish fed heat-inactivated SE6, only TLR2 was upregulated but not MyD88 and cytokines. This suggested that a MyD88-independent TLR2 signaling pathway may be involved in the probiotic recognition in grouper [198]. In a recent study, Qin et al. revealed that *L. casei* BL23 protected zebrafish larvae from *A. veronii* infection. Further data indicated that *L. casei* BL23 enhanced host immune responses, which may be attributable to exopolysaccharide-protein complex (EPSP) from BL23 via TLR1/TLR2 pathways [104].

Moreover, SCFAs and their salts showed immune stimulatory effect when used as feed additives in fish [199,200]. Therefore, the involvement of SCFAs in the immunostimulatory effect of aquatic probiotics deserves more investigation. Moreover, isolation and characterization of SCFAs-producing commensal microbes in the intestine of fish may bring about novel aquatic probiotics.

3.4. Interference of quorum sensing

Quorum sensing (QS) is a cell density dependent process that enables bacteria to communicate with each other based on the production, secretion and sensing of the auto-inducer molecules and then subsequently regulate virulence associated gene expression [201]. Interrupting quorum sensing may represent a novel alternative approach to combat bacterial pathogens. Some bacteria can produce quorum quenching (QQ) enzymes. The approach has been recommended as a promising non-antibiotic strategy for bacterial disease therapy

[201–203]. *N*-Acyl-homoserine lactones (AHLs) are the main signal molecules produced by many Gram-negative bacteria, such as the aquatic pathogens *Vibrio* spp. and *Aeromonas* spp. [204]. The probiotic strain *Bacillus* sp. QSI-1, isolated from the gut of a healthy crucian (*Carassius auratus gibelio*), has been reported to protect fish from *A. hydrophila* infection [205]. Zhou et al. demonstrated that quorum quenching probiotics *Bacillus* sp. QSI-1 can modulate the gut microbiota community by degrading AHLs [50]. The authors also revealed a reduction in the abundance of the fish pathogen *A. hydrophila* in the GI tract. These results indicated that QSI-1 protect fish from *A. hydrophila* infection by quorum quenching. These results provide new insight into the mechanisms of probiotics, and suggest that quorum quenching probiotics can be used as an alternative strategy to combat bacterial infection in aquaculture instead of antibiotics.

3.5. Competition for adhesion sites

Competition of adhesion sites has been reported in several studies. Zhou et al. evaluated the GI tract adhesion property of ten *Lactobacillus* strains [206]. They observed that while having similar antibacterial activity *in vitro*, the highly-adhesive strain *L. plantarum* JCM 1149T conferred stronger resistance against *A. hydrophila* infection in zebrafish compared with the less-adhesive strain *L. acidophilus* JCM 1132T. Further, an *ex vivo* intestinal sac experiment showed that *L. plantarum* JCM 1149T can compete for intestinal adhesion sites with *A. hydrophila* and alleviated gut mucosa damage caused by *A. hydrophila* [207]. These results highlight GI tract adhesion (adhesion to mucosa) as the favorable criterion in the selection of dietary probiotics in aquaculture, which may confer the probiotics disease resistance property through competition for adhesion sites with the pathogens.

4. Regulation and safety issues

According to the catalogue of feed additives authorized by Chinese Ministry of Agriculture (2013), probiotics permitted to be supplemented in animal feed include bacteria, and fungi (for example yeast). The permitted bacterial genera include *Lactobacillus*, *Bacillus*, *Enterococcus, Pediococcus*, etc., while yeast permitted for use as feed additive mainly includes *Saccharomyces cerevisiae*. For further regulation, an industry standard is needed to normalize the production and usage of related products. Notably, there is no specific regulation in China for probiotics used to improve pond water and sediments, and the commercial probiotic products for this purpose are not well managed in the current stage, which deserves attention.

Although probiotics are used as alternatives of antibiotics, much attention has been directed to the production of inhibitory substances in the selection and study of aquaculture probiotics. It has been indicated that the antagonistic effects of *Bacillus* strains against aquatic pathogens were attributed to the production of antibiotics difficidin and surfactin [208], implying that the use of some *Bacillus* strains as probiotics in aquaculture might induce the same problems as antibiotics usage. As proposed by Gatesoupe, the risk to select probiotic-resistant pathogens should not be underestimated [46]. Moreover, the risk of transferring antibiotic resistance from probiotics to pathogenic bacteria should not be neglected, as some probiotic *Lactobacillus* stains have been reported to transfer antibiotic resistance genes *in vitro* and in rodent models [209,210]. In addition, previous studies have revealed that administration suspension (including cessation) of *Lactobacillus* strains may lead to gut dysbiosis and increase pathogen susceptibility of hybrid tilapia [211]. Furthermore, He et al. showed that *L. rhamnosus* GG, a well-known probiotic for humans, induced injury to the mucosa of zebrafish when applied as a probiotic strain for disease protection [212]. Similarly, a *Lactobacillus plantarum* strain originally isolated from Sabalan cheese induced damaged epithelial cells and disorganized microvilli in the intestine of beluga (*Huso huso*) [213]. Both of the studies indicated that a probiotic that is safe for human and terrestrial

animals may not be safe for aquatic animals. Consequently, the safety of potential aquaculture probiotics should be carefully evaluated in aquatic animal models.

5. Selection criteria and perspectives

The probiotics for aquatic usage -are different from probiotics for terrestrial animals, as certain influencing factors are fundamentally different from terrestrial probiotics. Therefore, a selection criteria list specific for aquatic probiotics is highly important. Previous reviews have proposed selection criteria for aquatic probiotics [13,14,214–216]. Following on from these papers we propose the basic criteria for aquatic probiotics: 1) Safety. The strain must be safe for both the aquatic host and human, with no plasmids encoded antibiotic resistance genes. 2) Adaptability. The strain should survive the intestinal tract of aquatic host. Colonization and persistence in the intestine are preferred quality but are not required. For water additive, the strain should survive in the aquatic environment. 3) Function. The strain should benefit the aquatic host. The beneficial effect can be on growth, digestion, immunity, disease resistance, or general welfare. For water additive, the strain should be able to improve water quality or sediments. 4) Convenience. The strain should be convenient for storage and administration. Based on these criteria, an authorized catalogue for probiotics permitted for aquatic animal use will promote the regulation of this field.

Although many studies about probiotics in aquaculture have emerged in China, the approach has been generally empirical. Moreover, the mechanisms underlying the beneficial effects of probiotics in aquatic systems are rarely studied, and the potential harmful effects of some probiotics have been generally neglected. Further studies are warranted to elucidate the mechanism of the beneficial effects and potential harmful effects of the probiotics, which may guide the selection and function-oriented manipulation/design of more efficacious and safe aquaculture probiotics. In addition, given the potential drawbacks of probiotics, administration of the probiotic effector ingredients might be a better way to obtain the health benefits associated with probiotic consumption [217]. The probiotic effectors include the structural components of the probiotic cells and secretory components such as metabolites, enzymes and functional proteins. In-depth study of well-accepted probiotic strains will promote the finding of probiotic effectors, and further topics involving the probiotic effectors may include structure-activity relationship (SAR) as well as synergy among different effectors.

Acknowledgments

References

[1] C.E. Boyd, C.S. Tucker, Pond Aquaculture Water Quality Management, Springer Science & Business Media, 2012.

[2] C.M. Moffitt, L. Cajas-Cano, Blue growth: the 2014 FAO state of world fisheries and aquaculture, Fisheries 39 (11) (2014) 552–553.

[3] S.H. Hoseinifar, Y. Sun, A. Wang, Z. Zhou, Probiotics as means of diseases control in aquaculture, A Review of current knowledge and future perspectives, Front. Microbiol. 9 (2018) 2429.

[4] I. Sommerset, B. Krossøy, E. Biering, P. Frost, Vaccines for fish in aquaculture, Expert Rev. Vaccines 4 (1) (2005) 89–101.

[5] Y. Huang, L. Zhang, L. Tiu, H. Wang, Characterization of antibiotic resistance in commensal bacteria from an aquaculture ecosystem, Front. Microbiol. 6 (2015) 914.

[6] J. Romero, C.G. Feijoó, P. Navarrete, Antibiotics in aquaculture–use, abuse and alternatives, Health and environment in aquaculture, in: Edmir Carvalho (Ed.), Health and Environment in Aquaculture, InTech, 2012, pp. 159–198.

[7] H. Chen, S. Liu, X. Xu, S. Liu, G. Zhou, K. Sun, J. Zhao, G. Ying, Antibiotics in

[8] typical marine aquaculture farms surrounding Hailing Island, South China: occurrence, bioaccumulation and human dietary exposure, Mar. Pollut. Bull. 90 (1–2) (2015) 181–187.

