Int Aquat Res (2026) 18:1–12
https://doi.org/10.22034/IAR.2026.2009725.1966

REVIEW

Integration of probiotics, prebiotics and phytobiotics as a holistic approach to improve shrimp growth and immunity against pathogen

Nor Asma Husna Yusoff . Joey Joe Yee Ng . Farizan Abdullah . Ahmad Najmi Ishak . Marina Hassan

Received: 08 September 2025 / Accepted: 05 February 2026 / Published online: 26 September 2026
© The Author(s) 2026

Abstract Shrimp aquaculture is the most widely farmed crustacean sector due to its high nutritional value, rapid growth, and environmental adaptability. However, the intensification of farming has increased the risk of pathogen transmission and disease outbreaks. While antibiotics and chemotherapeutics were traditionally used to manage these issues, their overuse has led to antimicrobial resistance (AMR), environmental degradation, and food safety concerns. Consequently, sustainable natural alternative are increasingly being explored. Probiotics and prebiotics are commonly applied to regulate microbial communities and improve water quality, whereas plant-derived phytobiotics enhance shrimp immunity and reduce infection risks. Although numerous studies have reviewed these strategies individually, few have examined their combined application. This review emphasizes the synergistic potential of probiotics, prebiotics, and phytobiotics as an integrated approach to strengthen shrimp health, enhance disease resistance, and promote sustainable aquaculture practices that improve productivity and environmental safety.

Keywords Antimicrobial resistance (AMR) . Food security . Natural product . Sustainability

Introduction

Aquaculture has emerged as an important source of both marine and freshwater products to meet the growing demand for high-protein nutrition and global food security. Among cultured species, shrimp represents one of the fastest-growing commodities worldwide, valued for its high nutritional profile and market demand. The shrimp market was projected to expand at a compound annual growth rate (CAGR) of 4.18% through 2026,, reaching an estimated value of US$23.4 billion (Sampath et al. 2025). However, this rapid expansion is heavily constrained by various bacterial and viral disease outbreaks, which are frequently exacerbated by intensive farming conditions and inadequate management (Kim et al. 2021; Sampath et al. 2025). In addition, fluctuations in water quality, caused by the accumulation of toxic nitrogenous compounds, promote the pathogen proliferation, compromising shrimp health and overall productivity (Kim et al. 2021).

Alongside water quality management, gut health plays a critical role in protecting shrimp from disease and supporting overall growth performance. To date, farmers and industries have relied on various chemical disinfectants and antibiotics to control and prevent disease outbreaks. However, their overuse has raised significant concerns regarding food safety and the emergence of antimicrobial-resistant microorganisms

Nor Asma Husna Yusoff . Joey Joe Yee Ng . Ahmad Najmi Ishak . Marina Hassan (✉)
Higher Institution Centre of Excellence (HICoE), Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia Terengganu, 21300 Kuala Nerus, Terengganu, Malaysia
e-mail: marina@umt.edu.my

Farizan Abdullah
Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21300 Kuala Nerus, Kuala Terengganu, Terengganu, Malaysia

(Sampath et al. 2025). Although vaccination has been proposed as an alternative to antibiotics, its application in invertebrates remains limited because of their relatively simple immune systems (Rowley and Pope 2012), (Rowley and Pope 2012). Therefore, natural and sustainable strategies are essential to address these challenges. Among the most promising approaches is the use of probiotics, which serve as natural and sustainable disease-control agents, along with their combinations with prebiotics known as synbiotics and plant-derived phytobiotics (de la Peña et al. 2024). While the individual application of these strategies in cultured systems has been widely reported to bring multiple benefits (Carvalho et al. 2025; Muharrama et al. 2021), this review focuses on the combined use of these three components within a single culture system as potential synergistic strategies for optimizing shrimp growth and overall productivity. Table 1 summarizes recent studies on the application of probiotics, prebiotics, and phytobiotics in shrimp aquaculture, demonstrating significant improvements in immunity and production performance.

Probiotic, prebiotic, synbiotics and phytobiotic as functional additives in shrimp aquaculture and their mechanisms of actions

Probiotic

Probiotics are live microorganisms that can benefit host health when administered in adequate amounts, particularly by enhancing immunity, inhibiting bacterial pathogens, and improving intestinal barrier function (Xu et al. 2021). Dysbiosis of the intestinal microbiota can impair shrimp health, reduce disease resistance, and compromise immune responses, thereby increasing susceptibility to infections (Huang et al. 2020). A variety of commercial probiotics have been isolated and are widely available, predominantly belonging to the genera *Bacillus*, *Enterococcus*, *Aspergillus*, *Lactobacillus*, *Saccharomyces*, *Pseudomonas*, *Bifidobacterium*, and *Streptococcus* (Kim et al. 2021; Knipe et al. 2021). In aquaculture system, commercial probiotics are usually formulated into feeds or water additives to enhance shrimp growth and health (Carvalho et al. 2025). Among these, *Bacillus* spp. are the most commonly used due to their ability to grow efficiently on inexpensive carbon and nitrogen sources (Kewcharoen and Srisapoome 2019). Notably, many *Bacillus* spp. produce robust spores without harming shrimp hosts, while effectively improving water quality, growth performance, and disease resistance (de la Peña et al. 2024; Kim et al. 2021; Sampath et al. 2025).

