Ann. Anim. Sci., Vol. 24, No. 4 (2024) 995–1006 *DOI: 10.2478/aoas-2024-0031*

sciendo

BACILLUS SP. AS POTENTIAL PROBIOTICS FOR USE IN TILAPIA FISH FARMING AQUACULTURE – A REVIEW

Srirengaraj Vijayaram[1], Chi-Chung Chou[1♦], Hary Razafindralambo[2,3], Hamed Ghafarifarsani[4♦], Elahe Divsalar[5], Hien Van Doan[6]

[1]Department of Veterinary Medicine, College of Veterinary Medicine, National Chung-Hsing University, 145 Xingda Rd. Taichung, Taiwan 40227
[2]ProBioLab, Campus Universitaire de la Faculté de Gembloux Agro-Bio Tech/Université de Liège, B-5030 Gembloux, Belgium
[3]BioEcoAgro Joint Research Unit, TERRA Teaching and Research Centre, Microbial Processes and Interactions, Gembloux Agro-Bio Tech/Université de Liège, B-5030 Gembloux, Belgium
[4]Department of Animal Science, Chaharmahal and Bakhtiari Agricultural and Natural Resources Research and Education Center, Agricultural Research, Education and Extension Organization (AREEO), Shahrekord, Iran
[5]Department of Food Hygiene and Quality Control, Faculty of Veterinary Medicine, Urmia University, Urmia, Iran
[6]Department of Animal and Aquatic Sciences, Faculty of Agriculture, Chiang Mai University, Chiang Mai, Thailand
[♦]Corresponding authors: hamed_ghafari@alumni.ut.ac.ir; ccchou@nchu.edu.tw

Abstract

Aquaculture is a crucial and rapidly expanding industry in global food production. Fisheries are also an essential socio-economic activity, providing abundant resources and remarkable prospects. However, due to the deteriorating ecological environment, aquatic animals are often exposed to traumatic conditions and are susceptible to bacterial infections that pose significant challenges for aquaculture production. The indiscriminate use of antibiotics in the past has led to the emergence of multidrug-resistant pathogens and sudden outbreaks of infectious diseases, resulting in serious economic losses. Moreover, the use of expensive chemotherapeutic drugs and antibiotics has negative impacts on aquatic environments. Therefore, it is increasingly important to adopt alternative natural agents, such as probiotics and their metabolites, to enhance healthy fish production. Probiotics are microorganisms that have numerous beneficial effects on their hosts. They are environmentally friendly, non-toxic, and cost-effective. This review specifically focuses on the use of *Bacillus* sp. as probiotics to promote healthy tilapia production in the aquatic sector, while also examining their interactions with the immune system and gut microbiota. The information presented in this review can guide future research and promote effective and healthy tilapia culture production.

Key words: *Bacillus* sp., disease resistance, gut health, immune system, tilapia, wastewater treatment

Fish and fishery products are essential sources of protein and micronutrients for human health (Carbone and Faggio, 2016). Tilapia (*Oreochromis niloticus*) is the second most farmed fish globally, it is a freshwater species (Narimbi et al., 2018; Trosvik et al., 2013). The production of tilapia has steadily increased with the growing demand and market value (Andriani et al., 2019; Lumsangkul et al., 2022; Elumalai et al., 2021; Kurian et al., 2021; Van Doan et al., 2019). Tilapia is a resilient fish that can thrive in various environments, grow rapidly, and withstand challenging conditions (FAO, 2018). The increase in production has also led to a rise in infections and disease outbreaks, resulting in significant economic losses (Van Hai, 2015 a, b; Abarike et al., 2018 a; Joffre et al., 2018; Elabd et al., 2022; Hamed et al., 2021). The most frequently identified infection agent in Nile tilapia culture is *Streptococcus agalactiae* (Van Doan et al., 2018). Various bacteria, including *Streptococcus* spp., *Francisella orientalis*, *Edwardsiella* spp., and *Vibrio* spp., can cause severe skin lesions, septicemia, nervous system damage, and meningoencephalitis, resulting in high economic losses in tilapia farming (Xu et al., 2019). Intensive feeding practices, high stocking densities, disease outbreaks, and environmental and management issues can lead to increased mortality rates in farmed tilapia (Lee et al., 2019; Dawood et al., 2020). Aquaculture infections can be caused by bacteria, viruses, and parasites (Carbone and Faggio, 2016; Bastos Gomes et al., 2017). Fish commonly contract bacterial infections from *Vibrio* sp., *Streptococcus* sp., *Aeromonas* sp., *Pseudomonas* sp., *Clostridium* sp., *Yersinia* sp., *Acinetobacter* sp., and *Lactococcus* sp. (Santos et al., 2018; Yi et al., 2018). Researchers have recently been exploring ways to strengthen the immune systems of fish as a means of managing and preventing disease outbreaks (Cerezuela et al., 2012). Phagocytosis is a crucial element of the non-specific immune response, as it recognizes and breaks down pathogens and other foreign substances (Secombes, 1990; Steinhagen and Jendrysek, 1994). The use of antibiotics in aquaculture for disease control and growth promotion can alter intestinal microbiota and increase bacterial resistance, which can be harmful or toxic to aquatic species (Dawood et al., 2018; Elumalai et al., 2020; Hoseinifar et al., 2020). To counter this, various subsequent processes are being used, including probiotics, prebiotics, para-probiotics, vaccines, and medicinal plants (Pérez-Sánchez et al., 2014; Van Hai, 2015 a, b; Abarike et al., 2018 b; Choudhury and Kamilya, 2018; Kuebutornye et al., 2019). Potential probiotic strains possess various characteristic features that enable them to survive the harsh conditions of the gastrointestinal tract. These features include tolerance to acid and bile salts, resistance to gastric juices, ability to produce extracellular enzymes and antimicrobial components that can kill or suppress the growth of pathogens *in vitro*, capability to adhere to intestinal mucus, and ability to colonize the gut (Ringø, 2020). Furthermore, these probiotic strains must meet biosafety requirements, such as non-haemolytic activity and susceptibility to antibiotics, among others (Ringø, 2020). Probiotics offer a promising solution for aquaculture as they bring numerous benefits in comparison to other preventive measures. They provide support in improving fish growth and health, while also protecting the environment. Using probiotics can help boost disease resistance in aquaculture (Abarike et al., 2018 a; Hlordzi et al., 2020; Van Hai, 2015 a, b). Numerous types of bacterial genomes are regulated by bioproducts, which govern bacterial functions, physiology, and cell development. (Grubbs et al., 2017). It is important to conduct a comparative genomic experiment for a specific probiotic strain. Generalizing the results may not be accurate (Lehri et al., 2017). Dietary administration of *B. subtilis* probiotics had a significant impact on the phagocytic and respiratory burst functions of tilapia (Aly et al., 2008 a). There are various types of probiotic *Bacillus* species, each with unique characteristics such as the ability to produce non-pathogenic and nontoxic substances, improve the quality of water, and withstand harsh conditions due to their sporulation capability. These traits differentiate them from other probiotics and provide them with advantages such as heat tolerance and longer shelf-life (Kavitha et al., 2018; Buruiană et al., 2014; Kuebutornye et al., 2019; Geng et al., 2012). Probiotic *Bacillus* species used in aquaculture are sourced from various places, including soil, water, decaying matter, the gastrointestinal tract of fish and other vertebrates, and commercial sources. Over the years, *Bacillus* sp. has demonstrated its benefits in the aquaculture industry, and several studies have reported its positive effects in Nile tilapia culture (Sumon et al., 2018; Adorian et al., 2018; Sankar et al., 2017; Kuebutornye et al., 2019; Han et al., 2015; Wang et al., 2017) and enhancement of immune function and promotion of growth in other fish species (Irianto and Austin, 2002). In addition, they aid in the development of the host's digestive system, maintain the balance of intestinal microbiota, and influence the structure of the intestines (Allameh et al., 2016; Dagá et al., 2013). Therefore, probiotics have become vital ingredients in feed supplements, while improving the immune system and growth functions as above-mentioned, also inhibiting the growth of pathogens (Amir et al., 2019; Kuebutornye et al., 2020 a; Tachibana et al., 2021; Moustafa et al., 2021; El-Saadony et al., 2021; Liu et al., 2021; Hassaan et al., 2021). They are a successful and environmentally friendly alternative to antibiotics, improving rearing water quality and the fish's response to stress (Elsabagh et al., 2018). Figure 1 illustrates the difference between live probiotic cells and their dead or inactive counterparts, known as paraprobiotics or postbiotics. Paraprobiotics are nonviable probiotic cells with either whole or broken cell structure that provide certain beneficial effects for the host. These beneficial microbes lose their capability due to exposure to various factors that can modify their cell structure, such as severed DNA filaments, a disorder in the cell membrane, or mechanical damage in the cell envelope (Zendeboodi et al., 2020; de Almada et al., 2016). Currently, there is limited understanding of the impact of probiotics on single or mixed *Bacillus* strains when rearing tilapia in the environmental conditions of tilapia farms. As such, this review aims to investigate the effects of utilizing probiotic *Bacillus* strains to enhance the quality of water, intestinal health, disease resistance, immune system, and growth performance of farmed tilapia (El-Saadony et al., 2021).