[8] W. Xiong, Y. Sun, T. Zhang, X. Ding, Y. Li, M. Wang, Z. Zeng, Antibiotics, antibiotic resistance genes, and bacterial community composition in fresh water aquaculture environment in China, Microb. Ecol. 70 (2) (2015) 425–432.

[9] S.H. Hoseinifar, M. Dadar, E. Ringø, Modulation of nutrient digestibility and digestive enzyme activities in aquatic animals: the functional feed additives scenario, Aquacult. Res. 48 (8) (2017) 3987–4000.

[10] W.h. organization, Health and nutritional properties of probiotics in food including powder milk with live lactic acid bacteria, a joint FAO/WHO expert consultation. Cordoba, Argentina, 1-4 October 2001, http://www.who.int/foodsafety/publications/fs_management/probiotics/en/index.html, (2002).

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

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

[13] A. Farzanfar, The use of probiotics in shrimp aquaculture, FEMS Immunol. Med. Microbiol. 48 (2) (2006) 149–158.

[14] D.L. Merrifield, A. Dimitroglou, A. Foey, S.J. Davies, R.T. Baker, J. Bøgwald, M. Castex, E. Ringø, The current status and future focus of probiotic and prebiotic applications for salmonids, Aquaculture 302 (1–2) (2010) 1–18.

[15] A. Irianto, B. Austin, Probiotics in aquaculture, J. Fish. Dis. 25 (11) (2002) 633–642.

[16] S. Salminen, A. Ouwehand, Y. Benno, Y. Lee, Probiotics: how should they be defined ? Trends Food Sci. Technol. 10 (3) (1999) 107–110.

[17] Y. Wang, J. Li, J. Lin, Probiotics in aquaculture: challenges and outlook, Aquaculture 281 (1–4) (2008) 1–4.

[18] Z. Qi, X. Zhang, N. Boon, P. Bossier, Probiotics in aquaculture of China - current state, problems and prospect, Aquaculture 290 (1–2) (2009) 15–21.

[19] A. Newaj-Fyzul, A.H. Al-Harbi, B. Austin, Review: developments in the use of probiotics for disease control in aquaculture, Aquaculture 431 (2014) 1–11.

[20] N.V. Hai, The use of probiotics in aquaculture, J. Appl. Microbiol. 119 (4) (2015) 917–935.

[21] C. Chi, B. Jiang, X. Yu, T. Liu, L. Xia, G. Wang, Effects of three strains of intestinal autochthonous bacteria and their extracellular products on the immune response and disease resistance of common carp, Cyprinus carpio, Fish Shellfish Immunol. 36 (1) (2014) 9–18.

[22] H. Wu, L. Sun, C. Li, Z. Li, Z. Zhang, X. Wen, Z. Hu, Y. Zhang, S. Li, Enhancement of the immune response and protection against Vibrio parahaemolyticus by indigenous probiotic Bacillus strains in mud crab (Scylla paramamosain), Fish Shellfish Immunol. 41 (2) (2014) 156–162.

[23] K. Hao, Z. Wu, D. Li, X. Yu, G. Wang, F. Ling, Effects of dietary administration of Shewanella xiamenensis A-1, Aeromonas veronii A-7, and Bacillus subtilis, single or combined, on the grass carp (Ctenopharyngodon idella) intestinal microbiota, Probiotics Antimicro 9 (4) (2017) 386–396.

[24] M. Wang, G. Liu, M. Lu, X. Ke, Z. Liu, F. Gao, J. Cao, H. Zhu, M. Yi, D. Yu, Effect of Bacillus cereus as a water or feed additive on the gut microbiota and immunological parameters of Nile tilapia, Aquacult. Res. 48 (6) (2017) 3163–3173.

[25] X. Zhou, Z. Tian, Y. Wang, W. Li, Effect of treatment with probiotics as water additives on tilapia (Oreochromis niloticus) growth performance and immune response, Fish Physiol. Biochem. 36 (3) (2010) 501–509.

[26] Y. Wang, L. Fu, J. Lin, Probiotic (Bacillus coagulans) cells in the diet benefit the white shrimp Litopenaeus vannaemei, J. Shellfish Res. 31 (3) (2012) 855–860.

[27] Q. Liang, X. Zhang, K.H. Lee, Y. Wang, K. Yu, W. Shen, L. Fu, M. Shu, W. Li, Nitrogen removal and water microbiota in grass carp culture following supplementation with Bacillus licheniformis BSK-4, World J. Microbiol. Biotechnol. 31 (11) (2015) 1711–1718.

[28] W. Li, X. Zhang, W. Song, B. Deng, Q. Liang, L. Fu, J. Zheng, Y. Wang, D. Yu, Effects of Bacillus preparations on immunity and antioxidant activities in grass carp (Ctenopharyngodon idellus), Fish Physiol. Biochem. 38 (6) (2012) 1585–1592.

[29] Y. Xu, Y. Wang, J. Lin, Use of Bacillus coagulans as a dietary probiotic for the common carp, Cyprinus carpio, J. World Aquacult. Soc. 45 (4) (2014) 403–411.

[30] J. Li, Y. Xu, L. Jin, X. Li, Effects of a probiotic mixture (Bacillus subtilis YB-1 and Bacillus cereus YB-2) on disease resistance and non-specific immunity of sea cucumber, Apostichopus japonicus (Selenka), Aquacult. Res. 46 (12) (2015) 3008–3019.

[31] Q. Gao, C. Xiao, M. Min, C. Zhang, S. Peng, Z. Shi, Effects of probiotics dietary supplementation on growth performance, innate immunity and digestive enzymes of silver pomfret, Pampas argenteus, Indian J. Anim. Res. 50 (6) (2016) 936–941.

[32] D. Wu, S. Zhao, N. Peng, C. Xu, J. Wang, Y. Liang, Effects of a probiotic (Bacillus subtilis FY99-01) on the bacterial community structure and composition of shrimp (Litopenaeus vannamei, Boone) culture water assessed by denaturing gradient gel electrophoresis and high-throughput sequencing, Aquacult. Res. 47 (3) (2016) 857–869.

[33] Y. Duan, Y. Zhang, H. Dong, Y. Wang, X. Zheng, J. Zhang, Effect of dietary Clostridium butyricum on growth, intestine health status and resistance to ammonia stress in Pacific white shrimp Litopenaeus vannamei, Fish Shellfish Immunol. 65 (2017) 25–33.

[34] E. Ringø, S. Sperstad, R. Myklebust, S. Refstie, Å. Krogdahl, Characterisation of the microbiota associated with intestine of Atlantic cod (Gadus morhua L.): the effect of fish meal, standard soybean meal and a bioprocessed soybean meal, Aquaculture 261 (3) (2006) 829–841.

[35] S.K. Nayak, Role of gastrointestinal microbiota in fish, Aquacult. Res. 41 (11)

(2010) 1553–1573.

[36] C. Ramírez, J. Romero, Fine flounder (*Paralichthys adspersus*) microbiome showed important differences between wild and reared specimens, Front. Microbiol. 8 (2017) 271.

[37] J. Li, B. Tan, K. Mai, Q. Ai, W. Zhang, W. Xu, Z. Liufu, H. Ma, Comparative study between probiotic bacterium *Arthrobacter* XE-7 and chloramphenicol on protection of *Penaeus chinensis* post-larvae from pathogenic *vibrios*, Aquaculture 253 (1–4) (2006) 140–147.

[38] Z. Xia, M. Zhu, Y. Zhang, Effects of the probiotic *Arthrobacter* sp. CW9 on the survival and immune status of white shrimp (*Penaeus vannamei*), Lett. Appl. Microbiol. 58 (1) (2014) 60–64.

[39] Y. Zhang, K. Tang, X. Shi, X. Zhang, *Flaviramulus ichthyoenteri* sp nov., an N-acylhomoserine lactone-degrading bacterium isolated from the intestine of a flounder (*Paralichthys olivaceus*), and emended descriptions of the genus *Flaviramulus* and *Flaviramulus basaltis*, Int. J. Syst. Evol. Microbiol. 63 (2013) 4477–4483.

[40] Y. Zhang, J. Liu, K. Tang, M. Yu, T. Coenye, X. Zhang, Genome analysis of *Flaviramulus ichthyoenter*i Th78T in the family Flavobacteriaceae: insights into its quorum quenching property and potential roles in fish intestine, BMC Genomics 16 (38) (2015) (5 February 2015)-(5 February 2015).