Previous studies have shown that the inclusion of *Bacillus* spp. in feed and rearing water enhances the growth and survival of *Litopenaeus vannamei* during the zoea and mysis developmental stages, particularly against *Vibrio* spp. (de la Peña et al. 2024). The probiotic efficacy of *Bacillus* spp. is largely attributed to their ability to secrete quorum-quenching enzymes, bacteriocins, and proteases, which inhibit pathogen colonization in the shrimp gut, tract and enhance phagocytic activity, and promote resistance to pathogens (Zhao et al. 2025). Quorum quenching (QQ) refers to the inactivation of quorum sensing (QS) molecules to control bacterial diseases. Quorum sensing is a bacterial communication system in which microbes release and detect small molecules called autoinducers to assess population density (Moreno-Gámez et al. 2023). The mechanism involves bacterial enzymes degrading chemical signals, such as acyl-homoserine lactones (AHLs) thereby preventing pathogens from organizing into harmful biofilms. Monzón-Atienza et al. (2024) demonstrated that *Bacillus* spp. can disrupt AHL signalling molecules and interfere with the quorum sensing of pathogenic bacteria. Additionally, the production of AHL lactonase and AHL acylase by *Bacillus* spp. enables the disruption of quorum sensing in *Vibrio harveyi*, reducing its pathogenicity and protecting shrimp larvae from vibriosis (Shaheer et al. 2021). Beyond immunomodulation, *Bacillus* spp. also contributes to bioremediation by removing excess nitrogen and nitrites from rearing water, thereby mitigating water quality deterioration (Monier et al. 2023; Sampath et al. 2025).

In addition to *Bacillus* probiotics, *Lactobacillus* spp. also exhibit strong antagonistic activity against aquatic pathogens. Luo et al. (2023) demonstrated that dietary supplementation with lactic acid bacteria (LAB), such as *Lactobacillus plantarum* W2, enhanced shrimp growth, increased gut microbial diversity and improve resistance to vibriosis. Similarly, *Lactobacillus fermentum* isolated from estuarine sediments inhibits *Vibrio* growth by lowering gut pH to below 5 through bacteriocin production, thereby disrupting *Vibrio* quorum sensing and improving intestinal morphology (Goh et al. 2022). Other probiotics, including a mixture of *Shewanella algae* A3 and *Serratia marcescens* Van80 UB3, have also shown promising

Table 1 Some recent findings on the application of probiotics, prebiotics, synbiotics, and phytobiotics in the shrimp aquaculture

Approach	Shrimp species	Research outcomes	References
Probiotics			
A microbial mixture of *Bacillus albus* SMG-1, *Bacillus safensis* SMG-2	*L. vannamei*	Tolerates 1–50 ppt salinity and effectively removes ammonia and nitrites from culture water.	Kim et al. (2021)
B. subtilis AQUA-GROW®	*L. vannamei*	Inclusion of 1–1.5 g/kg enhanced shrimp growth, survival, feed digestion, lipid composition, immune response, and antioxidant activity after a 56-day feeding trial.	Eissa et al. (2022)
Marine purple non-sulfur bacteria (PNSB), *Rhodovulum sulfidophilum* KKMI01	*Marsupenaeus japonicus*	Requires as low as 1×10^3 CFU/mL in rearing water, making it economically viable for open ponds. Promotes shrimp growth, stimulates innate immunity (e.g., proPO, SOD, lysozyme, antimicrobial peptides, Toll, IMD), and poses no pathogenic risk to other organisms or humans.	Miyasaka et al. (2023)
PRO-2 (Sanolife® INVE Aquaculture, Belgium): a microbial mixture of *B. pumilus*, *B. licheniformes*, and *B. subtilis*	*L. vannamei*	Effectively enhances shrimp survival against *Vibrio* pathogens after over 7 days of application and can also decontaminate shrimp aquaculture equipment.	de la Peña et al. (2024)
Pediococcus acidilactici	*P. vannamei*	Inclusion of 3 g/kg dietary *P. acidilactici* improved shrimp growth, FCR, gut microbiota, immunity, antioxidant levels, and survival against *F. solani*.	Jastaniah et al. (2024)
Rhodobacter sphaeroides	*P. vannamei*	Inclusion at 10^7 CFU/mL significantly enhanced shrimp growth, immune response (e.g., crustin, ALF, penaeidin3), and resistance to *V. parahaemolyticus*, while also improving shrimp quality through increased astaxanthin, aspartic, and glutamic acid levels.	Sudpraseart et al. (2025)
A mix of *Shewanella algae* and *Serratia marcescens* Van80 at 10^6CFU/g	*L. vannamei*	Enhanced shrimp growth, gene expression (IGF-1, ecdysteroid, myosin), digestion (amylase, lipase, protease), and immunity (RB, proPO, phagocytosis, THC), with no significant tissue alterations.	Sutanti et al. (2025)
Prebiotics			
Yeast cell wall extract	*P. vannamei*	Enhanced shrimp growth, survival, and beneficial gut microbiota.	Arce et al. (2021)
β-1, 3 glucan	*L. vannamei*	Supplementing 0.156 g/kg β-1,3 glucan for 70 days improved shrimp growth, SOD, amylase activity, and feed utilization.	Xu et al. (2021)
FOS	*P. vannamei* post-larvae	Dietary 0.4 % FOS enhanced shrimp growth, stimulated immunity (proPO, lysozyme, lectins), and reduced *Vibrio* and *Pseudomonas* spp.	Barrios et al. (2023)
β-1, 3 glucan and FOS	*L. vannamei*	Supplementing 1.5 g/kg glucan and FOS for 75 days improved shrimp growth, digestion, non-specific immunity, antioxidant activity, and reduced mortality against *F. solani*.	Eissa et al. (2023)
Inulin	*L. vannamei*	Feeding 10–20 g/kg inulin-coated diet for 30 days enhanced immune gene expression, increased resistance to *Vibrio* spp. and WSSV, and improved gut microbial diversity and abundance.	Allie et al. (2025)
Inulin	*L. vannamei*	A 1.0 % inulin diet improved shrimp growth, survival, lysozyme and SOD activity, while reducing oxidative stress (MDA level). 16S rRNA analysis showed increased beneficial bacteria (*Xanthomarina* spp.) and reduced pathogens (*Flavobacteria*, *Vibrio* spp.).	Park et al. (2025)
Synbiotics (probiotic + prebiotic)			
Kappaphycus alvarezii + *Spirulina* sp. + probiotic *Halomonas alkaliphile*	*L. vannamei*	Feeding 0.375 % *K. alvarezii* + 0.125 % *Spirulina* sp. + 10^9 CFU/kg *H. alkaliphile* for 14 days significantly improved shrimp growth and survival against *V. harveyii*.	Situmorang et al. (2021)
Pseudoalteromonas piscicida 1UB and FOS	*L. vannamei*	Synbiotics supplementation for 40 days significantly enhanced shrimp growth, immune responses, and resistance against WSSV–*V. harveyi* coinfection.	Nababan et al. (2022)
Lactobacillus salivarius (ATCC 11741) with pectin	Narrow-clawed crayfish juvenile, *Postantacus leptodactylus*	Synbiotic treatment yielded the best growth rate and FCR, enhanced digestive enzyme activity (amylase, protease), increased probiotic abundance in the GI tract, and improved antioxidative and non-immune responses, leading to higher resistance against *A. hydrophila* infection.	Jastaniah et al. (2022) Das et al. (2024)
10^7 *L. acidophilus* + 2.5 g/kg *M. oleifera*	*L. vannamei*	Dietary synbiotic promoted shrimp growth, and up-regulated several metabolisms and immunity signaling pathways which enhanced immunity against pathogens.	
Encapsulated gel-like agarose microbeads with xanthan gum and *L. plantarum*	*L. vannamei*	*In vitro* test showed a 30-fold increase in probiotic growth with xanthan gum after 24 h incubation. Antimicrobial compounds (bacteriocins, lactic acid) inhibited *V. parahaemolyticus*. Synbiotic encapsulation enhanced probiotic viability while limiting pathogen access to prebiotics.	Wei et al. (2024)
Fermented *Bacillus coagulans* with polysaccharides (*Atractylodes macrocephala*, *Saposhnikovia divaricate*, mannose, *Astragalus* and *Yupingfeng*)	*Macrobrachium nipponense*	Inclusion of *B. coagulans* with *Yupingfeng* and *Astragalus* polysaccharides enhanced shrimp immunity and antioxidant activity after an 8-week feeding trial.	Wang et al. (2024)