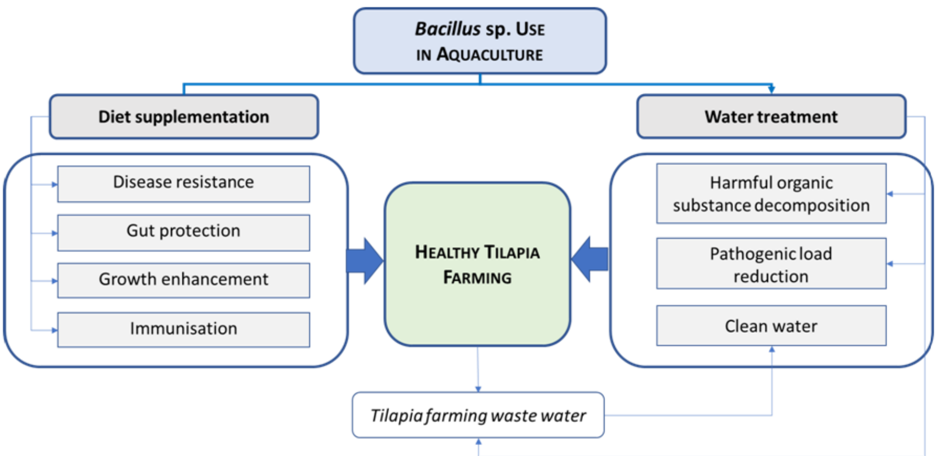

Figure 1. Role of *Bacillus* sp. tilapia fish farming

Table 1. Applications of *Bacillus* species as diet supplements in tilapia fish

Bacillus species	Source	Doses	Fish species	Pathogens	Applications	References
Bacillus subtilis	Commercial	3.9×10^7 CFU/g	Nile tilapia	*A. hydrophila*	Immuno-stimulation	(Addo et al., 2017)
		1.5×10^9 CFU/g	Nile tilapia	*A. hydrophila*		(Iwashita et al., 2015)
	NM	NM	Nile tilapia	*Flavobacte-rium columnare*	Immuno-stimulation	(Mohamed and Refat, 2011)
		1.1×10^5 CFU/g	Nile tilapia	NM	Immuno-stimulation	(Hassaan et al., 2018)
		10^6 and 10^{12} CFU/g diet fed	Nile tilapia	*S. iniae*	Disease resistance	(Aly et al., 2008 b)
		2.05×10^{10} CFU/kg	Yoshitomi tilapia	*A. hydrophila*	Disease resistance	(Tang et al., 2017)
B. subtilis SB3615	NM	4×10^7 CFU/g	Nile tilapia	*S. iniae*	Disease resistance	(Addo et al., 2016)
B. amyloliquefaciens	Commercial	1×10^6 CFU/g	Nile tilapia	*Clostridium perfrin-gens*	Immuno-stimulation	(Selim and Reda, 2015)
	NM	10^6–10^7 CFU/g	Nile tilapia	*A. hydrophila*	Disease resistance	(Chen et al., 2019)
B. cereus	NM	0.5%	Juvenile Nile tilapia	NM	Increase Hb	(Garcia-Marengoni et al., 2015)
B. licheniformis Dahb1 (HM235407.1)	NM	1×10^7 CFU/g	Mozambique tilapia	*A. hydrophila*	Disease resistance	(Gobi et al., 2018)
B. licheniformis	NM	0.1%	Hybrid red tilapia	*S. agalactiae*	Disease resistance	(Ng et al., 2014)
B. pumilus AQAH-BS01	NM	1×10 ^{7}–10^9 CFU/g	Nile tilapia	*S. agalactiae*	Disease resistance	(Srisapoome and Areecho, 2017)
B. subtilis and *B. licheniformis*	Commercial	5–10 g/ kg	Nile tilapia	*S. agalactiae*	Immuno-stimulation	(Abarike et al., 2018 a, b)
B. cereus and *B. subtilis*	NM	0.5%	Nile tilapia	NM	Increase HCT	(Garcia-Marengoni et al., 2015)

NM: not mentioned; NA: not applicable, HCT: haematocrit; Hb: haemoglobin, CFU: colony forming unit.

Dietary supplementation

Probiotic *Bacillus* species have become popular in aquaculture due to their ability to withstand unfavourable conditions through sporulation. Feed supplements containing these species are non-pathogenic, environmentally friendly, and have little toxic effects (Zendeboodi et al., 2020). They also may produce antimicrobial components that fight pathogenic infections and secrete hydrolytic enzymes to improve nutrient utilization (Zendeboodi et al., 2020). During a 4–8 weeks trial, Nile tilapia was fed with probiotic *B. subtilis* HAINUP40 (10^8 CFU/g) as an additive. The probiotic significantly improved growth, immunity, and disease resistance (de Almada et al., 2016). The probiotic *B. subtilis* supplement is used in tilapia culture at different concentrations, such as 3 g/kg^{-1} (BS3), 5 g/kg^{-1} (BS5), 7 g/kg^{-1} (BS7), and 10 g/kg^{-1} (BS10). When added to 10 g/kg^{-1} (BS10) diets, it can improve the growth, immune system, and infection resistance against *S. agalactiae* infection in tilapia (Kuebutornye et al., 2019). Dietary inclusion of probiotic *B. licheniformis* Dahb1 at a concentration of 10^7 CFU/g can enhance the immune system, antioxidant activity, and infection tolerance in Mozambique tilapia against *Aeromonas hydrophila* during a 4-week trial period (Liu et al., 2017). *Bacillus* sp. NP5 probiotic and paraprobiotic supplements improved Nile tilapia's immune system, survival rate, and infection resistance against *S. agalactiae* in a 30-day trial (Gobi et al., 2018). During an 84-day trial period, Nile tilapia was fed a diet that included a probiotic supplement consisting of 1.85 × 10^5 *B. pumilus* CFU/kg of diet and 0.5 g of protease kg^{-1}. After the trial period, it was observed that the immune response, intestinal histological morphometric, growth performance, haematological, serum biochemical, metabolic gene expression, and intestinal bacterial flora of the tilapia were significantly improved. This positive outcome was achieved despite the diet being free of fish meal (Mulyadin et al., 2021). Dietary inclusion of *Bacillus* probiotics (10^8 CFU/g) enhanced growth, feed utilization, and disease resistance against *A. hydrophila* in Nile tilapia over a 30-day trial (Hassaan et al., 2021). During a feeding experiment in tilapia farming, the effects of different concentrations of probiotic *B. subtilis* LT3-1 were studied. The concentrations used were 3.8 × 10^{10} (B1), 7.6 × 10^{10} (B2), 1.14 × 10^{11} (B3), and 1.52 × 10^{11} (B4) CFU/kg, compared to a reference feeding without probiotics, over six weeks. The results showed that the optimal concentration of probiotic *B. subtilis* LT3-1

(3.8×10^{10}–7.6×10^{10} CFU/kg) significantly improved growth and the immune system of tilapia. Additionally, it provided increased resistance against *S. agalactiae* infection in tilapia farming (Samson et al., 2020). There is limited information available on the efficiency of probiotic *Bacillus* species in Nile tilapia farming in terms of their effects on gut health and mucosal immunity, particularly their host connection (Kuebutornye et al., 2019). Dietary inclusion of probiotics *B. subtilis* TPS4, *B. velezensis* TPS3N, and *B. amyloliquefaciens* TPS17, either alone or in combination, significantly improved tilapia farming by enhancing mucosal immunity, intestinal health, and disease tolerance towards *A. hydrophila* infection (Zhu et al., 2019). A feeding assessment was conducted to examine different concentrations (0.5% to 2%) of probiotics (Biogen) during 120 days of Nile tilapia farming. The study results showed a significant improvement in growth rate and nutrient efficiency (Kuebutornye et al., 2020 b, c). Table 1 lists some applications of single and combined *Bacillus* species and strains as diet supplements for tilapia fish.

Mechanisms and impact on tilapia health

Gastrointestinal tract of tilapia

The intestinal microbiome has a substantial impact on the maintenance of gut well-being and the metabolism of the individuals it inhabits. The intestinal lining is influenced by various internal elements, such as feeding patterns, as well as external factors, including the microbial population in water, dietary choices, and the surrounding environment (Nayak 2010 a; Yukgehnaish et al., 2020). The intricate and dynamic microbial community within the intestinal tract can be influenced by and has the potential to govern aspects of fish nutrition, well-being, mucosal growth, maturation, metabolic processes, and the ability to resist infections in tilapia (Standen et al., 2015). Numerous investigations have demonstrated the gut microbiota's capacity to establish connections with the host's tissues and oversee functions related to energy metabolism, body weight, fat distribution, insulin sensitivity, and lipid metabolism (Zhang and Zhang, 2013; Falcinelli et al., 2015; Kim et al., 2018). The study by Sánchez et al. (2017) demonstrates the significant contribution of gut bacterial populations. These contributions include fortifying the epithelial barrier, restraining the proliferation of pathogens, promoting the development of gut-associated lymphoid tissue, breaking down indigestible polysaccharides, and producing essential bio-products such as vitamins, fatty acids, amino acids, and bacteriocins (Sánchez et al., 2017). The gut microbiota has been recognized as a biological indicator for assessing nutritional well-being, nutrient absorption, and the reinforcement of the immune system in fish (Adeoye et al., 2016; Ray et al., 2012; Niu et al., 2019). The influence of the intestinal microbial community is pivotal in the context of dietary supplements for fish (Zhang et al., 2019 a). Probiotics for fish have a beneficial role in enhancing gut microbial equilibrium and modifying the innate immune responses in fish (Liu et al., 2016). Beneficial gut microbes serve a crucial role in preserving the host's intestinal microbial equilibrium by replacing harmful bacteria with beneficial ones and thwarting the colonization of pathogens in the gut. The specific choice of beneficial microbes used determines their effectiveness in achieving this balance (Nayak, 2010 b). The dietary introduction of two probiotics can withstand the digestive process throughout the fish's growth period and can yield various positive impacts on the host (Ringø et al., 2016; Li et al., 2018). The inclusion of probiotic *B. subtilis* in the diet resulted in substantial enhancements in intestinal structure, as well as increased growth and the accumulation of protein and lipids throughout the entire body of tilapia. This outcome was compared with the control group in the study report (Sayes et al., 2018). In a 56-day experiment with Nile tilapia, the addition of probiotic *B. subtilis* C-3102 at a concentration of 2.5×10^5 CFU/g resulted in a remarkable improvement in the composition of the intestinal microbiota. Furthermore, it triggered an increase in the expression of cytokines, specifically IL-1b, TGF-β, and TNF-α, and a decrease in the expression of intestinal HSP70, as reported in a study (Adeoye et al., 2016 a, b).