[41] E. Ringø, Z. Zhou, J.G. Vecino, S. Wadsworth, J. Romero, Å. Krogdahl, R. Olsen, A. Dimitroglou, A. Foey, S. Davies, Effect of dietary components on the gut microbiota of aquatic animals. A never-ending story? Aquacult. Nutr. 22 (2) (2016) 219–282.

[42] R. She, T. Li, D. Luo, J. Li, L. Yin, H. Li, Y. Liu, X. Li, Q. Yan, Changes in the intestinal microbiota of gibel carp (*Carassius gibelio*) associated with cyprinid herpesvirus 2 (CyHV-2) infection, Curr. Microbiol. 74 (10) (2017) 1130–1136.

[43] N.T. Tran, J. Zhang, F. Xiong, G. Wang, W. Li, S. Wu, Altered gut microbiota associated with intestinal disease in grass carp (*Ctenopharyngodon idellus*), World J. Microbiol. Biotechnol. 34 (6) (2018) 71.

[44] A. Nematollahi, A. Decostere, F. Pasmans, F. Haesebrouck, *Flavobacterium psychrophilum* infections in salmonid fish, J. Fish. Dis. 26 (10) (2003) 563–574.

[45] A.M. Declercq, F. Haesebrouck, W. Van den Broeck, P. Bossier, A. Decostere, Columnaris disease in fish: a review with emphasis on bacterium-host interactions, Vet. Res. 44 (1) (2013) 27.

[46] F.J. Gatesoupe, The use of probiotics in aquaculture, Aquaculture 180 (1) (1999) 147–165.

[47] A. Ray, K. Ghosh, E. Ringø, Enzyme-producing bacteria isolated from fish gut: a review, Aquacult. Nutr. 18 (5) (2012) 465–492.

[48] H. Dong, Y. Su, Y. Mao, X. You, S. Ding, J. Wang, Dietary supplementation with *Bacillus* can improve the growth and survival of the kuruma shrimp *Marsupenaeus japonicus* in high-temperature environments, Aquacult. Int. 22 (2) (2014) 607–617.

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

[50] S. Zhou, A. Zhang, H. Yin, W. Chu, *Bacillus* sp. QSI-1 modulate quorum sensing signals reduce *Aeromonas hydrophila* level and alter gut microbial community structure in fish, Front. Cell. Infect. Microbiol. 6 (2016) 184.

[51] M. Wang, G. Liu, M. Lu, X. Ke, Z. Liu, F. Gao, J. Cao, H. Zhu, M. Yi, D. Yu, Effect of *Bacillus cereus* as a water or feed additive on the gut microbiota and immunological parameters of Nile tilapia, Aquacult. Res. 48 (6) (2017) 3163–3173.

[52] Y. Sun, H. Yang, R. Ma, W. Lin, Probiotic applications of two dominant gut *Bacillus* strains with antagonistic activity improved the growth performance and immune responses of grouper *Epinephelus coioides*, Fish Shellfish Immunol. 29 (5) (2010) 803–809.

[53] Y. Sun, H. Yang, R. Ma, K. Song, W. Lin, Molecular analysis of autochthonous microbiota along the digestive tract of juvenile grouper *Epinephelus coioides* following probiotic *Bacillus pumilus* administration, J. Appl. Microbiol. 110 (4) (2011) 1093–1103.

[54] Y. Sun, H. Yang, K. Huang, J. Ye, C. Zhang, Application of autochthonous *Bacillus* bioencapsulated in copepod to grouper *Epinephelus coioides* larvae, Aquaculture 392 (2013) 44–50.

[55] Q. Ai, H. Xu, K. Mai, W. Xu, J. Wang, W. Zhang, Effects of dietary supplementation of *Bacillus subtilis* and fructooligosaccharide on growth performance, survival, non-specific immune response and disease resistance of juvenile large yellow croaker, *Larimichthys crocea*, Aquaculture 317 (1–4) (2011) 155–161.

[56] W. Li, B. Deng, Z. Cui, L. Fu, N. Chen, X. Zhou, W. Shen, D. Yu, Several indicators of immunity and antioxidant activities improved in grass carp given a diet containing *Bacillus* additive, J. Anim. Vet. Adv. 11 (14) (2012) 2392–2397.

[57] Z. Wu, X. Feng, L. Xie, X. Peng, J. Yuan, X. Chen, Effect of probiotic *Bacillus subtilis* Ch9 for grass carp, *Ctenopharyngodon idella* (Valenciennes, 1844), on growth performance, digestive enzyme activities and intestinal microflora, J. Appl. Ichthyol. 28 (5) (2012) 721–727.

[58] Y. Yu, F. Lv, C. Wang, A. Wang, W. Zhao, W. Yang, Effects of *Bacillus coagulans* on growth performance, disease resistance, and HSP70 gene expression in juvenile gibel carp, *Carassius auratus* gibelio, J. World Aquacult. Soc. 47 (5) (2016) 729–740.

[59] D. Zhang, X. Guan, Growth and probiotic characteristics of *Bacillus subtilis* B2 in sea cucumber *Apostichopus japonicus*, Fish. Sci. 35 (3) (2016) 234–238.

[60] W. Shen, L. Fu, W. Li, Y. Zhu, Effect of dietary supplementation with *Bacillus subtilis* on the growth, performance, immune response and antioxidant activities of the shrimp (*Litopenaeus vannamei*), Aquacult. Res. 41 (11) (2010) 1691–1698.

[61] Y. Zhao, W. Zhang, W. Xu, K. Mai, Y. Zhang, Z. Liufu, Effects of potential probiotic *Bacillus subtilis* T13 on growth, immunity and disease resistance against *Vibrio*

[62] *splendidus* infection in juvenile sea cucumber *Apostichopus japonicus*, Fish Shellfish Immunol. 32 (5) (2012) 750–755.

[63] X. Zhang, L. Fu, B. Deng, Q. Liang, J. Zheng, J. Sun, H. Zhu, L. Peng, Y. Wang, W. Shen, W. Li, Bacillus subtilis SC02 supplementation causes alterations of the microbial diversity in grass carp water, World J. Microbiol. Biotechnol. 29 (9) (2013) 1645–1653.

[63] H. Liu, S. Wang, Y. Cai, X. Guo, Z. Cao, Y. Zhang, S. Liu, W. Yuan, W. Zhu, Y. Zheng, Z. Xie, W. Guo, Y. Zhou, 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 (2017) 326–333.

[64] G. Wang, X. Tian, S. Dong, M. Peng, D. Wang, Effects of dietary *Bacillus cereus* G19, *B. cereus* BC-01, and *Paracoccus marcusii* DB11 supplementation on the growth, immune response, and expression of immune-related genes in coelomocytes and intestine of the sea cucumber (*Apostichopus japonicus* Selenka), Fish Shellfish Immunol. 45 (2) (2015) 800–807.

[65] Y. Zhao, L. Yuan, J. Wan, Z. Xu, Y. Wang, H. Sun, Effects of potential probiotic *Bacillus cereus* EN25 on growth, immunity and disease resistance of juvenile sea cucumber *Apostichopus japonicus*, Fish Shellfish Immunol. 49 (2016) 237–242.

[66] F. Yan, X. Tian, S. Dong, Effect of *Bacillus baekryungensis* YD13 supplemented in diets on growth performance and immune response of sea cucumber (*Apostichopus japonicus*), J. Ocean Univ. China 13 (5) (2014) 805–810.

[67] B. Han, W. Long, J. He, Y. Liu, Y. Si, L. Tian, 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) (2015) 225–231.

[68] Y. Yan, H. Xia, H. Yang, S. Hoseinifar, Y. Sun, Effects of dietary live or heat-inactivated autochthonous *Bacillus pumilus* SE5 on growth performance, immune responses and immune gene expression in grouper *Epinephelus coioides*, Aquacult. Nutr. 22 (3) (2016) 698–707.

[69] J. Wang, H. Yang, H. Xia, J. Ye, K.L. Lu, X. Hu, Y. Feng, L. Ruan, Y. Sun, Supplementation of heat-inactivated *Bacillus clausii* DE5 in diets for grouper, *Epinephelus coioides*, improves feed utilization, intestinal and systemic immune responses and not growth performance, Aquacult. Nutr. 24 (2) (2018) 821–831.

[70] X. Zhou, Y. Wang, W. Li, Effect of probiotic on larvae shrimp (*Penaeus vannamei*) based on water quality, survival rate and digestive enzyme activities, Aquaculture 287 (3–4) (2009) 349–353.