Table 1 Continued

FOS, GOS, MOS, and inulin	*P. vannamei*	Prebiotic addition in biofloc showed no significant effect on shrimp growth but improved beneficial microbiota diversity, potentially enhancing long-term shrimp health and survival.	Rosales-Leija et al. (2025)
B. subtilis BF 12 hydrolyzed squid by-products protein	*P. monodon*	Synbiotic supplementation at 0.5 % for 50 days enhanced shrimp growth, boosted immune response, and improved intestinal villi morphology.	Pan et al. (2024)
Lactobacillus rhamnosus inulin, chitosan oligosaccharide, *Saposhnikovia divaricate* polysaccharide, *Acanthopanax senticosus* polysaccharide, *Atractylodes macrocephala* Koidz. polysaccharide, *Astragalus* polysaccharide, *Yupingfeng* polysaccharide, xylooligosaccharide and mannose.	*M. rosenbergii*	Synbiotic feed inclusion improved overall shrimp growth, with 3 % *Yupingfeng* yielding the most effective synbiotic response.	Li et al. (2024)
MOS with *B. subtilis* WB60	*L. vannamei*	Application of fermented MOS and *B. subtilis* (50–75 g/acre) as water additives significantly improved shrimp growth, immunity, feed use, gut microbiota, water quality, and resistance to *V. parahaemolyticus*. Histological analysis showed enhanced hepatopancreas and intestinal muscle structures, with longer villi suggesting better nutrient digestion and absorption.	Eissa et al. (2025)
1 % noni extract (*M. citrifolia*) + 10^8 CFU/kg *L. plantarum* CMT1		Enhanced shrimp digestion (amylase, lipase), lower FCR, larger size, and improved resistance agaisnt *V. parahaemolyticus*.	Phan et al. (2025)
Phytobiotics			
Chamomile oil from *Matricaria chamomilla*	*Penaeus indicus*	Inclusion of 3 g/kg chamomile oil in shrimp feed for 56 days boosted shrimp growth, innate immunity, antioxidant activity, and resistance against *V. parahaemolyticus* due to higher flavonoids and terpenoids contents.	Abdel-Tawwab et al.(2022)
Piperine	*L. vannamei*	Dietary inclusion of 1–2 g/kg piperine enhanced shrimp growth, innate immunity, antioxidant and antiprotease activity, and resistance to *Vibrio* spp. Increased intestinal microvilli height also improved nutrient digestion and absorption.	Shin et al. (2023)
A fermented herbal mix made from mulberry leaf, Javanese turmeric, and fingerroot.	*P. monodon*	Supplementation of 100 mL/kg fermented mixture diet for 30 days improved juvenile shrimp growth rate, moulting, and feed digestibility.	Ilham et al. (2024)
Spirulina platensis	*L. vannamei*	Dietary inclusion of 4–8 g/kg *S. platensis* improved shrimp growth, antioxidant capacity (SOD, CAT, GPx), and survival against *V. parahaemolyticus*. Histological analysis showed better muscle structure and minimal hepatopancreas damage (reduced fibrosis, improved hepatocyte nuclei, and tubule lining) compared to control.	Ahmed et al. (2025)
Desertifilum tharense NIOF17/006		Supplementation at 3.4–4.2 g/kg improved shrimp growth, immunity, feed utilization, and reduced malondialdehyde levels after an 8-week feeding trial.	Ashour et al. (2025)
Probiotic, prebiotic, and phytobiotic			
A mix of *Lactobacillus plantarum*, *Lactobacillus acidophilus*, *Lactobacillus salivarius*, and *Bacillus subtilis*, plant extract *Arthrospira*, and MOS	*Penaeus aztecus*	Enriched synbiotic diets with probiotics promoted healthy shrimp growth under biofloc conditions and increased B-cell numbers in the hepatopancreas.	Kaya (2025)