Disease resistance

Probiotic *Bacillus* species demonstrate a strong inhibitory activity against a wide range of fish pathogens, including *Aeromonas*, *Vibrio*, *Streptococcus*, *Yersinia*, *Pseudomonas*, *Clostridium*, *Acinetobacter*, *Edwardsiella*, *Flavobacterium*, white spot syndrome virus, and communicable hypodermal and hematopoietic necrosis virus. These inhibitory effects are achieved through various mechanisms, including the synthesis of bacteriocins, regulation of virulence gene expression, competition for adhesion sites, production of lytic enzymes, synthesis of antibiotics, immunostimulation, nutrient and energy competition, and the production of organic acids. These multifaceted mechanisms contribute to the enhanced ability to combat pathogens in the aquaculture industry (He et al., 2013). Kuebutornye et al. (2020 d) investigated the identification and characterization of probiotics derived from the Nile tilapia fish gut, specifically *B. subtilis* TPS4 (MK130899), *B. velezensis* TPS3N (MK130897), and *B. amyloliquefaciens* TPS17 (MK130898). These probiotics displayed susceptibility to a variety of antibiotics, including gentamicin, penicillin, ampicillin, tetracycline, cephalexin, chloramphenicol, kanamycin, ceftriaxone, amikacin, cefoperazone, erythromycin, doxycycline, ciprofloxacin, and clindamycin (except TPS4), and furazolidone (except TPS17) (Kuebutornye et al., 2020 c). Moreover, these probiotics exhibited strong antimicrobial effects against various fish pathogens, including *S. agalactiae*, *A. hydrophila*, and *Vibrio harveyi*. The results of the study suggest that probiotic *Bacillus* species have significant potential for application in tilapia aquaculture, as they can contribute to enhancing disease resistance and overall health in these fish (Kuebutornye et al., 2020 b). The addition of microencapsulated probiotic *Bacillus* sp. NP5 to the diet significantly enhanced immune responses, promoted growth, and increased resistance to *S. agalactiae* infection in tilapia culture (Agung and Yuhana, 2015). Probiotic *Bacillus* species exhibit strong antagonistic properties against pathogens, are capable of synthesizing beneficial metabolites and antibiotics, possess immunomodulatory abilities, and can effectively contribute to disease control in aquaculture (Al-Ajlani and Hasnain, 2010; Amin et al., 2015; McKeen et al., 1985; Silo-Suh et al., 1994). The dietary inclusion of the potential probiotic *B. velezensis* LF01 strain demonstrated the most robust antagonistic effect against *S. agalactiae*. Additionally, the probiotic's bioproduct exhibited substantial antimicrobial activity against a variety of fish pathogens, including *S. agalactiae*, *A. hydrophila*, *Streptococcus iniae*, *Edwardsiella tarda*, *Edwardsiella ictaluri*, *A. schubertii*, *A. veronii*, *A. jandaei*, and *Vibrio harveyi* in tilapia culture. As a result, the inclusion of the probiotic *Bacillus velezensis* LF01 in the diet significantly enhanced the infection resistance to *S. agalactiae* in tilapia culture (Zhang et al., 2019 b). The inclusion of a potential probiotic *Bacillus* species combination in the diet exhibits superior immunomodulatory effects in countering *S. iniae* infection within the context of tilapia culture (Moustafa et al., 2021). The inclusion of the probiotic *B. subtilis* strain HAINUP40 in the diet has been found to enhance disease resistance against *S. agalactiae* in tilapia culture (Zhao, 2014).

Immune system enhancement of tilapia

The addition of single or combined probiotic and exogenous enzyme diet supplements has demonstrated a significant improvement in the immune system, including increased phagocytic and lysozyme activity in tilapia (Hassaan et al., 2021). These enhancements in phagocytic and lysozyme functions have significantly fortified the immune system of fish, making them more effective in defending against harmful microbes (MacArthur and Fletcher, 1985). The incorporation of a diet containing probiotic *Bacillus* species has been shown to enhance the immune system of fish (Tort et al., 2003; Magnadóttir, 2006; Uribe et al., 2011; Thompson, 2017; Wilson, 2017). Probiotic *B. subtilis* C-3102 has been found to produce bioproducts such as β-glucan and bacteriocins, which are included in diet supplements to promote the stimulation of the immune system in tilapia (He et al., 2013). The addition of *B. subtilis* NZ86 or O14VRQ to the diet has significantly enhanced the immune system's response against pathogens in tilapia culture (Galagarza et al., 2018). In a 50-day experiment, the dietary incorporation of marine thermotolerant probiotic *B. paralicheniformis* SO-1 at a concentration of 5–10 g/kg resulted in notable improvements in the immune system's capacity, feed digestion, and overall performance in tilapia (Makled et al., 2019). Dietary inclusion of probiotic *Bacillus* species has been shown to enhance the immune system, with a particular increase in globulin levels in Nile tilapia (Elsabagh et al., 2018; Zhou et al., 2010). In a feeding trial lasting 84 days, the dietary administration of *Bacillus subtilis* at a concentration of 5×10^6 CFU/g of feed notably improved the nonspecific immune system, including lysozyme and phagocytic activities of macrophages. Additionally, it helped reduce stress associated with high stocking densities in Nile tilapia (Telli et al., 2014). The dietary inclusion of *B. subtilis* strains NZ86 or O14VRQ at 51 days in a feeding trial significantly enhanced the innate immune response, phagocytic, respiratory, and complement activities, as well as upregulated the expression of proinflammatory and cytokine genes in Nile tilapia (Galagarza et al., 2018). In a separate study, the oral dietary administration of *B. subtilis* spores exposed to specific immunogenic proteins improved the immune system and increased resistance against *S. agalactiae* in Nile tilapia (Yao et al., 2019). Furthermore, the probiotic *B. amyloliquefaciens*, when added at concentrations of 10^6 and 10^4 CFU/g after a 30-day feeding trial, particularly increased serum lysozyme activity, enhanced serum killing, elevated serum nitric oxide levels, and raised interleukin-1 (IL-1) and tumor necrosis factor α (TNF α) mRNA levels in anterior kidney tissues. This led to improved disease resistance against *Clostridium perfringens* type D or *Yersinia ruckeri* in Nile tilapia (Selim and Reda, 2015). In yet another study, the dietary incorporation of *B. cereus* at 1.0×10^7 CFU/g during a 42-day trial period significantly improved the immune system and regulated gut microbiota in Nile tilapia. The direct method of administration was found to be more efficient compared to the indirect method (Wang et al., 2017).

Effect of growth enhancement of tilapia

Dietary incorporation of probiotic *Bacillus amyloliquefaciens* at concentrations of 1×10^4 and 1×10^6 CFU/g during a 60-day trial significantly improved various growth parameters, including body weight (BW), weight gain (WG), specific growth rate (SGR), and food conversion ratio (FCR). Additionally, it led to increased intestinal villi height and helped maintain gut microbiota (Reda and Selim, 2015). In another study, the inclusion of potential probiotic *Bacillus safeness* NPUST1 at concentrations of 10^6 CFU/g and 10^7 CFU/g during an 8-week feeding trial notably improved weight gain, feed efficiency, specific growth rate, and the overall health status of tilapia (110). Furthermore, the dietary administration of potential probiotic *B. licheniformis* at 10^9 CFU/g has been shown to enhance weight gain, feed efficiency, specific growth rate, and overall immunity in tilapia culture. This probiotic presents an alternative approach for both feeding and therapeutic purposes in the aquaculture sector (Wu et al., 2021). The effects of various probiotic *Bacillus* strains in tilapia fish are diverse: probiotic *Bacillus* sp. KUAQ1 and *Bacillus* sp. KUAQ2 dietary supplements did not have a significant impact on standard daily growth, normal weight, exact growth ratio, or feed conversion ratio in tilapia fry following an 8-week feeding trial (Yaqub et al., 2021).

Dietary administration of *B. subtilis* at a concentration of 1.6 × 10^{10} CFU/g significantly improved weight gain and increased thrombocyte counts in the tilapia bloodstream. This dietary management also led to modifications in the gut microbiota and reduced the presence of potential pathogenic species (Sookchaiyaporn et al., 2020). The dietary inclusion of *B. licheniformis* Dahb1 at concentrations of 10^5–10^7 CFU/g significantly improved final weight (FW), specific growth ratio (SGR), and feed conversion ratio (FCR) in tilapia fish after a 4-week trial period (Tachibana et al., 2021). Probiotic *B. subtilis* strain HAINUP40 at a concentration of 10^8 CFU/g notably increased the percent weight gain (PWG), final body weight, specific growth ratio (SGR), and significantly reduced feed conversion ratio in Nile tilapia during an 8-week feeding trial (Gobi et al., 2018). Probiotic *B. subtilis* E221 at a concentration of 10^8 CFU/g, administered over an 8-week trial period in Nile tilapia, significantly improved weight gain, specific growth rate, and feed conversion ratio. It also played a role in modulating gut microbiota composition under hypersaline stress (Liu et al., 2017). Dietary supplementation with *B. subtilis* at 4 g/kg during a 12-week feeding trial notably improved average body weight (BW), body length (BL), weight gain (WG), and specific growth ratio (SGR) for Nile tilapia fingerlings under the given experimental conditions (Tang et al., 2020).