[71] Y. Yi, Z. Zhang, F. Zhao, H. Liu, L. Yu, J. Zha, G. Wang, Probiotic potential of *Bacillus velezensis* JW: antimicrobial activity against fish pathogenic bacteria and immune enhancement effects on *Carassius auratus*, Fish Shellfish Immunol. 78 (2018) 322–330.

[72] K. Hao, J. Liu, F. Ling, X. Liu, L. Lu, L. Xia, G. Wang, Effects of dietary administration of *Shewanella haliotis* D4, *Bacillus cereus* D7 and *Aeromonas bivalvium* D15, single or combined, on the growth, innate immunity and disease resistance of shrimp, *Litopenaeus vannamei*, Aquaculture 428–429 (2014) 141–149.

[73] H. Liu, Z. Li, B. Tan, Y. Lao, Z. Duan, W. Sun, X. Dong, Isolation of a putative probiotic strain S12 and its effect on growth performance, non-specific immunity and disease-resistance of white shrimp, *Litopenaeus vannamei*, Fish Shellfish Immunol. 41 (2) (2014) 300–307.

[74] P. Chai, X. Song, G. Chen, H. Xu, J. Huang, Dietary supplementation of probiotic *Bacillus* PC465 isolated from the gut of *Fenneropenaeus chinensis* improves the health status and resistance of *Litopenaeus vannamei* against white spot syndrome virus, Fish Shellfish Immunol. 54 (2016) 602–611.

[75] X. Yang, S. Wang, D. Zhang, L. Zhou, Isolation and nitrogen removal characteristics of an aerobic heterotrophic nitrifying-denitrifying bacterium, *Bacillus subtilis* A1, Bioresour. Technol. 102 (2) (2011) 854–862.

[76] Q. Zhang, Y. Liu, G. Ai, L. Miao, H. Zheng, Z. Liu, The characteristics of a novel heterotrophic nitrification-aerobic denitrification bacterium, *Bacillus methylotrophicus* strain L7, Bioresour. Technol. 108 (2012) 35–44.

[77] R. Yao, L. Qiu, Z. Wang, A. Gong, Z. Wang, H. Cai, Isolation and characteristics of heterotrophic nitrification-aerobic denitrification bacterium, *Bacillus cereus* X7 at High Salinity, in: H. Li, Q. Xu, H. Ge (Eds.), Environmental Engineering, Pts 1-42014, pp. 111-114.

[78] F. Douglas, R. Hambleton, G. Rigby, An Investigation of the oxidation-reduction potential and of the effect of oxygen on the germination and outgrowth of *Clostridium butyricum* Spores, using platinum electrodes, J. Appl. Bacteriol. 36 (4) (1973) 625–633.

[79] M. Junghare, S. Subudhi, B. Lal, Improvement of hydrogen production under decreased partial pressure by newly isolated alkaline tolerant anaerobe, *Clostridium butyricum* TM-9A: optimization of process parameters, Int. J. Hydrogen Energy 37 (4) (2012) 3160–3168.

[80] X. Liao, G. Ma, J. Cai, Y. Fu, X. Yan, X. Wei, R. Zhang, Effects of *Clostridium butyricum* on growth performance, antioxidation, and immune function of broilers, Poultry Sci. 94 (4) (2015) 662–667.

[81] X. Liao, R. Wu, G. Ma, L. Zhao, Z. Zheng, R. Zhang, Effects of *Clostridium butyricum* on antioxidant properties, meat quality and fatty acid composition of broiler birds, Lipids Health Dis. 14 (1) (2015) 36.

[82] D. Vandak, M. Telgarský, E. Šturdík, Influence of growth factor supplements on butyric acid production from sucrose by *Clostridium butyricum*, Folia Microbiol. 40 (6) (1995) 669–672.

[83] Q. Gao, Y. Xiao, P. Sun, S. Peng, F. Yin, X. Ma, Z. Shi, In vitro protective efficacy of *Clostridium butyricum* against fish pathogen infections, Indian J. Microbiol. 53 (4) (2013) 453–459.

[84] Q. Gao, C. Xiao, M. Min, C. Zhang, S. Peng, Z. Shi, Effects of probiotics dietary supplementation on growth performance, innate immunity and digestive enzymes of silver pomfret, *Pampus argenteus*, Indian J. Anim. Res. 50 (6) (2016) 936–941.

[85] Z. Song, T. Wu, L. Cai, L. Zhang, X. Zheng, Effects of dietary supplementation with *Clostridium butyricum* on the growth performance and humoral immune response in *Miichthys miiuy*, J. Zhejiang Univ. - Sci. B 7 (7) (2006) 596–602.

[86] X. Pan, T. Wu, L. Zhang, Z. Song, H. Tang, Z. Zhao, *In vitro* evaluation on adherence and antimicrobial properties of a candidate probiotic *Clostridium butyricum* CB2 for farmed fish, J. Appl. Microbiol. 105 (5) (2008) 1623–1629.

[87] Y. Duan, Y. Wang, H. Dong, J. Zhang, Changes in the intestine microbial, digestive and immune-related genes of *Litopenaeus vannamei* in response to dietary probiotic Clostridium butyricum supplementation, Front. Microbiol. 9 (2018) 2191.

[88] H. Li, X. Tian, S. Dong, Growth performance, non-specific immunity, intestinal histology and disease resistance of *Litopenaeus vannamei* fed on a diet supplemented with live cells of *Clostridium butyricum*, Aquaculture 498 (2019) 470–481.

[89] Y. Duan, Y. Zhang, H. Dong, Y. Wang, J. Zhang, Effect of the dietary probiotic *Clostridium butyricum* on growth, intestine antioxidant capacity and resistance to high temperature stress in kuruma shrimp *Marsupenaeus japonicus*, J. Therm. Biol. 66 (2017) 93–100.

[90] Y. Duan, H. Dong, Y. Wang, Y. Zhang, J. Zhang, Effects of the dietary probiotic *Clostridium butyricum* on intestine digestive and metabolic capacities, SCFA content and body composition in *Marsupenaeus japonicus*, J. Ocean Univ. China 17 (3) (2018) 690–696.

[91] Y. Miyazaki, H. Yokota, H. Takahashi, M. Fukuda, H. Kawakami, S. Kamiya, T. Hanawa, Effect of probiotic bacterial strains of *Lactobacillus, Bifidobacterium*, and *Enterococcus* on enteroaggregative *Escherichia coli*, J. Infect. Chemother. 16 (1) (2010) 10–18.

[92] Y. Sun, H. Yang, Z. Ling, J. Chang, J. Ye, Gut microbiota of fast and slow growing grouper *Epinephelus coioides*, Afr. J. Microbiol. Res. 3 (11) (2009) 713–720.

[93] Y. Sun, Y. Hongling, M.A. Rulong, S. Kai, Survival of lactic acid bacteria isolated from gut of *Epinephelus coioides* in mimic gastrointestinal environments, J. Fish. Sci. China 17 (1) (2010) 128–135.

[94] Y. Sun, H. Yang, R. Ma, K. Huang, J. Ye, Culture-independent characterization of the autochthonous gut microbiota of grouper *Epinephelus coioides* following the administration of probiotic *Enterococcus faecium*, Aquacult. Int. 20 (4) (2012) 791–801.

[95] Y. Sun, H. Yang, R. Ma, K. Song, J. Li, Effect of *Lactococcus lactis* and *Enterococcus faecium* on growth performance, digestive enzymes and immune response of grouper *Epinephelus coioides*, Aquacult. Nutr. 18 (3) (2012) 281–289.

[96] Y. Sha, L. Wang, G. Sun, M. Liu, B. Wang, Effects of two lactic acid bacteria species and the corresponding supernatants on the activities of digestive enzymes in *Litopenaeus vannamei*, Mar. Sci. 40 (3) (2016) 59–64.

[97] J. Cui, M. Xiao, M. Liu, Z. Wang, F. Liu, L. Guo, H. Meng, H. Zhang, J. Yang, D. Deng, S. Huang, Y. Ma, C. Liu, Coupling metagenomics with cultivation to select host-specific probiotic micro-organisms for subtropical aquaculture, J. Appl. Microbiol. 123 (5) (2017) 1274–1285.

[98] C. Li, Y. Ren, S. Jiang, S. Zhou, J. Zhao, R. Wang, Y. Li, Effects of dietary supplementation of four strains of lactic acid bacteria on growth, immune-related response and genes expression of the juvenile sea cucumber *Apostichopus japonicus* Selenka, Fish Shellfish Immunol. 74 (2018) 69–75.