proPO: prophenoloxidase, SOD: superoxide dismutase, CFU: colony forming unit, RB: respiratory burst, THC: total hemocyte count, DHC: differential hemocyte count, WSSV: white spot syndrome virus, FCR: feed conversion ratio, FOS: fructooligosaccharides, GOS: galactooligosaccharides, MOS: mannanligosaccharides

effects by enhancing digestive enzyme activities (i.e., amylase, lipase, and protease) and upregulating key growth-related genes such as insulin-like growth factor 1 (IGF-1), ecdysteroid, and myosin (Sutanti et al. 2025). In addition, *Enterococcus faecium* strains 13A and 13G isolated from the gut of *L. vannamei* exhibit strong probiotic potential against pathogenic *Vibrio* spp. through the production of bacteriocins and peptidoglycan hydrolase (PGH) enzymes that degrade the *Vibrio* cell wall (de la Cruz et al. 2023). The proposed mechanisms underlying probiotic application in shrimp include direct colonization of the gastrointestinal tract, stabilization of beneficial microbial communities, stimulation of immune responses, and inhibition of pathogens through competitive exclusion. Competitive exclusion operates through two main pathways: interference competition, in which probiotics produce antagonistic substances such as bacteriocins, organic acids, and lysozyme that suppress pathogen growth; and exploitation competition, whereby probiotics compete with pathogens for nutrients and attachment sites (Yao et al. 2021). In addition, the proliferation of beneficial bacteria enhances the immune status of cultured shrimp resulting in improved growth performance and weight gain compared with traditional culture systems (Hussain et al. 2021).

Prebiotic

Prebiotics are defined as non-digestible natural food substrates that are selectively metabolized by specific host-associated microorganisms, thereby supporting their growth and activity and ultimately enhancing host growth performance and immune function (Shen et al. 2023). In shrimp aquaculture, prebiotics are commonly administered either through the diet or directly into the rearing water, particularly in biofloc systems, where they serve as carbon sources for microorganisms and play a critical role in regulating the structure and function of microbial communities (Rosales-Leija et al. 2025). Commonly used prebiotics in shrimp culture include mannan oligosaccharides (MOS), fructooligosaccharides (FOS), inulin, galactooligosaccharides (GOS), xylooligosaccharides (XOS), isomaltooligosaccharides (IMO), and β-glucan (Mustafa et al. 2020; Shen et al. 2023). In addition, *in vitro* fermentation models using prebiotic substrates and shrimp gut microbiota have demonstrated significant changes in microbial composition, resulting in increased production of short-chain fatty acids (SCFAs) and the suppression of potentially pathogenic bacteria (Shen et al. 2023). From a theoretical perspective, inorganic carbon sources tend to favour the growth of chemoautotrophic bacteria, whereas organic carbon sources promote the dominance of heterotrophic bacteria within aquaculture systems (Ferreira et al. 2021), underscoring the importance of appropriate prebiotic selection. Additionally, prior to application, complex carbon molecules often require microbial pretreatment to enhance carbon solubility, reduce fibre content, and increase the bioavailability of nutrients such as proteins (Romano et al. 2018).

The use of specific prebiotics, particularly β-glucan, has been reported to effectively stimulate the growth of *Bacillus* spp. by reducing intestinal pH, increasing SCFA ratios, and enhancing amylase activity, thereby improving gut health in *L. vannamei* (Eissa et al. 2023). Inulin has also been shown to function as an effective carbon source for probiotics by promoting their proliferation and the production of exoenzymes such as inulinase, which subsequently enhance nutrient digestion in the shrimp gut (Escobedo-Fregoso et al. 2021). A simple and cost-effective strategy involves the use of inulin-coated feed, which has been shown to increase gut microbial diversity and enhance immune responses in *L. vannamei* (Allie et al. 2025). Moreover, supplementation with MOS in biofloc systems for *Farfantepenaeus aztecus* culture has been demonstrated to improve growth performance, feed utilization, survival, and water quality (Genc et al. 2024). These effects are particularly important in sustainable biofloc systems, where nutrient stability and water quality are essential for optimal production.