Indirect use through water quality management

Probiotic microflora treatments in aquaculture water provide a range of benefits, including:

Reduction of Pathogenic Load: These treatments help decrease the presence of harmful microorganisms in the aquatic environment (Soltan et al., 2016). Improved Water Quality: Probiotic *Bacillus* species have been used to significantly enhance water quality in shrimp aquaculture ponds. This enhancement is achieved by reducing levels of ammonia, phosphate, nitrate, nitrite, and chemical oxygen demand, resulting in improved conditions for shrimp growth and harvesting (Xiang-Hong et al., 2003). Organic Pollutant Reduction: Probiotic *Bacillus* species are directly applied to pond water to reduce organic pollutants and other contaminants. They work by breaking down organic matter into smaller units, thereby improving water quality. This effect is also beneficial for larval survival and growth in hatcheries (Porubcan, 1991 a, b). Water Quality Enhancement: Commercial probiotics such as *B. licheniformis* and *B. subtilis* have notably improved water quality guidelines, meeting acceptable ranges for pH, dissolved oxygen (DO) concentration, and ammonia levels, which are essential for successful fish cultivation (Das et al., 2017). Nutrient Reduction: The addition of probiotic *Bacillus* species in aquaculture ponds, with concentrations of 10^9 CFU/g feed/m^3, significantly reduces the levels of phosphorus, ammonia, nitrogenous compounds, biochemical oxygen demand (BOD), and chemical oxygen demand (COD). This treatment allows for the reuse of aquaculture wastewater following a bioremediation process, making it suitable for fish and prawn rearing (Loh, 2017). Alteration of Water Quality Criteria: Treatment with *B. megaterium* leads to significant changes in water quality criteria such as pH, alkalinity, total dissolved solids (TDS), DO, ammonia, phosphorus, BOD, and COD. Temperature and transparency remain unaffected by the treatment (El-Haroun et al., 2006). Water Quality Modulation: *Bacillus* species-treated water can modulate various water quality specifications, including pH, transparency, alkalinity, hardness, TDS, DO, COD, BOD, phosphates, nitrogenous species, heavy metals, oil spillage, and the reduction of pathogenic microorganisms. The bioremediation process involving *Bacillus* species achieves maximum results and is a suitable method for managing wastewater in aquaculture (Hlordzi et al., 2020). Nitrification: The addition of *Bacillus* probiotics promotes nitrification, a process that reduces hydrogen ion concentration and contributes to maintaining appropriate pH levels (Camargo and Alonso, 2006). Organic Matter Removal: *Bacillus* species are effective in removing organic matter from culture systems, which can help maintain water quality (Luis-Villaseñor et al., 2011). Involvement in the Nitrogen Cycle: *Bacillus species* play various roles in the nitrogen cycle, including ammonification, nitrification, denitrification, and nitrogen fixation (Hui et al., 2019; Rout et al., 2017; Verbaendert et al., 2011). For example, *Bacillus amyloliquefaciens* DT transforms organic nitrogen into ammonium, while *B. cereus* PB8 reduces NO_2–N from wastewater (Yousuf et al., 2017; Hui et al., 2019; Barman et al., 2018). Sludge Reduction: Probiotic *Bacillus* species in aquaculture wastewater help convert different forms of nitrogen, remove organic pollutants, recycle nutrients in the water column, and reduce sludge accumulation (Soltani et al., 2019). Metal and Hydrocarbon Degradation: Certain *Bacillus* strains, such as *B. fusiformis*, can improve low concentrations of Ca^{2+}, Mg^{2+}, and Fe^{2+} and degrade petroleum hydrocarbons (Dongfeng et al., 2011). In summary, probiotic *Bacillus* species have a significant impact on aquaculture water by enhancing water quality, reducing pollutants, and promoting a more sustainable and healthier aquatic environment. Additional applications of *Bacillus* species to better water quality criteria in aquaculture are listed in Table 2.

Conclusion

Tilapia fish holds significant economic importance in the aquaculture sector, but the growth in its production has been accompanied by increased susceptibility to infections and disease outbreaks, resulting in substantial economic losses. The conventional use of chemotherapeutic agents and antibiotics for disease control has raised concerns about their negative impact on aquatic species and the overall aquatic environment. As an alternative approach, probiotics, particularly those from the *Bacillus* genera, have emerged as promising solutions to promote healthy aquatic production in the field of aquaculture.

Table 2. *Bacillus* species treated to improve water quality parameter in aquaculture

Bacillus species	Sources	Doses	Water quality parameter	Role of applications	References
B. velezensis AP193	Soil and catfish intestine	NS	Total phosphorus, total nitrogen, nitrate	Water	(Thurlow et al., 2019)
Bacillus sp. YB1701	Coastal sediment	1×10^5 CFU/mL	*A. hydrophila* and *Vibrio parahemolyticus*, COD	Water	(Zhou et al., 2018)
B. subtilis FY99-01	Commercial	5×10^4 CFU/mL	pH, nitrite, phosphorus	Water	(Wu et al., 2016)
B. licheniformisi, B. subtilis, B. polymyxa, B. laterosporus and *B. circulans*	Commercial	10^8 CFU/L	Ammonia nitrogen, total bacteria count	Water	(Yaqub et al., 2021)
B. cereus PB88	Shrimp ponds	NS	*Vibrio harveyi, Vibrio vulnificus*, NO^{-2}–N	Denitrification medium	(Naderi Samani et al., 2016)
B. megaterium	Soil	NS	Copper, iron, zinc, manganese	Heavy metal solution	(Barman et al., 2018)
B. subtilis	Fermented pickles	10^5 and 10^8 CFU/mL	Ammonia, nitrite and nitrate ions	Synthetic pond water, water	(Stefanescu, 2015)

NM: not mentioned; NS: not specified; cfu: colony forming unit; COD: chemical oxygen demand; BOD: biochemical oxygen demand; TDS: total dissolved solids; TAN: total ammonia nitrogen.

Through this review, it has become evident that *Bacillus* probiotics offer a range of advantages and effects in tilapia farming:

Enhanced Disease Resistance: Probiotics have been shown to improve the disease resistance of tilapia, reducing the incidence of infections and disease outbreaks.

Boosted Immune System: Probiotic supplementation enhances the immune system of tilapia, making them more resilient to various pathogens.

Improved Growth Performance: Tilapia treated with probiotics exhibit enhanced growth performance, resulting in larger and healthier fish.

Enhanced Gut Health: Probiotics play a pivotal role in maintaining gut health in tilapia, contributing to better digestion and nutrient absorption.

Enhanced Water Quality: Probiotics, particularly those of the *Bacillus* genus, have been effective in improving water quality in aquaculture settings. They reduce the presence of pollutants, break down organic matter, and mitigate the negative effects of pathogenic microorganisms, resulting in a healthier aquatic environment.

Looking ahead, future innovations in aquaculture may involve various beneficial components, including prebiotics, synbiotics, nutrients, biomolecules, combinations of nanoparticles and probiotics, herbal fermented and mixed probiotics, and biopolymer-encapsulated probiotics. These novel combinations and approaches can further enhance feed additives, leading to healthier and more sustainable tilapia production in the aquaculture sector. By exploring and implementing these innovative strategies, aquaculture can continue to thrive while minimizing the environmental impact and ensuring the health of aquatic species.

Authors contribution

Srirengaraj Vijayaram: conceptualization, writing – original draft, literature search, table preparation, validation. Chi-Chung Chou: writing – review and editing, supervision, validation. Hary Razafindralambo: writing – review and editing, manuscript outline. Hamed Ghafarifarsanid: writing – review and editing, supervision, validation. Elahe Divsalar: writing – review and editing. Hien Van Doan: writing – review and editing.

Conflict of interest

The authors have no conflict of interest to declare for the publication of the present work.

Compliance with ethical standards

All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

Funding

The following address mentioned to funding: National Science and Technology Council, Taiwan, Grant Number: 112-2811-B-005-032.

Data availability statement

The data that support the findings of this study are openly available in ORBI at https://orbi.uliege.be/my-orbi. Existing literature was used, as well as open and restricted access papers, peer review journals, relevant reports that are available in literature databases such as ORBI, Google Scholar, and Pubmed.

References

Abarike E.D., Cai J., Lu Y., Yu H., Chen L., Jian J., Tang J., Jun L., Kuebutornye F.K.A (2018 a). Effects of a commercial probiotic BS containing *Bacillus subtilis* and *Bacillus licheniformis* on growth, immune response and disease resistance in Nile tilapia, *Oreochromis niloticus*. Fish Shellfish Immunol., 82: 229–238.

Abarike E.D., Jian J., Tang J. et al. (2018 b). Influence of traditional Chinese medicine and *Bacillus* species (TCMBS) on growth, immune response and disease resistance in Nile tilapia, *Oreochromis niloticus*. Aquac. Res., 49: 2366–2375.