[99] E. Ringo, S. Hossein, K. Ghosh, H.V. Doan, B.R. Beck, S. Song, Lactic acid bacteria in finfish–an update, Front. Microbiol. 9 (2018) 1818.

[100] D. Zeng, A. Lei, Effect of *Lactobacillus* supplementation on growth and disease resistance in tilapia, Journal of Southern Agriculture 42 (3) (2011) 328–331.

[101] G. Wang, Y. Huang, Y. Zhou, S. Dong, W. Huang, Q. Yan, Effects of *Lactobacillus* on growth performance, digestive enzyme activities and non-specific immunity of *Litopenaeus vannamei*, Chinese Journal of Animal Nutrition 22 (1) (2010) 228–234.

[102] Y. Huang, X. Zhou, G. Wang, Z. Kuang, H. Zhao, W. Mo, J. Cao, Effects of *Lactobacillus* on immunity and disease resistance of tilapia (*Oreochromis niloticus × O. aureus*), Fish. Sci. 33 (10) (2014) 601–605.

[103] C. Zhang, J. Zhang, W. Guan, X. Zhang, S. Guan, Q. Zeng, G. Cheng, W. Cui, Effects of *Lactobacillus delbrueckii* on immune response, disease resistance against *Aeromonas hydrophila*, antioxidant capability and growth performance of *Cyprinus carpio Huanghe* var, Fish Shellfish Immunol. 68 (2017) 84–91.

[104] C. Qin, Z. Zhang, Y. Wang, S. Li, C. Ran, J. Hu, Y. Xie, W. Li, Z. Zhou, EPSP of *L. casei* BL23 protected against the infection caused by *Aeromonas veronii* via enhancement of immune response in zebrafish, Front. Microbiol. 8 (2017).

[105] X. Zheng, Y. Duan, H. Dong, K. Yang, Y. Yang, J. Zhang, Effects of *Lactobacillus plantarum* on growth performance, gut histology and activity of digestive enzymes in Pacific white leg shrimp, *Litopenaeus vannamei*, Fish. Sci. 35 (1) (2016) 1–6.

[106] X. Zheng, Y. Duan, H. Dong, J. Zhang, Effects of dietary *Lactobacillus plantarum* in different treatments on growth performance and immune gene expression of white shrimp *Litopenaeus vannamei* under normal condition and stress of acute low salinity, Fish Shellfish Immunol. 62 (2017) 195–201.

[107] X. Zheng, Y. Duan, H. Dong, J. Zhang, Effects of dietary *Lactobacillus plantarum* on growth performance, digestive enzymes and gut morphology of *Litopenaeus vannamei*, Probiotics Antimicro 10 (3) (2018) 504–510.

[108] C. Zheng, W. Wang, Effects of *Lactobacillus pentosus* on the growth performance, digestive enzyme and disease resistance of white shrimp, *Litopenaeus vannamei* (Boone, 1931), Aquacult. Res. 48 (6) (2017) 2767–2777.

[109] H. Yang, Y. Han, T.J. Ren, Z.Q. Jiang, F.Q. Wang, Y.T. Zhang, Effects of dietary heat-killed *Lactobacillus plantarum* L-137 (HK L-137) on the growth performance, digestive enzymes and selected non-specific immune responses in sea cucumber, *Apostichopus japonicus* Selenka, Aquacult. Res. 47 (9) (2016) 2814–2824.

[110] L. Yu, Q. Zhai, J. Zhu, C. Zhang, T. Li, X. Liu, J. Zhao, H. Zhang, F. Tian, W. Chen, Dietary *Lactobacillus plantarum* supplementation enhances growth performance and alleviates aluminum toxicity in tilapia, Ecotoxicol. Environ. Saf. 143 (2017) 307–314.

[111] Q. Zhai, H. Wang, F. Tian, J. Zhao, H. Zhang, W. Chen, Dietary *Lactobacillus plantarum* supplementation decreases tissue lead accumulation and alleviates lead toxicity in Nile tilapia (*Oreochromis niloticus*), Aquacult. Res. 48 (9) (2017) 5094–5103.

[112] X. Gao, M. Zhang, X. Li, Y. Han, F. Wu, Y. Liu, The effects of feeding *Lactobacillus pentosus* on growth, immunity, and disease resistance in *Haliotis discus hannai* Ino, Fish Shellfish Immunol. 78 (2018) 42–51.

[113] F. Xie, F. Zhang, K. Zhou, Y. Zhao, Q. Zhao, H. Sun, Isolation, identification and fermentation optimization of lactic acid bacteria for aquaculture water purification, Acta Microbiol. Sin. 57 (2) (2017) 304–314.

[114] X. Zhou, Y. Wang, J. Yao, W. Li, 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) (2010).

[115] H. Yang, Y. Sun, R. Ma, K. Song, K. Wang, W. Lin, Antagonistic property of lactic acid bacteria MM1 and MM4 isolated from the intestine of grouper *Epinephelus coioides*, Oceanol. Limnol. Sinica 41 (4) (2010) 544–548.

[116] W. Zhang, M. Liu, X. Dai, Biological characteristics and probiotic effect of *Leuconostoc lactis* strain isolated from the intestine of black porgy fish, Braz. J. Microbiol. 44 (3) (2013) 685–691.

[117] J.F. Rawls, B.S. Samuel, J.I. Gordon, Gnotobiotic zebrafish reveal evolutionarily conserved responses to the gut microbiota, P. Natl. Acad. Sci. 101 (13) (2004) 4596–4601.

[118] O. Rotem, Z. Pasternak, E. Jurkevitch, Bdellovibrio and like Organisms, the Prokaryotes, Springer, 2014, pp. 3–17.

[119] Y. Guo, Q. Pan, S. Yan, Y. Chen, M. Li, D. Chen, H. Han, B. Wu, J. Cai, *Bdellovibrio* and like organisms promoted growth and survival of juvenile abalone Haliotis discus hannai Ino and modulated bacterial community structures in its gut, Aquacult. Int. 25 (4) (2017) 1625–1643.

[120] L. Zhang, J. Shen, J. Chen, The effects of *Bdellovibrio bacteriovorus* on the water quality and bacterial population in the grass carp ponds, Journal of Hydroecology (01) (2009) 6–10.

[121] Z. Zhang, Z. Song, D. Li, Isolation of *Bdellovibrio* bacteria from the gut of eel and the study of its prevention of bacterial diseases in aquaculture, Journal of Fujian Fisheries (02) (2009) 54–58.

[122] H. Cao, S. He, H. Wang, S. Hou, L. Lu, X. Yang, *Bdellovibrios*, potential biocontrol bacteria against pathogenic *Aeromonas hydrophila*, Vet. Microbiol. 154 (3–4) (2012) 413–418.

[123] H. Li, C. Chen, Q. Sun, R. Liu, J. Cai, *Bdellovibrio* and like organisms enhanced growth and survival of *Penaeus monodon* and altered bacterial community structures in its rearing water, Appl. Environ. Microbiol. 80 (20) (2014) 6346–6354.

[124] C. Wen, M. Xue, H. Liang, S. Zhou, Evaluating the potential of marine *Bacteriovorax* sp. DA5 as a biocontrol agent against vibriosis in *Litopenaeus vannamei* larvae, Vet. Microbiol. 173 (1–2) (2014) 84–91.

[125] J. Chen, X. Li, G. Tong, L. Huang, X. Wei, W. Wu, Effects of *B. bacteriovorus* on disease prevention in tilapia farming, Journal of Anhui Agricultural Sciences 39 (17) (2011) 10494–10496.

[126] W. Chu, W. Zhu, Isolation of *Bdellovibrio* as biological therapeutic agents used for the treatment of *Aeromonas hydrophila* infection in fish, Zoonoses Public Hlth 57 (4) (2010) 258–264.

[127] H. Cao, J. An, W. Zheng, S. He, *Vibrio cholerae* pathogen from the freshwater-cultured whiteleg shrimp *Penaeus vannamei* and control with *Bdellovibrio bacteriovorus*, J. Invertebr. Pathol. 130 (2015) 13–20.

[128] H.G. Trüper, J.F. Imhoff, The Genus Ectothiorhodospira, the Prokaryotes, Springer, 1981, pp. 274–278.

[129] C. Wen, M. Xue, H. Liang, Y. Wu, X. Li, Beneficial effects of *Ectothiorhodospira shaposhnikovii* WF on larval cultivation of *Litopenaeus vannamei*, Benef. Microbes 6 (4) (2015) 525–533.