Previous studies have also reported that agavin-supplemented diets significantly enhance the diversity of beneficial gut bacteria in shrimp, leading to improved health status and immune function (Ochoa-Romo et al. 2022). Likewise, supplementation with yeast cell wall products containing β-glucans, MOS, proteoglycans, and fungal-derived enzymes has been shown to promote beneficial bacterial growth, stabilize the gut microbiome, and enhance disease resistance (Arce et al. 2021). Notably, Chen et al. (2022) reported that *L. vannamei* fed diets supplemented with sulphate-based alginate polysaccharides (SBAP) exhibited improved nutrient utilization, growth performance, and intestinal health, along with reduced disease severity following pathogen challenge. In addition to shrimp, the use of palm kernel cake–based diets as a low-

cost prebiotic source has been shown to improve immune responses and survival in the freshwater crayfish *Cherax quadricarinatus* (Winanti et al. 2025). More recently, the exoskeleton of black soldier fly larvae (*Hermetia illucens*) has been explored as a sustainable prebiotic source, demonstrating significant improvements in health status and immune responses in catfish (Santana et al. 2025). Mechanistically, fermented substrates enhance the release of non-digestible polysaccharides and bioactive metabolites, which are subsequently utilized by gut microbiota to support microbial growth and stimulate immune-related pathways.

The mechanisms of action of prebiotic inclusion in shrimp diets are facilitated through several interconnected processes, most notably the production of SCFAs, which lower gut pH, inhibit *Vibrio* proliferation, and act as signalling molecules that enhance innate immune responses and the expression of immune-related genes (Goh et al. 2022). In particular, MOS can mimic intestinal binding sites, facilitating pathogen attachment to MOS molecules and enabling the subsequent excretion of pathogen complexes with faeces, thereby reducing intestinal colonization (Gainza and Romero 2020). Apart from immune protection, MOS supplementation has also been reported to increase lipid deposition in shrimp muscle, potentially improving product quality and market value through enhanced polyunsaturated (PUFA) and monounsaturated fatty acid (MUFA) contents (Rosales-Leija et al. 2025). Despite these benefits, their effectiveness is dependent on environmental conditions, species composition, and appropriate dosage levels (de la Peña et al. 2024).

Synbiotics

As a more advanced approach offering greater benefits than the application of probiotics or prebiotics alone, synbiotic formulations have emerged as a leading biocontrol strategy in intensive shrimp aquaculture. As early as 2005, synbiotic approaches were applied in aquafeeds due to their complementary functions and synergistic effects on shrimp growth and health (Panigrahi et al. 2005). For instance, Kaushik et al. (2022) reported that combining probiotics with prebiotics generally improves the physicochemical properties of rearing water through mechanisms such as competitive exclusion and the stimulation of beneficial bacterial communities, ultimately reducing infection risk. Similarly, synbiotic diets containing inulin combined with *B. subtilis* and *Lactobacillus* spp. were found to enhance gut bacterial diversity in shrimp and promote beneficial taxa such as *Rhodobacteraceae* while suppressing pathogenic bacteria (Escobedo-Fregoso et al. 2021). The combined application of *Pseudoalteromonas piscicida* 1UB and the prebiotic FOS significantly improved growth parameters and stimulated innate immune responses, including prophenoloxidase (proPO) and respiratory burst activities, indirectly enhancing host resistance (Nababan et al. 2022). At a more advanced level, Wei et al. (2024) reported that encapsulation-based synbiotics containing *L. plantarum* and xanthan gum improved delivery and efficacy in the shrimp host. This effectiveness was attributed to antimicrobial substances secreted by encapsulated probiotics, while the prebiotic component limited nutrient availability to pathogens and selectively stimulated nearby probiotic growth.

Beyond commercial prebiotics, plant-derived alternatives from fruits and vegetables are increasingly being explored as sustainable and cost-effective options. Phan et al. (2025) reported that synbiotic combinations using noni fruit (*Morinda citrifolia*) extract with *L. plantarum* CMT1 enhanced shrimp growth performance, digestive enzyme activity, and survival against *V. parahaemolyticus* infection. Similarly, Das et al. (2024) found that including *Moringa oleifera* together with *L. acidophilus* in *L. vannamei* diets improved growth, gastrointestinal microbiota diversity, and regulated multiple immune- and metabolism-related signalling pathways. Consistently, Situmorang et al. (2021) reported that synbiotic diets containing the red seaweed *Kappaphycus alvarezii*, *Spirulina* spp., and *Halomonas alkaliphile* improved survival, growth, and resistance to vibriosis in post-larval *L. vannamei* under high stocking-density stress. Overall, synbiotic supplementation, including plant-derived prebiotics, demonstrates superior effectiveness compared to probiotics or prebiotics alone, highlighting its potential as a functional feed strategy for disease prevention and mitigation in shrimp aquaculture. The efficacy of synbiotics relies on a synergistic mechanism, in which specific prebiotic substrates ensure the survival, colonization, and optimal function of probiotic strains. Since maintaining probiotic viability in the gut is a primary challenge, precise substrate formulation is critical. Mechanistically, prebiotics selectively support probiotic colonization in the shrimp GI tract, leading to SCFA production, pH reduction, and the competitive exclusion of acid-sensitive pathogens such as *Vibrio* spp. (Yao et al. 2021). In addition to pathogen control, synbiotics actively modulate host immunity by triggering the prophenoloxidase (proPO) system and boosting hemocyte production (Prabawati et al.

2022). They also enhance antioxidant defenses, as evidenced by elevated superoxide dismutase (SOD) and catalase activity and reduced malondialdehyde (MDA) levels, while improving non-specific immune markers such as alkaline phosphatase (ALP), acid phosphatase (ACP), and lysozyme (Arce et al. 2021; Yao et al. 2021).