Addo S., Carrias A.A., Williams M.A., Liles M.R., Terhune J.S., Davis D.A. (2016). Effects of *Bacillus subtilis* strains on growth, immune parameters, and *Streptococcus iniae* susceptibility in Nile tilapia, *Oreochromis niloticus*. J. World Aquacult. Soc., 48: 257–267.

Addo S., Carrias A.A., Williams M.A., Liles M.R., Terhune J.S., Davis D.A. (2017). Effects of *Bacillus subtilis* strains and the prebiotic Previda® on growth, immune parameters and susceptibility to *Aeromonas hydrophila* infection in Nile tilapia, *Oreochromis niloticus*. Aquacult. Res., 48: 4798–4810.

Adeoye A.A., Jaramillo-Torres A., Fox S.W., Merrifield D.L., Davies S.J. (2016). Supplementation of formulated diets for tilapia (*Oreochromis niloticus*) with selected exogenous enzymes: Overall performance and effects on intestinal histology and microbiota. Anim. Feed Sci. Technol., 215: 133–143.

Adeoye A.A., Yomla R., Jaramillo-Torres A., Rodiles A., Merrifield D.L., Davies S.J. (2016). Combined effects of exogenous enzymes and probiotic on Nile tilapia (*Oreochromis niloticus*) growth, intestinal morphology and microbiome. Aquaculture, 463: 61–70.

Adorian T.J., Jamali H., Farsani H.G., Darvishi P., Hasanpour S., Bagheri T., Roozbehfar R. (2018). Effects of probiotic bacteria *Bacillus* on growth performance, digestive enzyme activity, and hematological parameters of Asian Sea bass, *Lates calcarifer* (Bloch). Prob. Antimicrob. Prot., 11: 1–8.

Agung L.A., Yuhana M. (2015). Application of micro-encapsulated probiotic *Bacillus* NP5 and prebiotic mannan oligosaccharide (MOS) to prevent streptococcosis on tilapia *Oreochromis niloticus*. Res. J. Microbiol., 10: 571.

Al-Ajlani M.M., Hasnain S. (2010). Bacteria exhibiting antimicrobial activities; screening for antibiotics and the associated genetic studies. Open Conf. Proc J., 1: 230–238.

Allameh S.K., Yusoff F.M., Ringø E., Daud H.M., Saad C.R., Ideris A. (2016). Effects of dietary mono-and multiprobiotic strains on growth performance., gut bacteria and body composition of Javanese carp (*Puntius gonionotus*, Bleeker 1850). Aquacult. Nutr., 22: 367–373.

Aly S.M., Ahmed Y.A.G., Ghareeb A.A.A., Mohamed M.M. (2008 a). Studies on *Bacillus subtilis* and *Lactobacillus acidophilus*, as potential probiotics, on the immune response and resistance of Tilapia nilotica (*Oreochromis niloticus*) to challenge infections. Fish Shellfish Immunol., 25: 128e36.

Aly S.M., Mohamed M.F., John G. (2008 b). Effect of probiotics on survival. growth and challenge infection in Tilapia nilotica (*Oreochromis niloticus*). Aquacult. Res., 39: 647–656.

Amin M., Rakhisi Z., Ahmady A.Z. (2015). Isolation and identification of *Bacillus* species from soil and evaluation of their antibacterial properties. Avicenna J. Clin Microb. Infec., 2: 10–13.

Amir I., Zuberi A., Kamran M., Imran M. (2019). Evaluation of the commercial application of dietary encapsulated probiotic (*Geotrichum candidum* QAUGC01): Effect on growth and immunological indices of rohu (*Labeo rohita*, Hamilton 1822) in semi-intensive culture system. Fish Shellfish Immunol., 95: 464–472.

Andriani Y., Anna Z., Iskandar I., Wiyatna M.F. (2019). The effectiveness of commercial probiotics appropriation on feed on Nile tilapia (*Oreochromis niloticus*)'s growth and feed conversion ratio. Asian J. Microbiol. Biotechnol. Environ. Sci., 21: 1–4.

Barman P., Bandyopadhyay P., Kati A., Paul T., Mandal A.K., Mondal K.C., Das Mohapatra P.K. (2018). Characterization and strain improvement of aerobic denitrifying EPS producing bacterium *Bacillus cereus* PB88 for shrimp water quality management. Waste Biomass Valorization, 9: 1319–1330.

Bastos Gomes G., Jerry D.R., Miller T.L., Hutson K.S. (2017). Current status of parasiticiliates *Chilodonella* spp. (Phyllopharyngea: Chilodonellidae) in freshwater fish aquaculture. J. Fish Dis., 40: 703–715.

Buruiană C.T., Profir A.G., Vizireanu C. (2014). Effects of probiotic *Bacillus* species in aquaculture – an overview. The Annals of the University Dunarea de Jos of Galati. Fascicle VI-Food Technol., 38: 9–17.

Camargo J.A., Alonso Á. (2006). Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. Environ Int., 32: 831–849.

Carbone D., Faggio C. (2016). Importance of prebiotics in aquaculture as immunostimulants. Effects on immune system of *Sparus aurata* and *Dicentrarchus labrax*. Fish Shellfish Immunol., 54: 172–178.

Cerezuela R., Guardiola F.A., González P., Meseguer J., Esteban M.Á. (2012). Effects of dietary *Bacillus subtilis*, *Tetraselmischuii*, and *Phaeodactylum tricornutum*, singularly or in combination, on the immune response and disease resistance of sea bream (*Sparus aurata* L.). Fish Shellfish Immunol., 33: 342–349.

Chen S., Liu C., Hu S. (2019). Dietary administration of probiotic *Paenibacillus ehimensis* NPUST1 with bacteriocin-like activity improves growth performance and immunity against *Aeromonas hydrophila* and *Streptococcus iniae* in Nile tilapia (*Oreochromis niloticus*). Fish Shellfish Immunol., 84: 695–703.

Choudhury T.G., Kamilya D. (2018). Paraprobiotics: an aquaculture perspective. Rev. Aquac., 1–13.

Dagá P., Feijoo G., Moreira M.T., Costas D., Villanueva A.G., Lema J.M. (2013). Bioencapsulated probiotics increased survival, growth and improved gut flora of turbot (*Psetta maxima*) larvae. Aquacult. Int., 21: 337–345.

Dawood M.A., Koshio S., Esteban M.Á. (2018). Beneficial roles of feed additives as immunostimulants in aquaculture: a review. Rev. Aquacult., 10: 950–974.

Dawood M.A., Metwally A.E.S., El-Sharawy M.E., Atta A.M., Elbialy Z.I., Abdel-Latif H.M., Paray B.A. (2020). The role of β-glucan in the growth, intestinal morphometry, and immune-related gene and heat shock protein expressions of Nile tilapia (*Oreochromis niloticus*) under different stocking densities. Aquaculture, 523: 735205.

de Almada C.N., Almada C.N., Martinez R.C., Sant'Ana A.S. (2016). Paraprobiotics: Evidences on their ability to modify biological responses, inactivation methods and perspectives on their application in foods. Trends Food Sci. Technol., 58: 96–114.

Dongfeng Z., Weilin W., Yunbo Z., Qiyou L., Haibin Y., Chaocheng Z. (2011). Study on isolation, identification of a petroleum hydrocarbon degrading bacterium Bacillus fusiformis sp. And influence of environmental factors on degradation efficiency. China Pet. Process. Petrochem. Technol., 13: 74–82.

Elabd H., Faggio C., Mahboub H.H., Emam M.A., Kamel S., E.l Kammar R., Matter A. (2022). *Mucuna pruriens* seeds extract boosts growth, immunity, testicular histology, and expression of immune-related genes of mono-sex Nile tilapia (*Oreochromis niloticus*). Fish Shellfish Immunol., 127: 672–680.

EL-Haroun E.R., Goda A.M.A.S., Kabir Chowdhury M.A. (2006). Effect of dietary probiotic Biogen supplementation as a growth promoter on growth performance and feed utilization of Nile tilapia *Oreochromis niloticus* (L.). Aquacult. Res., 37: 1473–1480.

El-Saadony M. T., Alagawany M., Patra A.K., Kar I., Tiwari R., Dawood M.A., Abdel-Latif H.M (2021). The functionality of probiotics in aquaculture: an overview. Fish Shellfish Immunol., 117: 36–52.

Elsabagh M., Mohamed R., Moustafa EM., Hamza A., Farrag F., Decamp O., Dawood M.A.O., Eltholth M. (2018). Assessing the impact of *Bacillus* strains mixture probiotic on water quality, growth performance, blood profile and intestinal morphology of Nile tilapia, *Oreochromis niloticus*. Aquac. Nutr., 24: 1–10.

Elumalai P., Kurian A., Lakshmi S., Faggio C., Esteban M.A., Ringø E. (2020). Herbal immunomodulators in aquaculture. Rev. Fish. Sci. Aquacult., 29: 33–57.

Elumalai P., Kurian A., Lakshmi S., Musthafa MS., Ringo E., Faggio C. (2021). Effect of *Leucas aspera* against *Aeromonas hydrophila* in Nile tilapia (*Oreochromis niloticus*): immunity and gene expression evaluation. Turk. J. Fish. Aquatic. Sci., 22.

Falcinelli S., Picchietti S., Rodiles A., Cossignani L., Merrifield D.L., Taddei A.R. (2015). *Lactobacillus rhamnosus* lowers zebrafish lipid content by changing gut microbiota and host transcription of genes involved in lipid metabolism. Sci. Rep., 5: 9336.