[130] I. Llamas, A. del Moral, V. Béjar, M.D. Girón, R. Salto, E. Quesada, Plasmids from *Halomonas eurihalina*, a microorganism which produces an exopolysaccharide of biotechnological interest, FEMS Microbiol. Lett. 156 (2) (1997) 251–257.

[131] M. Kamekura, Production and function of enzymes of eubacterial halophiles, FEMS Microbiol. Lett. 39 (1-2) (1986) 145–150.

[132] L. Zhang, K. Mai, B. Tan, Q. Ai, C. Qi, W. Xu, W. Zhang, Z. Liufu, X. Wang, H. Ma, Effects of dietary administration of probiotic *Halomonas* sp B12 on the intestinal microflora, immunological parameters, and midgut histological structure of shrimp, *Fenneropenaeus chinensis*, J. World Aquacult. Soc. 40 (1) (2009) 58–66.

[133] F. Yan, X. Tian, S. Dong, Y. Niu, Isolation, identification and characterization of a low-temperature degrading bacterium, Periodical of Ocean University of China 41 (3) (2011) 24–30.

[134] F. Yan, X. Tian, S. Dong, Z. Fang, G. Yang, Growth performance, immune response, and disease resistance against *Vibrio splendidus* infection in juvenile sea cucumber *Apostichopus japonicus* fed a supplementary diet of the potential probiotic *Paracoccus marcusii* DB11, Aquaculture 420 (2014) 105–111.

[135] J. Lalucat, A. Bennasar, R. Bosch, E. García-Valdés, N.J. Palleroni, Biology of *Pseudomonas stutzeri*, Microbiol. Mol. Biol. Rev. 70 (2) (2006) 510–547.

[136] B. Deng, L. Fu, X. Zhang, J. Zheng, L. Peng, J. Sun, H. Zhu, Y. Wang, W. Li, X. Wu, D. Wu, The denitrification characteristics of *Pseudomonas stutzeri* SC221-M and its application to water quality control in grass carp aquaculture, PLoS One 9 (12) (2014).

[137] L. Fu, X. Zhang, Y. Wang, L. Peng, W. Li, Nitrogen removal characteristics of *Pseudomonas stutzeri* F11 and its application in grass carp culture, Fish. Sci. 83 (1) (2017) 89–98.

[138] W. Zhang, W. Liang, C. Li, Inhibition of marine *Vibrio* sp. by pyoverdine from *Pseudomonas aeruginosa* PA1, J. Hazard Mater. 302 (2016) 217–224.

[139] L. Zhang, X. Tian, S. Kuang, G. Liu, C. Zhang, C. Sun, Antagonistic activity and mode of action of phenazine-1-carboxylic acid, produced by marine bacterium *Pseudomonas aeruginosa* PA31x, against *Vibrio anguillarum in vitro* and in a

zebrafish *in vivo* model, Front. Microbiol. 8 (2017) 289.

[140] C. Chi, J. Liu, S. Fei, C. Zhang, Y. Chang, X. Liu, G. Wang, Effect of intestinal autochthonous probiotics isolated from the gut of sea cucumber (*Apostichopus japonicus*) on immune response and growth of *A. japonicus*, Fish Shellfish Immunol. 38 (2) (2014) 367–373.

[141] Y. Ma, F. Sun, C. Zhang, P. Bao, S. Cao, M. Zhang, Effects of *Pseudoalteromonas* sp BC228 on digestive enzyme activity and immune response of juvenile sea cucumber (*Apostichopus japonicus*), J. Ocean Univ. China 13 (6) (2014) 1061–1066.

[142] X. Sun, G. Zhao, C. Gu, L. Liu, M. Zhu, Z. Liu, Screening for and identification of an anti-clam *Vibrio* marine bacterium from an aquaculture pond in the yellow sea, Clean. - Soil, Air, Water 44 (3) (2016) 304–308.

[143] C.M.A. Caipang, M.F. Brinchmann, V. Kiron, Antagonistic activity of bacterial isolates from intestinal microbiota of Atlantic cod, *Gadus morhua*, and an investigation of their immunomodulatory capabilities, Aquacult. Res. 41 (2) (2010) 249–256.

[144] Y. Sun, H. Yang, R. Ma, C. Zhang, W. Lin, Effect of dietary administration of *Psychrobacter* sp. on the growth, feed utilization, digestive enzymes and immune responses of grouper *Epinephelus coioides*, Aquacult. Nutr. 17 (3) (2011) e733–e740.

[145] H. Yang, Y. Sun, R. Ma, J. Li, K. Huang, Probiotic *Psychrobacter* sp. improved the autochthonous microbial diversity along the gastrointestinal tract of grouper *Epinephelus coioides*, J. Aquacult. Res. Dev. 2 (Special issue) (2011) 001-001.

[146] H. Xia, H. Yang, J. Ye, K. Huang, W. Zou, Y. Sun, Effect of viable and heat-inactivated *Psychrobacter* sp. SE6 on growth performance and immune function of juvenile grouper (*Epinephelus coioides*), J. Fish. China 37 (1) (2013) 86–93.

[147] Y. Wang, Q. Gu, Effect of probiotics on white shrimp (*Penaeus vannamei*) growth performance and immune response, Mar. Biol. Res. 6 (3) (2010) 327–332.

[148] Y. Wang, Use of probiotics *Bacillus coagulans, Rhodopseudomonas palustris* and *Lactobacillus acidophilus* as growth promoters in grass carp (*Ctenopharyngodon idella*) fingerlings, Aquacult. Nutr. 17 (2) (2011) E372–E378.

[149] X. Zhang, M. Shu, Y. Wang, L. Fu, W. Li, B. Deng, Q. Liang, W. Shen, Effect of photosynthetic bacteria on water quality and microbiota in grass carp culture, World J. Microbiol. Biotechnol. 30 (9) (2014) 2523–2531.

[150] X. Wang, P.J. Quinn, Endotoxins: Structure, Function and Recognition, Springer Science & Business Media, 2010.

[151] M. Adams, M. Moss, Food microbiology. 3. Vydání, Royal Society of Chemistry 138 (140) (2008) 26 Dostupné z http://app.knovel.com/hotlink/toc/id:kpFME00011/food-microbiology-3rd/foodmicrobiology-3rd.

[152] H. Jiang, X. Liu, Y. Chang, X. Leng, D. Li, G. Wang, Selection of potential probiotics from the abalone intestinal and their effects on juvenile small abalone *Haliotis discus* hannai, Chin. J. Oceanol. Limnol. 2 (2013) 482–487.

[153] H. Jiang, X. Liu, Y. Chang, M. Liu, G. Wang, Effects of dietary supplementation of probiotic *Shewanella colwelliana* WA64, *Shewanella olleyana* WA65 on the innate immunity and disease resistance of abalone, *Haliotis discus* hannai Ino, Fish Shellfish Immunol. 35 (1) (2013) 86–91.

[154] Z. Wu, C. Jiang, F. Ling, G. Wang, Effects of dietary supplementation of intestinal autochthonous bacteria on the innate immunity and disease resistance of grass carp (*Ctenopharyngodon idellus*), Aquaculture 438 (2015) 105–114.

[155] B. Austin, D. Austin, Bacterial fish pathogens: disease of farmed and wild fish, Springer-praxis in Aquaculture in Fisheries, Praxis Publication Ltd, Chichester, UK, 2012.

[156] K. Mujeeb Rahiman, Y. Jesmi, A.P. Thomas, A. Mohamed Hatha, Probiotic effect of *Bacillus* NL110 and *Vibrio* NE17 on the survival, growth performance and immune response of *Macrobrachium rosenbergii* (de Man), Aquacult. Res. 41 (9) (2010) e120–e134.

[157] F.R. Silva-Aciares, P.O. Carvajal, C.A. Mejías, C.E. Riquelme, Use of macroalgae supplemented with probiotics in the *Haliotis rufescens* (Swainson, 1822) culture in Northern Chile, Aquacult. Res. 42 (7) (2011) 953–961.

[158] N. Liu, S. Zhang, W. Zhang, C. Li, *Vibrio* sp. 33 a potential bacterial antagonist of *Vibrio splendidus* pathogenic to sea cucumber (*Apostichopus japonicus*), Aquaculture 470 (2017) 68–73.

[159] C. Ran, L. Huang, Z. Liu, L. Xu, Y. Yang, P. Tacon, E. Auclair, Z. Zhou, A comparison of the beneficial effects of live and heat-inactivated baker's yeast on Nile tilapia: suggestions on the role and function of the secretory metabolites released from the yeast (vol 10, e0145448, 2015, PLoS One 11 (3) (2016) 2.