Phytobiotic

Phytobiotics are non-toxic plant-derived compounds commonly administered to target animals via methods such as feed supplementation, bath immersion, or injection (Shin et al. 2023). These compounds including flavonoids, essential oils (EOs), phenolics, and terpenoids typically possess antioxidant, immunostimulatory, and biocidal properties, enhancing shrimp immunity and reducing mortality during disease outbreaks (Quiroz-Guzmán et al. 2023). Generally, phytobiotic supplementation requires at least 4 to 5 weeks of administration to achieve measurable effects. Their sustainability, cost-effectiveness, low toxicity, and simple extraction methods have made phytobiotics a prominent alternative in aquaculture (Hernández-Cabanyero et al. 2023). Numerous studies have shown that blends of organic acids and EOs in feed benefit host immunity by promoting gut microbiota and resistance against pathogens. For example, Elias et al. (2024) reported that *Melaleuca cajuputi* leaf extract (MCLE)-gold nanoparticles applied via pellet spray enhanced immunological responses in *L. vannamei* and increased resistance against *V. parahaemolyticus*. Similarly, Hernández-Cabanyero et al. (2023) demonstrated that diets enriched with microencapsulated EO mixtures (thyme + cinnamon and oregano + cloves) reduced mortality in acute hepatopancreatic necrosis disease (AHPND)-infected *L. vannamei* and enhanced immune responses, likely through improved digestibility and increased secretion of digestive enzymes (Platel and Srinivasan 2000).

Several phytochemicals play key roles in enhancing nutrient digestion and stimulating digestive enzyme secretion. For instance, polyphenols, including flavonoids, phenolic acids, and tannins, can increase amylase and protease activity, facilitating the breakdown of macronutrients into absorbable forms (Abdel-Razek et al. 2026). Meanwhile, essential oils such as carvacrol, thymol, and eugenol also stimulate digestive enzyme secretion, improve gut morphology, and enhance nutrient digestibility (Tran et al. 2023). *In vivo* study have reported that isoquinoline alkaloid (IQ) additives in *L. vannamei* diets significantly improved growth performance and overall health, with no lesions observed in the hepatopancreas or intestine (Bussabong et al. 2021). Additionally, piperine supplementation increased intestinal microvilli height through enhanced structural protein synthesis, improving nutrient digestion and absorption (Shin et al. 2023). Observed improvements in immunity were attributed to enhanced phagocytic activity and elevated activities of non-specific immune mediators, including SOD, lysozyme and phenoloxidase (Bussabong et al. 2021). However, plants containing alkaloids should be carefully evaluated, as excessive dietary levels may reduce feed intake due to poor palatability (Glencross 2001).

According to Abidin et al. (2023), phytobiotics exert their effects in shrimp mainly by maintaining intestinal mucosa integrity and selectively modulating gut microbiota composition. For instance, flavonoid-enriched extracts from *Agave lechuguilla* significantly promoted beneficial gut microbiota, which then indirectly inhibits pathogenic *Vibrio* and improving innate immunity and growth in *Penaeus vannamei* (Quiroz-Guzmán et al. 2023). Phytobiotics also act as a complementary layer in integrated feeding strategies by supplying bioactive compounds that modulate oxidative stress and immune signalling pathways (Abidin et al. 2023). Phytochemicals such as phenolics, flavonoids, and diterpenoids enhance the expression of antioxidant enzymes (e.g., SOD, catalase, glutathione peroxidase), neutralize reactive oxygen species (ROS), and prevent excessive inflammatory responses that could damage host tissues (Ochoa-Romo et al. 2022). Yin et al. (2022) revealed that diterpenoids from *Andrographis paniculata* enhance resistance to *V. parahaemolyticus* while regulating ROS–JNK-dependent pathways to prevent detrimental inflammation and apoptosis. Similarly, agavin has been reported to modulate gut microbiota composition, promoting beneficial bacterial communities that enhance disease resistance and resilience, supporting its role as a sustainable prebiotic-like component (Ochoa-Romo et al. 2022). However, the effectiveness of phytobiotics also depends on the method of administration. Bussabong et al. (2021) suggested that oral supplementation is generally most effective, as it promotes antibacterial properties by preventing *Vibrio* colonization in the gastrointestinal tract and suppressing disease outbreaks. Meanwhile, injection is less preferable due to the risk of physical injury, which can compromise survival and increase susceptibility to infection (Tammas

et al. 2024). Administering phytobiotics via rearing water is considered practical for shrimp culture, as it minimizes handling stress, reduces injury, and allows prophylactic treatment of large populations (Azad et al. 2005).

Tripartite synergistic mechanisms of probiotics, prebiotics and phytobiotics: as a holistic approach for cultured shrimp

The combination of probiotics, prebiotics, and phytobiotics might represent one of the most comprehensive and synergistic strategies to mitigate disease occurrence and promote shrimp health, contributing to food safety and sustainable aquaculture. Generally, their mechanisms of action include modulation of gut microbiota, enhancement of gastrointestinal (GI) integrity, and stimulation of host immune responses. Probiotics improve gut health by producing vitamins and short-chain fatty acids (SCFAs), while also enhancing nutrient digestion and absorption (Das et al. 2024). Thereafter, the addition of prebiotics, such as fructooligosaccharides (FOS), mannan oligosaccharides (MOS), inulin, and galactooligosaccharides (GOS), provides an additional carbon source for probiotics, supporting their growth and overall performance more effectively than prebiotics or probiotics alone (Das et al. 2024; Shen et al. 2023). The choice of carbon source is also critical for shaping bacterial communities in cultured systems: inorganic carbon favours chemoautotrophic bacteria, whereas organic carbon promotes heterotrophic bacteria, which help regulate ammonia and nitrite levels (Ferreira et al. 2021). Incorporating phytobiotics into systems already containing synbiotic components is expected to act synergistically to suppress pathogenic microbes through the antimicrobial effects of phytochemical compounds. Immunologically, each component targets distinct aspects of the shrimp immune system. Probiotics stimulate innate immune responses by increasing prophenoloxidase (proPO), superoxide dismutase (SOD), lysozyme, and catalase activities, as well as enhancing digestive enzyme activities such as amylase and lipase to improve feed utilization (Ashour et al. 2025). In particular, prebiotics contribute further immune modulation through microbial fermentation products, including bacteriocins, lactic acid, and SCFAs.