FAO (2018). Food and Agriculture Organization of the United Nations. Global aquaculture production 1950–2016. Retrieved from http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en

Fathi M., Dickson C., Dickson M., Leschen W., Baily J., Muir F., Ulrich K., Weidmann M. (2017). Identification of Tilapia Lake Virus in Egypt in Nile tilapia affected by 'summer mortality' syndrome. Aquaculture, 473: 430–432.

Galagarza O.A., Smith S.A., Drahos D.J., Eifert J.D., Williams R.C., Kuhn D.D. (2018). Modulation of innate immunity in Nile tilapia (*Oreochromis niloticus*) by dietary supplementation of *Bacillus subtilis* endospores. Fish Shellfish Immunol., 83: 171–179.

Garcia-Marengoni N., Cézar de Moura M., Escocard de Oliveira N.T., Bombardelli R.A., Menezes-Albuquerque D. (2015). Uso de los probióticos *Bacillus cereus* var. toyoi y *Bacillus subtilis* C-3102 en la dieta de juveniles de tilapia del Nilo cultivada en jaulas. Latin Am. J. Aquatic. Res., 43: 601–606.

Geng X., Dong X.H., Tan B.P. (2012). Effects of dietary probiotic on the growth performance., non-specific immunity and disease resistance of cobia, *Rachycentron canadum*. Aquac. Nutr., 18: 46–55.

Gobi N., Vaseeharan B., Chen J.C., Rekha R., Vijayakumar S., Anjugam M. (2018). Dietary supplementation of probiotic *Bacillus licheniformis* Dahb1 improves growth performance, mucus and serum immune parameters, antioxidant enzyme activity as well as resistance against *Aeromonas hydrophila* in tilapia *Oreochromis mossambicus*. Fish Shellfish Immunol., 74: 501–508.

Grubbs K.J., Bleich R.M., Santa Maria K.C., Allen SE., Farag S., Shank E.A. (2017). Large-Scale bioinformatics analysis of *Bacillus* genomes uncovers conserved roles of natural products in bacterial physiology. mSystems, 2: e00040-17.

Hamed H.S., Ismal S.M., Faggio C. (2021). Effect of allicin on antioxidant defense system, and immune response after carbofuran exposure in Nile tilapia, *Oreochromis niloticus* Comp Biochem Physiol Part C: Toxicol. Pharmacol., 240: 108919.

Han B., Long W., He J., Liu Y., Si Y., Tian L. (2015). Effects of dietary *Bacillus licheniformis* on growth performance, immunological parameters, intestinal morphology and resistance of juvenile Nile tilapia (*Oreochromis niloticus*) to challenge infections. Fish Shellfish Immunol., 46: 225–231.

Hassaan M.S., Soltan M.A., Jarmołowicz S., Abdo H.S. (2018). Combined effects of dietary malic acid and *Bacillus subtilis* on growth, gut microbiota and blood parameters of Nile tilapia (*Oreochromis niloticus*). Aquac. Nutr., 24: 83–93.

Hassaan M.S., Mohammady E.Y., Soaudy M.R., Elashry M.A., Moustafa M.M., Wassel M.A., Elsaied H.E. (2021). Synergistic effects of *Bacillus pumilus* and exogenous protease on Nile tilapia (*Oreochromis niloticus*) growth, gut microbes, immune response and gene expression fed plant protein diet. Anim. Feed Sci. Technol., 275: 114892.

He S., Zhang Y., Xu L., Yang Y., Marubashi T., Zhou Z., Yao B. (2013). Effects of dietary *Bacillus subtilis* C-3102 on the production., intestinal cytokine expression and autochthonous bacteria of hybrid tilapia *Oreochromis niloticus* × *Oreochromis aureus*. Aquaculture, 412: 125–130.

Hlordzi V., Kuebutornye F.K., Afriyie G., Abarike E.D., Lu Y., Chi S., Anokyewaa M.A. (2020). The use of *Bacillus* species in maintenance of water quality in aquaculture: A review. Aquacult. Rep., 18: 100503.

Hoseinifar S.H., Shakouri M., Yousefi S., Van Doan H., Shafiei S., Yousefi M., Faggio C. (2020). Humoral and skin mucosal immune parameters, intestinal immune related genes expression and antioxidant defense in rainbow trout (*Oncorhynchus mykiss*) fed olive (*Olea europea* L.) waste. Fish Shellfish Immunol., 100: 171–178.

Hui C., Wei R., Jiang H., Zhao Y., Xu L. (2019). Characterization of the ammonification, the relevant protease production and activity in a high-efficiency ammonifier *Bacillus amyloliquefaciens* DT. Int. Biodeteri. Biodeg., 142: 11–17.

Hura M.U.D., Zafar T., Borana K., Prasad J.R., Iqbal J. (2018). Effect of commercial probiotic *Bacillus megaterium* on water quality in composite culture of major carps. Int. J. Cur. Agricult. Sci., 8: 268–273.

Irianto A., Austin B. (2002). Probiotics in aquaculture. J. Fish Dis., 25: 633–642.

Iwashita M.K.P., Nakandakare I.B., Terhune J.S., Wood T., Ranzani-Paiva M.J.T. (2015). Dietary supplementation with *Bacillus subtilis*, *Saccharomyces cerevisiae* and *Aspergillus oryzae* enhance immunity and disease resistance against *Aeromonas hydrophila* and *Streptococcus iniae* infection in juvenile tilapia *Oreochromis niloticus*. Fish Shellfish Immunol., 43: 60–66.

Joffre O.M., Poortvliet P.M., Klerkx L. (2018). Are shrimp farmers actual gamblers? An analysis of risk perception and risk management behaviors among shrimp farmers in the Mekong Delta. Aquaculture, 495: 528–537.

Kavitha M., Raja M., Perumal P. (2018). Evaluation of probiotic potential of *Bacillus* spp. isolated from the digestive tract of freshwater fish *Labeo calbasu* (Hamilton., 1822). Aquac. Rep., 11: 59– 69.

Kim Y.A., Keogh J.B., Clifton P.M. (2018). Probiotics, prebiotics, synbiotics and insulin sensitivity. Nutr. Res. Rev., 31: 35–51.

Kuebutornye F.K.A., Abarike E.D., Lu Y. (2019). A review on the application of *Bacillus* as probiotics in aquaculture. Fish Shellfish Immunol., 87: 820–828.

Kuebutornye F.K., Abarike E.D., Lu Y., Hlordzi V., Sakyi M.E., Afriyie G., Xie C.X (2020 a). Mechanisms and the role of probiotic *Bacillus* in mitigating fish pathogens in aquaculture. Fish Physiol. Biochem., 46: 819–841.

Kuebutornye F.K., Abarike E.D., Sakyi M.E., Lu Y., Wang Z. (2020 b). Modulation of nutrient utilization, growth, and immunity of Nile tilapia., *Oreochromis niloticus*: the role of probiotics. Aquacult Int., 28: 277–291.

Kuebutornye F.K., Lu Y., Abarike E.D., Wang Z., Li Y., Sakyi M.E. (2020 c). *In vitro* assessment of the probiotic characteristics of three *Bacillus* species from the gut of Nile tilapia, *Oreochromis niloticus*. Probiotics Antimicrob. Proteins., 12: 412–424.

Kuebutornye F.K., Wang Z., Lu Y., Abarike E.D., Sakyi M.E., Li Y., Hlordzi V. (2020 d). Effects of three host-associated *Bacillus* species on mucosal immunity and gut health of Nile tilapia, *Oreochromis niloticus* and its resistance against *Aeromonas hydrophila* infection. Fish Shellfish Immunol., 97: 83–95.

Kurian A., Lakshmi S., Fawole F.J., Faggio C., Elumalai P. (2021). Combined effects of *Leucas aspera*, oxy-cyclodextrin and bentonite on the growth, serum biochemistry, and the expression of immune-related gene in Nile tilapia (*Oreochromis niloticus*). Turkish J. Fish. Aquat. Sci., 21: 147–158.

Lee J.M., Jang W.J., Hasan M.T., Lee B.J., Kim K.W., Lim S.G., Kong I.S. (2019). Characterization of a *Bacillus* sp. isolated from fermented food and its synbiotic effect with barley β-glucan as a biocontrol agent in the aquaculture industry. Appl. Microbiol. Biotechnol., 103: 1429–1439.

Lehri B., Seddon A.M., Karlyshev A.V. (2017). Potential probiotic-associated traits revealed from completed high quality genome sequence of *Lactobacillus fermentum* 3872. Stand. Genom. Sci., 12: 19.

Li X., Ringø E., Hoseinifar S.H. (2018). The adherence and colonization of microorganisms in fish gastrointestinal tract. Rev Aquacult., 11: 603–618.

Liu H., Wang S., Cai Y., Guo X., Cao Z., Zhang Y., Zhou Y. (2017). Dietary administration of *Bacillus subtilis* HAINUP40 enhances growth, digestive enzyme activities, innate immune responses and disease resistance of tilapia, *Oreochromis niloticus*. Fish Shellfish Immunol., 60: 326–333.

Liu Q., Wen L., Pan X., Huang Y., Du X., Qin J., Lin Y. (2021). Dietary supplementation of *Bacillus subtilis* and *Enterococcus faecalis* can effectively improve the growth performance, immunity, and resistance of tilapia against *Streptococcus agalactiae*. Aquacult. Nutr., 27: 1160–1172.

Liu Y., Yao Y., Li H., Qiao F., Wu J., Du Z., Zhang M. (2016). Influence of endogenous and exogenous estrogenic endocrine on intestinal microbiota in zebrafish. PLoS One, 11(10): e0163895.