[160] S. He, Z. Zhou, Y. Liu, P. Shi, B. Yao, E. Ringø, I. Yoon, Effects of dietary *Saccharomyces cerevisiae* fermentation product (DVAQUA®) on growth performance, intestinal autochthonous bacterial community and non-specific immunity of hybrid tilapia (*Oreochromis niloticus* ♀ × *O. aureus* ♂) cultured in cages, Aquaculture 294 (1) (2009) 99–107.

[161] L. Huang, C. Ran, S. He, P. Ren, J. Hu, X. Zhao, Z. Zhou, Effects of dietary *Saccharomyces cerevisiae* culture or live cells with *Bacillus amyloliquefaciens* spores on growth performance, gut mucosal morphology, hsp70 gene expression, and disease resistance of juvenile common carp (*Cyprinus carpio*), Aquaculture 438 (2015) 33–38.

[162] H. Li, G. Qiao, Q. Li, W. Zhou, K.M. Won, D.H. Xu, S.I. Park, Biological characteristics and pathogenicity of a highly pathogenic *Shewanella marisflavi* infecting sea cucumber, *Apostichopus japonicus*, J. Fish. Dis. 33 (11) (2010) 865–877.

[163] Y. Ma, Z. Liu, Z. Yang, P. YBao, C. Zhang, J. Ding, Effects of *Hanseniaspora opuntiae* C21 on the growth and digestive enzyme activity of juvenile sea cucumber *Apostichopus japonicas*, Chin. J. Oceanol. Limnol. 32 (4) (2014) 743–748.

[164] Z. Liu, Y. Ma, Z. Yang, M. Li, Liu, P. Bao, Immune responses and disease resistance of the juvenile sea cucumber *Apostichopus japonicus* induced by *Metschnikowia* sp. C14, Aquaculture 368 (2012) 10–18.

[165] Z. Yang, J. Sun, Z. Xu, C. Zhang, Q. Zhou, Beneficial effects of *Metschnikowia* sp. C14 on growth and intestinal digestive enzymes of juvenile sea cucumber

Apostichopus japonicus, Anim. Feed Sci. Technol. 197 (2014) 142–147.

[166] Z. Yang, J. Sun, Z. Xu, Beneficial effects of *Rhodotorula* sp. C11 on growth and disease resistance of juvenile Japanese spiky sea cucumber *Apostichopus japonicus*, J. Aquat. Anim. Health 27 (2) (2015) 71–76.

[167] J. Wang, L. Zhao, J. Liu, H. Wang, S. Xiao, Effect of potential probiotic *Rhodotorula benthica* D30 on the growth performance, digestive enzyme activity and immunity in juvenile sea cucumber *Apostichopus japonicus*, Fish Shellfish Immunol. 43 (2) (2015) 330–336.

[168] S. Yang, Z. Wu, J. Jian, X. Zhang, Effect of marine red yeast *Rhodosporidium paludigenum* on growth and antioxidant competence of *Litopenaeus vannamei*, Aquaculture 309 (1–4) (2010) 62–65.

[169] S. Yang, Z. Wu, J. Jian, Effect of marine red yeast *Rhodosporidium paludigenum* on antioxidant-related gene expression in *Litopenaeus vannamei*, Isr. J. Aquacult. Bamidgeh 65 (2013) IJA_65.2013.817-IJA_65.2013.817.

[170] R. Fuller, Probiotics in man and animals. A review, J. Appl. Bacteriol. 66 (5) (1989) 365–378.

[171] X. Geng, X. Dong, B. Tan, Q. Yang, S. Chi, H. Liu, X. Liu, Effects of dietary probiotic on the growth performance, non-specific immunity and disease resistance of cobia, *Rachycentron canadum*, Aquacult. Nutr. 18 (1) (2012) 46–55.

[172] M.J. Zorriehzahra, S.T. Delshad, M. Adel, R. Tiwari, K. Karthik, K. Dhama, C.C. Lazado, Probiotics as beneficial microbes in aquaculture: an update on their multiple modes of action: a review, Vet. Q. 36 (4) (2016) 228–241.

[173] R. He, J. Feng, X. Tian, S. Dong, B. Wen, Effects of dietary supplementation of probiotics on the growth, activities of digestive and non-specific immune enzymes in hybrid grouper (*Epinephelus lanceolatus* male x *Epinephelus fuscoguttatus* female), Aquacult. Res. 48 (12) (2017) 5782–5790.

[174] S. Liu, J. Chen, J. Li, H. Liu, J. Hu, L. Zhang, H. Han, G. Sun, C. Wang, Effects of complex-probiotic-preparation on the growth, digestive enzymes and the non-specific immune indices of Atlantic salmon (*Salmo salar*), Progress in Fishery Sciences 38 (5) (2017) 100–106.

[175] G.R. Gibson, M.B. Roberfroid, Dietary modulation of the human colonic microbiota: introducing the concept of prebiotics, J. Nutr. 125 (6) (1995) 1401–1412.

[176] U. Rodriguez-Estrada, S. Satoh, Y. Haga, H. Fushimi, J. Sweetman, 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*, Aquaculture Science 57 (4) (2009) 609–617.

[177] R. Cerezuela, J. Meseguer, M. Esteban, Current knowledge in synbiotic use for fish aquaculture: a review, J. Aquacult. Res. Dev. S1 (2011) 1–7.

[178] B.C. De, D. Meena, B. Behera, P. Das, P.D. Mohapatra, A. Sharma, Probiotics in fish and shellfish culture: immunomodulatory and ecophysiological responses, Fish Physiol. Biochem. 40 (3) (2014) 921–971.

[179] E. Ringø, R.E. Olsen, I. Jensen, J. Romero, H.L. Lauzon, Application of vaccines and dietary supplements in aquaculture: possibilities and challenges, Rev. Fish Biol. Fish. 24 (4) (2014) 1005–1032.

[180] E. Ringø, S. Song, Application of dietary supplements (synbiotics and probiotics in combination with plant products and β-glucans) in aquaculture, Aquacult. Nutr. 22 (1) (2016) 4–24.

[181] T.G. Huynh, Y.L. Shiu, T.P. Nguyen, Q.P. Truong, J.C. Chen, C.H. Liu, Current applications, selection, and possible mechanisms of actions of synbiotics in improving the growth and health status in aquaculture: a review, Fish Shellfish Immunol. 64 (2017) 367–382.

[182] Q. Zhang, H. Ma, K. Mai, W. Zhang, Z. Liufu, W. Xu, Interaction of dietary *Bacillus subtilis* and fructooligosaccharide on the growth performance, non-specific immunity of sea cucumber, *Apostichopus japonicus*, Fish Shellfish Immunol. 29 (2) (2010) 204–211.

[183] C. Zhang, X. Li, W. Xu, G. Jiang, K. Lu, L. Wang, W. Liu, Combined effects of dietary fructooligosaccharide and *Bacillus licheniformis* on innate immunity, antioxidant capability and disease resistance of triangular bream (*Megalobrama terminalis*), Fish Shellfish Immunol. 35 (5) (2013) 1380–1386.

[184] D. Yao, Q. Zou, W. Liu, S. Xie, A. Zhou, J. Chen, J. Zou, Effects of *Bacillus licheniformis* and xylo-oligosaccharide on growth performance, intestinal microflora and enzyme activities in grass carp *Ctenopharyngodon idella*, Journal of Dalian Ocean University 29 (2) (2014) 136–140.

[185] C. Zhang, X. Li, W. Xu, D. Zhang, K. Lu, L. Wang, H. Tian, W. Liu, Combined effects of dietary fructooligosaccharide and *Bacillus licheniformis* on growth performance, body composition, intestinal enzymes activities and gut histology of triangular bream (*Megalobrama terminalis*), Aquacult. Nutr. 21 (5) (2015) 755–766.

[186] Q. Zhang, B. Tan, K. Mai, W. Zhang, H. Ma, Q. Ai, X. Wang, Z. Liufu, Dietary administration of *Bacillus* (*B. licheniformis* and *B. subtilis*) and iso-maltooligosaccharide influences the intestinal microflora, immunological parameters and resistance against *Vibrio alginolyticus* in shrimp, *Penaeus japonicus* (Decapoda: penaeidae), Aquacult. Res. 42 (7) (2011) 943–952.

[187] X. Hu, Y. Cao, G. Wen, X. Zhang, Y. Xu, W. Xu, Y. Xu, Z. Li, Effect of combined use of *Bacillus* and molasses on microbial communities in shrimp cultural enclosure systems, Aquacult. Res. 48 (6) (2017) 2691–2705.