While probiotics and prebiotics contribute to maintaining cultured system health, phytobiotics provide additional immunostimulatory and anti-inflammatory effects by supporting tissue repair, wound healing, and inhibiting pathogen virulence factors such as quorum sensing (QS), thereby complementing the actions of probiotics and prebiotics. Collectively, the integration of these three components is hypothesized to promote growth, as reflected by increased weight gain, improved feed conversion ratio (FCR), and the upregulation of growth-related biomarkers such as insulin-like growth factor I and II. Simultaneous application of this tripartite combination is also expected to enhance shrimp immunity and pathogen resistance. Probiotics competitively inhibit pathogen colonization in the GI tract, while phytochemicals act as antimicrobial agents to suppress pathogen proliferation. Together, these effects improve intestinal integrity and maintain microbial balance. To date, only a limited number of studies have investigated this integrated approach. For example, Kaya (2025) demonstrated that synbiotic diets enriched with a probiotic mixture of *Arthrospira* and MOS under biofloc conditions significantly increased gut microbiota diversity, enhanced B-cell abundance in the hepatopancreas, and promoted overall growth. Specific examples include agavin, a prebiotic that promotes beneficial microbial communities to indirectly inhibit *Vibrio* (Ochoa-Romo et al. 2022), and yeast cell wall components (MOS and β-glucans) that improve microbial balance, pathogen exclusion, and shrimp immunity (Arce et al. 2021). Overall, the tripartite synergy of probiotics, prebiotics, and phytobiotics cumulatively modulates the gut microbiome, enhances intestinal integrity, promotes nutrient digestion and absorption, and boosts growth and disease resistance. Nevertheless, continuous monitoring and adherence to stringent safety regulations are essential to meet international standards.

Challenges and future directions

Despite the clear benefits of functional feed additives, their broader application in shrimp aquaculture faces several challenges. One major concern is the potential contamination of commercial probiotics with antimicrobial-resistant (AMR) and potentially pathogenic microorganisms, including *Vibrio*, *Aeromonas*, *Pseudomonas*, and *Flavobacterium*, particularly in products originating from low- and middle-income countries (Knipe et al. 2024). These findings highlight the critical need for rigorous quality control and regular mon-

itoring before probiotics can be included in the food chain. Probiotic delivery faces practical challenges because biofilters and UV sterilization reduce probiotics viability, although encapsulation strategies may alleviate these losses (Wei et al. 2024). Moreover, high temperatures during feed pelleting (95–100 °C) can inactivate probiotics and diminish the bioactivity of phytobiotics, underscoring the importance of optimized processing conditions during feed formulation (Yao et al. 2021). For prebiotics, precise dosing and careful selection of carbon sources are crucial to support the growth of targeted probiotics in shrimp gut, with partially fermented substrates serving as alternatives. Similarly, phytobiotic applications require careful formulation to account for variability in phytochemical composition and to prevent potential toxicity (Pudota 2025). Taken together, these challenges indicate that further research is necessary to refine application strategies before establishing optimal doses and formulations for this tripartite synergistic approach to prevent losses while supporting sustainable and safe aquaculture practices.

Conclusion and future recommendations

The synergistic use of probiotics, prebiotics, and phytobiotics represents a promising holistic strategy to reduce disease incidence and enhance productivity in shrimp aquaculture. This tripartite approach is expected to improve feed utilization, immune responses, and survival rates against pathogens, particularly in intensive farming systems. Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA) have been developed to promote sustainability and mimic the natural environment of cultured animals; however, high initial costs, the need for specialized labour, and limited species suitability remain significant constraints. Despite the potential benefits of this integrated strategy, variable efficacy due to the lack of standardized plant products and limited field-scale studies continues to pose challenges. Integrating omics tools enables a deeper understanding of host–microbe interactions and create more precise supplement formulations. It is also important to provide ongoing education to farmers to ensure the best use of this approach. In summary, continued research and collaboration between farmers and policymakers are needed to make this approach sustainable.

Authors' contributions All authors have contributed to the final manuscript. Nor Asma Husna Yusoff: data curation, formal analysis, writing original draft, review, and editing. Joey Joe Yee Ng: writing review and editing. Farizan Abdullah and Ahmad Najmi Ishak: writing review and editing. Marina Hassan: conceptualization, validation, writing review and editing.

Conflict of interest The authors declare no competing interests.