Loh J.Y. (2017). The role of probiotics and their mechanisms of action: an aquaculture perspective. World Aquacult., 48: 19–23.

Luis-Villaseñor I.E., Macías-Rodríguez M.E., Gómez-Gil B., Ascencio-Valle F., Campa-Córdova Á.I. (2011). Beneficial effects of four

Bacillus strains on the larval cultivation of *Litopenaeus vannamei*. Aquaculture, 321: 136–144.

Lumsangkul C., Linh N.V., Chaiwan F., Abdel-Tawwab M., Dawood M.A., Faggio C., Van Doan H. (2022). Dietary treatment of Nile tilapia (*Oreochromis niloticus*) with aquatic fern (*Azolla caroliniana*) improves growth performance, immunological response, and disease resistance against *Streptococcus agalactiae* cultured in bio-floc system. Aquacult. Rep., 24: 101114.

MacArthur J.I., Fletcher T.C. (1985). Phagocytosis in fish. Fish Immunol., pp. 29–46. https://doi.org/10.1016/B978-0-12-469230-5.50007-6

Magnadóttir B. (2006). Innate immunity of fish (overview). Fish Shellfish Immunol., 20: 137–151.

Makled S.O., Hamdan A.M., El-Sayed A.F.M. (2019). Effects of dietary supplementation of a marine thermotolerant bacterium, *Bacillus paralicheniformis* SO-1, on growth performance and immune responses of Nile tilapia, *Oreochromis niloticus*. Aquacult. Nutr., 25: 817–827.

McKeen C.D., Reilly C.C., Pusey P.L. (1985). Production and partial characterization of antifungal substances antagonistics to *Monilinia fructicola* from *Bacillus subtilis*. Phytopathology, 76: 136–139.

Mohamed M.H., Refat N.A.A. (2011). Pathological evaluation of probiotic, *Bacillus subtilis*, against *Flavobacterium columnare* in Tilapia nilotica (*Oreochromis niloticus*) fish in Sharkia Governorate, Egypt. J. Am. Sci., 7: 244–256.

Moustafa E.M., Farrag F.A., Dawood M.A., Shahin K., Hamza A., Decamp O., Omar A.A. (2021). Efficacy of *Bacillus* probiotic mixture on the immunological responses and histopathological changes of Nile tilapia (*Oreochromis niloticus*, L.) challenged with *Streptococcus iniae*. Aquacult Res., 52: 2205–2219.

Mulyadin A., Widanarni W., Yuhana M., Wahjuningrum D. (2021). Growth performance., immune response, and resistance of Nile tilapia fed paraprobiotic *Bacillus* sp. NP5 against *Streptococcus agalactiae* infection. J. Akuak. Ind., 20: 34–46.

Naderi Samani M., Jafaryan H., Gholipour H., Harsij M., Farhangi M. (2016). Effect of different concentration of profitable *Bacillus* on bioremediation of common carp (*Cyprinus carpio*) pond discharge. Iranian J. Aquatic Anim. Health, 2: 44–54.

Narimbi J., Mazumder D., Sammut J. (2018). Stable isotope analysis to quantify contributions of supplementary feed in Nile tilapia *Oreochromis niloticus* (GIFT strain) aquaculture. Aquac. Res., 49: 1866–1874.

Nayak S.K. (2010 a). Probiotics and immunity: a fish perspective. Fish Shellfish Immunol., 29: 2–14.

Nayak S.K. (2010 b). Role of gastrointestinal microbiota in fish. Aquacult. Res., 41: 1553–1573.

Ng W.K., Kim Y.C., Romano N., Koh C.B., Yang S.Y. (2014). Effects of dietary probiotics on the growth and feeding efficiency of red hybrid tilapia, *Oreochromis* sp., and subsequent resistance to *Streptococcus agalactiae*. J. Appl. Aquacult., 26: 22–31.

Niu K.M., Khosravi S., Kothari D., Lee W.D., Lim J.M., Lee B.J., Kim S.K. (2019). Effects of dietary multi-strain probiotics supplementation in a low fishmeal diet on growth performance, nutrient utilization, proximate composition, immune parameters, and gut microbiota of juvenile olive flounder (*Paralichthys olivaceus*). Fish Shellfish Immunol., 93: 258–268.

Pérez-Sánchez T., Ruiz-Zarzuela I., de Blas I., Balcázar J.L. (2014). Probiotics in aquaculture: a current assessment. Rev. Aquac., 5: 1–14.

Porubcan R.S. (1991 a). Reduction in chemical oxygen demand and improvement in *Penaeus monodon* yield in ponds inoculated with aerobic *Bacillus* bacteria. Proc. 22nd Annual Conference and Exposition of the World Aquaculture Society, https://cir.nii.ac.jp/crid/1570572700330081408

Porubcan R.S. (1991 b). Reduction of ammonia nitrogen and nitrite in tanks of *Penaeus monodon* using floating biofilters containing processed diatomaceous earth media pre-inoculated with nitrifying bacteria. Proc. 22nd Annual Conference and Exposition of the World Aquaculture Society, pp. 16–20.

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

Reda R.M., Selim K.M. (2015). Evaluation of *Bacillus amyloliquefaciens* on the growth performance, intestinal morphology, hematology and body composition of Nile tilapia, *Oreochromis niloticus*. Aquacult. Int., 23: 203–217.

Reddy K.V., Reddy A.V.K., Babu B.S., Lakshmi T.V. (2018). Applications of *Bacillus* sp. in aquaculture waste water treatment. Int. JS Res. Sci. Tech., 4: 1806–1812.

Ringø E., Zhou Z., Vecino J.G., Wadsworth S., Romero J., Krogdahl Å., Merrifield D.L. (2016). Effect of dietary components on the gut microbiota of aquatic animals. A never-ending story? Aquacult. Nutr., 22: 219–282.

Ringø E. (2020). Probiotics in shellfish aquaculture. Aquacult. Fish., 5: 1–27.

Rout P.R., Bhunia P., Dash R.R. (2017). Simultaneous removal of nitrogen and phosphorous from domestic wastewater using *Bacillus cereus* GS-5 strain exhibiting heterotrophic nitrification, aerobic denitrification and denitrifying phosphorous removal. Biores. Technol., 244: 484–495.

Samson J., Quiazon K.M., Choresca C. (2020). Application of probiotic *Bacillus* spp. isolated from African nightcrawler (*Eudrilus eugeniae*) on Nile tilapia (*Oreochromis niloticus* L.). bioRxiv., https://doi.org/10.1101/2020.03.08.982819

Sánchez B., Delgado S., Blanco-Míguez A., Lourenço A., Gueimonde M., Margolles A. (2017). Probiotics, gut microbiota, and their influence on host health and disease. Mol Nutr. Food Res., 61: 1–15.

Sankar H., Philip B., Philip R., Singh I.S.B. (2017). Effect of probiotics on digestive enzyme activities and growth of cichlids, *Etroplus suratensis* (Pearl spot) and *Oreochromis mossambicus* (Tilapia). Aquac. Nutr., 23: 852–864.

Santos R.A., Oliva-Teles A., Saavedra M.J., Enes P., Serra C.R. (2018). *Bacillus* spp. as source of natural antimicrobial compounds to control aquaculture bacterial fish pathogens. Front. Mar. Sci., https://doi.org/10.3389/conf.FMARS.2018.06.00129

Sayes C., Leyton Y., Riquelme C. (2018). Probiotic bacteria as an healthy alternative for fish aquaculture. In: Antibiotic use in animals, Savic S. (ed.). IntechOpen, pp. 115–132.

Secombes C. (1990). Isolation of salmonid macrophages and analysis of their killing activity. Techniq. Fish Immunol., pp. 137–154.

Selim K.M., Reda R.M. (2015). Improvement of immunity and disease resistance in the Nile tilapia, *Oreochromis niloticus*, by dietary supplementation with *Bacillus amyloliquefaciens*. Fish Shellfish Immunol., 44: 496–503.

Silo-Suh L.A., Lethbridge B.J., Raffel S.J., He H., Clardy J., Handelsman J. (1994). Biological activities of two fungistatic antibiotics produced by *Bacillus cereus* UW85. Appl. Environ. Microbiol., 60: 2023–2030.

Soltan M.A., Fouad I.M., Elfeky A. (2016). Growth and feed utilization of Nile tilapia, *Oreochromis niloticus* fed diets containing probiotic. Global Vet., 17: 442–450.

Soltani M., Ghosh K., Hoseinifar S.H., Kumar V., Lymbery A.J., Roy S., Ringø E. (2019). Genus *Bacillus*, promising probiotics in aquaculture: aquatic animal origin, bio-active components, bioremediation and efficacy in fish and shellfish. Rev. Fish. Sci. Aquacult., 27: 331–379.

Sookchaiyaporn N., Srisapoome P., Unajak S., Areechon N. (2020). Efficacy of *Bacillus* spp. isolated from Nile tilapia *Oreochromis niloticus* Linn. on its growth and immunity, and control of pathogenic bacteria. Fish. Sci., 86: 353–365.

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

Standen B.T.., Rodiles A., Peggs D.L., Davies S.J., Santos G.A., Merrifield D.L. (2015). Modulation of the intestinal microbiota and morphology of tilapia, *Oreochromis niloticus*, following the application of a multi-species probiotic. Appl. Microbiol. Biotechnol., 99: 8403–8417.

Stefanescu I.A. (2015). Bioaccumulation of heavy metals by *Bacillus megaterium* from phosphogypsum waste. Sci. Stud. Res., Chem. Chemic. Eng. Biotechnol. Food Industr., 16: 93–97.