[188] S. Lin, S. Mao, Y. Guan, L. Luo, L. Luo, Y. Pan, Effects of dietary chitosan oligosaccharides and *Bacillus coagulans* on the growth, innate immunity and resistance of koi (*Cyprinus carpio* koi), Aquaculture 342 (2012) 36–41.

[189] X. Wang, Y. Sun, L. Wang, X. Li, K. Qu, Y. Xu, Synbiotic dietary supplement affects growth, immune responses and intestinal microbiota of *Apostichopus japonicus*, Fish Shellfish Immunol. 68 (2017) 232–242.

[190] J. Ye, K. Wang, F. Li, Y. Sun, Single or combined effects of fructo- and mannan oligosaccharide supplements and *Bacillus clausii* on the growth, feed utilization, body composition, digestive enzyme activity, innate immune response and lipid metabolism of the Japanese flounder *Paralichthys olivaceus*, Aquacult. Nutr. 17 (4) (2011) E902–E911.

[191] X. Geng, X. Dong, B. Tan, Q. Yang, S. Chi, H. Liu, X. Liu, Effects of dietary chitosan and *Bacillus subtilis* on the growth performance, non-specific immunity and disease resistance of cobia, *Rachycentron canadum*, Fish Shellfish Immunol. 31 (3) (2011) 400–406.

[192] C. Liu, C. Chiu, P. Ho, S. Wang, Improvement in the growth performance of white shrimp, *Litopenaeus vannamei*, by a protease-producing probiotic, *Bacillus subtilis* E20, from natto, J. Appl. Microbiol. 107 (3) (2009) 1031–1041.

[193] C. Liu, C. Chiu, S. Wang, W. Cheng, Dietary administration of the probiotic, *Bacillus subtilis* E20, enhances the growth, innate immune responses, and disease resistance of the grouper, *Epinephelus coioides*, Fish Shellfish Immunol. 33 (4) (2012) 699–706.

[194] H. Xu, Y. Rong, M. Zhao, B. Song, Z. Chi, Antibacterial activity of the lipopetides produced by *Bacillus amyloliquefaciens* M1 against multidrug-resistant *Vibrio* spp. isolated from diseased marine animals, Appl. Microbiol. Biotechnol. 98 (1) (2014) 127–136.

[195] X. Gao, Y. Liu, L. Miao, E. Li, T. Hou, Z. Liu, Mechanism of anti-*Vibrio* activity of marine probiotic strain *Bacillus pumilus* H2, and characterization of the active substance, Amb. Express 7 (1) (2017) 23.

[196] X. Gao, Y. Liu, L. Miao, E. Li, G. Sun, Y. Liu, Z. Liu, Characterization and mechanism of anti-*Aeromonas salmonicida* activity of a marine probiotic strain, *Bacillus velezensis* V4, Appl. Microbiol. Biotechnol. 101 (9) (2017) 3759–3768.

[197] S.H. Hoseinifar, E. Ringø, A. Shenavar Masouleh, M.Á. Esteban, Probiotic, prebiotic and synbiotic supplements in sturgeon aquaculture: a review, Rev. Aquacult. 8 (1) (2016) 89–102.

[198] Y. Sun, H. Xia, H. Yang, Y. Wang, W. Zou, TLR2 signaling may play a key role in the probiotic modulation of intestinal microbiota in grouper *Epinephelus coioides*, Aquaculture 430 (2014) 50–56.

[199] S.H. Hoseinifar, Y.-Z. Sun, C.M. Caipang, Short-chain fatty acids as feed supplements for sustainable aquaculture: an updated view, Aquacult. Res. 48 (4) (2017) 1380–1391.

[200] D.P.R. Herlemann, M. Labrenz, K. Juergens, S. Bertilsson, J.J. Waniek, A.F. Andersson, Transitions in bacterial communities along the 2000 km salinity gradient of the Baltic Sea, ISME J. 5 (10) (2011) 1571–1579.

[201] C. Fuqua, M.R. Parsek, E.P. Greenberg, Regulation of gene expression by cell-to-cell communication: acyl-homoserine lactone quorum sensing, Annu. Rev. Genet. 35 (1) (2001) 439–468.

[202] K. Tang, X. Zhang, Quorum quenching agents: resources for antivirulence therapy, Mar. Drugs 12 (6) (2014) 3245–3282.

[203] F. Chen, Y. Gao, X. Chen, Z. Yu, X. Li, Quorum quenching enzymes and their application in degrading signal molecules to block quorum sensing-dependent infection, Int. J. Mol. Sci. 14 (9) (2013) 17477–17500.

[204] T. Defoirdt, Virulence mechanisms of bacterial aquaculture pathogens and anti-virulence therapy for aquaculture, Rev. Aquacult. 6 (2) (2014) 100–114.

[205] W. Chu, S. Zhou, W. Zhu, X. Zhuang, Quorum quenching bacteria *Bacillus* sp. QSI-1 protect zebrafish (*Danio rerio*) from *Aeromonas hydrophila* infection, Sci. Rep. 4 (5446) (2014) srep.05446.

[206] Z. Zhou, W. Wang, W. Liu, D.M. Gatlin III, Y. Zhang, B. Yao, E. Ringo, Identification of highly-adhesive gut *Lactobacillus* strains in zebrafish (*Danio rerio*) by partial rpoB gene sequence analysis, Aquaculture 370 (2012) 150–157.

[207] P. Ren, L. Xu, Y. Yang, S. He, W. Liu, E. Ringo, Z. Zhou, *Lactobacillus planarum* subsp. *plantarum* JCM 1149 vs. *Aeromonas hydrophila* NJ-1 in the anterior intestine and posterior intestine of hybrid tilapia *Oreochromis niloticus* female × *Oreochromis aureus* male: an *ex vivo* study, Fish Shellfish Immunol. 35 (1) (2013) 146–153.

[208] C. Ran, Isolation and Characterization of *Bacillus* Spp. As Potential Probiotics for Channel Catfish, Ictalurus punctatus, 2013.

[209] M. Egervärn, H. Lindmark, J. Olsson, S. Roos, Transferability of a tetracycline resistance gene from probiotic *Lactobacillus reuteri* to bacteria in the gastro-intestinal tract of humans, Antonie Leeuwenhoek 97 (2) (2010) 189–200.

[210] P.A. Cohen, Probiotic safety—No guarantees, JAMA Inter. Med. 178 (12) (2018) 1577–1578, https://doi.org/10.1001/jamainternmed.2018.5403.

[211] Z. Liu, W. Liu, C. Ran, J. Hu, Z. Zhou, Abrupt suspension of probiotics administration may increase host pathogen susceptibility by inducing gut dysbiosis, Sci. Rep. 6 (2016).

[212] S. He, C. Ran, C. Qin, S. Li, H. Zhang, W.M. de Vos, E. Ringo, Z. Zhou, Anti-infective effect of adhesive probiotic *Lactobacillus* in fish is correlated with their spatial distribution in the intestinal tissue, Sci. Rep. 7 (2017).

[213] W. Salma, Z. Zhou, W. Wang, F. Askarian, A. Kousha, M.T. Ebrahimi, R. Myklebust, E. Ringø, Histological and bacteriological changes in intestine of beluga (*Huso huso*) following *ex vivo* exposure to bacterial strains, Aquaculture 314 (1–4) (2011) 24–33.

[214] J.L. Balcázar, D. Vendrell, I. De Blas, I. Ruiz-Zarzuela, J.L. Múzquiz, Effect of *Lactococcus lactis* CLFP 100 and *Leuconostoc mesenteroides* CLFP 196 on *Aeromonas salmonicida* infection in brown trout (*Salmo trutta*), J. Mol. Microbiol. Biotechnol. 17 (3) (2009) 153–157.

[215] N.G. Vine, W.D. Leukes, H. Kaiser, Probiotics in marine larviculture, FEMS Microbiol. Rev. 30 (3) (2006) 404–427.

[216] G.D. Gómez, J.L. Balcázar, A review on the interactions between gut microbiota and innate immunity of fish, FEMS Immunol. Med. Microbiol. 52 (2) (2008) 145–154.

[217] A. Wang, C. Ran, E. Ringø, Z. Zhou, Progress in fish gastrointestinal microbiota research, Rev. Aquacult. 10 (3) (2018) 626–640.

[218] Y. Ma, Z. Liu, Z. Yang, M. Li, J. Liu, J. Song, Effects of dietary live yeast *Hanseniaspora opuntiae* C21 on the immune and disease resistance against *Vibrio splendidus* infection in juvenile sea cucumber *Apostichopus japonicus*, Fish Shellfish Immunol. 34 (1) (2013) 66–73.