Steinhagen D., Jendrysek S. (1994). Phagocytosis by carp granulocytes; *in vivo* and *in vitro* observations. Fish Shellfish Immunol., 4: 521e4.

Sumon M.S., Ahmmed F., Khushi S.S., Ahmmed M.K., Rouf M.A., Chisty M.A.H., Sarower M.G. (2018). Growth performance., digestive enzyme activity and immune response of *Macrobrachium rosenbergii* fed with probiotic *Clostridium butyricum* incorporated diets. J. King Saud. Univ. Sci., 30: 21–28.

Tachibana L., Telli G.S., Dias D.D.C., Gonçalves G.S., Guimarães M.C., Ishikawa C.M., Ranzani-Paiva M.J.T. (2021). *Bacillus subtilis* and *Bacillus licheniformis* in diets for Nile tilapia (*Oreochromis niloticus*): Effects on growth performance, gut microbiota modulation and innate immunology. Aquacult. Res., 52: 1630–1642.

Tang L., Huang K., Xie J., Yu D., Sun Huang Q. (2017). 1-Deoxynojirimycin from *Bacillus subtilis* improves antioxidant and antibacterial activities of juvenile Yoshitomi tilapia. Electron. J. Biotechnol., 30: 39–47.

Tang S., Liu S., Zhang J., Zhou L., Wang X., Zhao Q., Li E. (2020). Relief of hypersaline stress in Nile tilapia *Oreochromis niloticus* by dietary supplementation of a host-derived *Bacillus subtilis* strain. Aquaculture, 528: 735542.

Telli G.S., Ranzani-Paiva M.J.T., Dias D.D.C., Sussel F.R., Ishikawa C.M., Tachibana L. (2014). Dietary administration of *Bacillus subtilis* on hematology and non-specific immunity of Nile tilapia *Oreochromis niloticus* raised at different stocking densities. Fish Shellfish Immunol., 39: 305–311.

Thompson K.D. (2017). Immunology: improvement of innate and adaptive immunity. In: Fish Diseases, Jeney G. (ed.). Academic Press, pp. 1–17.

Thurlow C.M., Williams M.A., Carrias A., Ran C., Newman M., Tweedie J., Allison E., Jescovitch L.N., Wilson A.E., Terhune J.S., Liles M.R. (2019). *Bacillus velezensis* AP193 exerts probiotic effects in channel catfish (*Ictalurus punctatus*) and reduces aquaculture pond eutrophication. Aquaculture, 503: 347–356.

Tort L., Balasch J.C., Mackenzie S. (2003). Fish immune system. A crossroads between innate and adaptive responses. Inmunología, 22: 277–286.

Trosvik K.A., Webster C.D., Thompson K.R., Metts L.A., Gannam A., Twibell R. (2013). Effects on growth performance and body composition in Nile tilapia, *Oreochromis niloticus*, fry fed organic diets containing yeast extract and soyabean meal as a total replacement of fish meal without amino acid supplementation. Biol. Agric. Hortic., 29: 173–185.

Uribe C., Folch H., Enríquez R., Moran G.J.V.M. (2011). Innate and adaptive immunity in teleost fish: a review. Veterinarni Medicina, 56: 486.

Van Doan H., Hoseinifar S.H., Khanongnuch C., Kanpiengjai A., Unban K., Srichaiyo S. (2018). Host-associated probiotics boosted mucosal and serum immunity, disease resistance and growth performance of Nile tilapia (*Oreochromis niloticus*). Aquaculture, 491: 94–100.

Van Doan H., Hoseinifar S.H., Sringarm K., Jaturasitha S., Yuangsoi B., Dawood M.A., Faggio C. (2019). Effects of Assam tea extract on growth, skin mucus, serum immunity and disease resistance of Nile tilapia (*Oreochromis niloticus*) against *Streptococcus agalactiae*. Fish Shellfish Immunol., 93: 428–435.

Van Hai N. (2015 a). The use of medicinal plants as immunostimulants in aquaculture: A review. Aquaculture, 446: 88–96.

Van Hai N. (2015 b). Research findings from the use of probiotics in tilapia aquaculture: a review. Fish Shellfish Immunol., 45: 592–597.

Verbaendert I., Boon N., De Vos P., Heylen K. (2011). Denitrification is a common feature among members of the genus *Bacillus*. Sys. Appl. Microbiol., 34: 385–391.

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

Wilson A.B. (2017). MHC and adaptive immunity in teleost fishes. Immunogenetics, 69: 521–528.

Wu D.X., Zhao S.M., Peng N., Xu C.P., Wang J., Liang Y.X. (2016). 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. Aquac. Res., 47: 857–869.

Wu P.S., Liu C.H., Hu S.Y. (2021). Probiotic *Bacillus safensis* NPUST1 administration improves growth performance, gut microbiota, and innate immunity against *Streptococcus iniae* in Nile tilapia (*Oreochromis niloticus*). Microorganisms, 9: 2494.

Xiang-Hong W., Jun L., Wei-Shang J., Huai-Shu X. (2003). Application of probiotics in aquaculture. Ocean University of Qungo, Qingdao. Online, pp. l–10.

Xu J., Xie Y.D., Liu L., Guo S., Su YL., Li A.X. (2019). Virulence regulation of cel-EIIB protein mediated PTS system in *Streptococcus agalactiae* in Nile tilapia. J. Fish Dis., 42: 11–19.

Yao Y.Y., Chen D.D., Cui Z.W., Zhang X.Y., Zhou Y.Y., Guo X., Zhang Y.A. (2019). Oral vaccination of tilapia against *Streptococcus agalactiae* using *Bacillus subtilis* spores expressing Sip. Fish Shellfish Immunol., 86: 999–1008.

Yaqub A., Awan N.M., Kamran M., Majeed I. (2021). Evaluation of potential applications of dietary probiotic (*Bacillus licheniformis* SB3086): Effect on growth, digestive enzyme activity, hematological, biochemical, and immune response of Tilapia (*Oreochromis mossambicus*). Turkish J. Fisheries Aquatic Sci., 22.

Yi Y., Zhang Z., Zhao F. (2018). Probiotic potential of *Bacillus velezensis* JW: Antimicrobial activity against fish pathogenic bacteria and immune enhancement effects on *Carassius auratus*. Fish Shellfish Immunol., 78: 322–330.

Yousuf J., Thajudeen J., Rahiman M., Krishnankutty S., Alikunj A., Abdulla M.H. (2017). Nitrogen fixing potential of various heterotrophic *Bacillus* strains from a tropical estuary and adjacent coastal regions. J. Basic Microbiol., 57: 922–932.

Yukgehnaish K., Kumar P., Sivachandran P., Marimuthu K., Arshad A., Paray BA., Arockiaraj J. (2020). Gut microbiota metagenomics in aquaculture: factors influencing gut microbiome and its physiological role in fish. Rev. Aquac., 1–25.

Zendeboodi F., Khorshidian N., Mortazavian A.M., da Cruz A.G (2020). Probiotic: conceptualization from a new approach. Curr. Opin. Food Sci., 32: 103–123.

Zhang C., Zhang J., Fan W., Huang M., Liu M. (2019 a). Effects of dietary *Lactobacillus delbrueckii* on growth performance, body composition, digestive and absorptive capacity, and gene expression of common carp (*Cyprinus carpio* Huanghe var). Aquacult. Nutr., 25: 166–175.

Zhang D., Gao Y., Ke X., Yi M., Liu Z., Han X., Lu M. (2019 b). *Bacillus velezensis* LF01: *in vitro* antimicrobial activity against fish pathogens., growth performance enhancement., and disease resistance against streptococcosis in Nile tilapia (*Oreochromis niloticus*). Appl. Microbiol. Biotechnol., 103: 9023–9035.

Zhang Y., Zhang H. (2013). The effect of probiotics on lipid metabolism. In: Lipid Metabolism, Baez R.V. (ed.). IntechOpen, pp. 443–460.

Zhao D.F.., Wu W.L., Zhang Y.B., Liu Q.Y., Yang H., Zhao C. (2011). Study on the isolation, identification of a petroleum hydrocarbon degrading *Bacillus fusiformis* sp. bacteria and its influence of environmental factors on the degradation efficiency. China Petrol Proc. Petro Technol., 13: 74–82.

Zhao G.J. (2014). The screening of antagonistic bacteria and it's antagonism on the adhesion of *Streptococcus agalactiae* to the mucus of tilapia (Master): Hainan University, Haikou, China.

Zhou S., Xia Y., Zhu C., Chu W. (2018). Isolation of marine *Bacillus* sp. with antagonistic and organic-substances-degrading activities and its potential application as a fish probiotic. Mar Drugs., 16: 196.

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

Zhu C., Yu L., Liu W., Jiang M., He S., Yi G., Liang X. (2019). Dietary supplementation with *Bacillus subtilis* LT3-1 enhance the growth, immunity and disease resistance against *Streptococcus agalactiae*

infection in genetically improved farmed tilapia, *Oreochromis niloticus*. Aquacult. Nutr., 25: 1241–1249.
Zokaeifar H., Babaei N., Saad C.R., Kamarudin M.S., Sijam K., Balcazar J.L. (2014). Administration of *Bacillus subtilis* strains in the rearing water enhances the water quality, growth performance, immune response, and resistance against *Vibrio harveyi* infection in juvenile white shrimp, *Litopenaeus vannamei*. Fish Shellfish Immunol., 36: 68–74.

Received: 13 XII 2023
Accepted: 2 II 2024