References

AbdelTawwab M, AbdelRazek N, Tahoun AA, Awad SMM, ElAshram AM (2022) Effects of dietary supplementation of chamomile oil on Indian shrimp (*Penaeus indicus*) performance, antioxidant, innate immunity, and resistance to *Vibrio parahaemolyticus* infection. Aquaculture 552:738045. https://doi.org/10.1016/j.aquaculture.2022.738045

Abdel-Razek N, Khalil RH, Afifi AAM, Abdelrahiem TMM, Metwaly SA, Fathi M (2026) Dietary supplementation with *Ulva* sp. and garlic extracts enhances growth, immune response and digestive enzyme activity in Pacific whiteleg shrimp (*Litopenaeus vannamei*). J Fish Dis 49(1):e70011. https://doi.org/10.1111/jfd.70011

Abidin Z, Hu Y-F, Huang H-T, Huang C-Y, Wu Y-S, Nan F-H (2023) Effect of aqueous moringa (*Moringa oleifera*) leaf extract as a prebiotic on growth of the whiteleg shrimp, *Penaeus vannamei* Boone, 1931 (Decapoda, Penaeidae). Crustaceana 96(2):139–156

Ahmed RA, Jastaniah SDS, Alaidaroos BA, Shafi ME, El-Haroun E, Abd El Aziz YM, Abd El Megeed OHA, Al-Qurashi MM, Bahshwan SMA, Munir MB, Kari ZA, Mathew RT, Eissa MEH, Elfeky A (2025) Effects of dietary *Spirulina platensis* supplementation on growth performance, whole body composition, antioxidant activity, histological alterations, and resistance to *Vibrio parahaemolyticus* in Pacific white shrimp (*Litopenaeus vannamei*). Aquac Rep 40:102606. https://doi.org/10.1016/j.aqrep.2024.102606

Allie NU, Swain S, Praveena PE, Bhuvaneswari T, Panigrahi A, Lal KK, Otta SK (2025) A simple way of using prebiotic towards sustainable shrimp aquaculture practice. Aquac Int 33:297. https://doi.org/10.1007/s10499-025-01991-0

Arce KS, de Souza Valente C, do Vale Pereira G, Shapira B, Davies SJ (2021) Modulation of the gut microbiota of Pacific white shrimp (*Penaeus vannamei* Boone 1931) by dietary inclusion of a functional yeast cell wall-based additive. Aquac Nutr 27(4):1114–1127. https://doi.org/10.1111/anu.13252

Ashour M, Al-Souti AS, Mamoon A, Ali FS, Elshobary ME, Mabrouk MM, Mansour AIA, Mansour AT, El-Haroun E, Abdelhamid AF (2025) Cyanobacteria *Desertifilum tharense* NIOF17/006 as a novel aquafeed additive: Effect on the growth, immunity, digestive function and gene expression of whiteleg shrimp postlarvae. Front Mar Sci 12:1532370. https://doi.org/10.3389/fmars.2025.1532370

Azad IS, Panigrahi A, Gopal C, Paulpandi S, Mahima C, Ravichandran P (2005) Routes of immunostimulation vis-à-vis survival and growth of *Penaeus monodon* postlarvae. Aquaculture 248(1–4):227–234. https://doi.org/10.1016/j.aquaculture.2005.04.011

Barrios CY, Roncarati A, Martín Ríos LD, Rodríguez González M, González Salotén M, López Zaldívar Y, Arenal A (2023) Effects of fructooligosaccharides (FOS) on the immune response of the shrimp *Penaeus vannamei* and on the reduction in *Vibrio* spp. and *Pseudomonas* spp. in cultures of post-larvae. Microb Res 14(3):870–882. https://doi.org/10.3390/microbiolres14030060

Bussabong P, Rairat T, Chuchird N, Keetanon A, Phansawat P, Cherdkeattipol K, Kraitavin W (2021) Effects of isoquinoline alkaloids from *Macleaya cordata* on growth performance, survival, immune response, and resistance to *Vibrio parahaemolyticus* infection of Pacific white shrimp (*Litopenaeus vannamei*). PLoS One 16(5):e0251343. https://doi.org/10.1371/journal.pone.0251343

Carvalho A, Gonçalves FH, Pimentel OALF, Krummenauer D, McAlhaney E, Urick S, Clarington J, Senten Jv, Schwarz MH, Turan G, Poersch LH (2025) Effect of the synbiotic system on the performance of shrimp *Penaeus vannamei*, oyster *Crassostrea virginica* and macroalgae *Ulva lactuca* in an integrated system. Aquac Int 33:482. https://doi.org/10.1007/s10499-025-02167-6

Chen G, Liu B, Chen J, Liu H, Tan B, Dong X, Yang Q, Chi S, Zhang S, Yao M (2022) Supplementing sulfate-based alginate polysaccharide improves Pacific white shrimp (*Litopenaeus vannamei*) fed fishmeal replacement with cottonseed protein concentrate: Effects on growth, intestinal health and disease resistance. J Mar Sci Eng 10(2):7132362. https://doi.org/10.1155/2022/7132362

Das SP, Abidin Z, Huang HT, Lin YR, Huang CY, Wu YS, Hu YF, Nan FH (2024) Deciphering the influence of dietary synbiotics in white shrimp gut and its effects in regulating immune signalling pathways. Front Mar Sci 10:1342708. https://doi.org/10.3389/fmars.2023.1342708

de la Cruz CMC, Cornejo-Granados F, Gallardo-Becerra L, Rodríguez-Alegría ME, Ochoa-Leyva A, López Munguía A (2023) Complete genome sequence and characterization of a novel *Enterococcus faecium* with probiotic potential isolated from the gut of *Litopenaeus vannamei*. Microb Genom 9(3):mgen000938. https://doi.org/10.1099/mgen.0.000938

de la Peña LD, Moquera GL, Amar EC, Castellano JLA, Cabillon NAR, Arboleda JI, Nava JKP, Zamora RVJ, De Schryver P (2024) *In vitro* and *in vivo* evaluation of the efficacies of commercial probiotics and disinfectant against acute hepatopancreatic necrosis disease and luminescent vibriosis in *Litopenaeus vannamei*. Res Vet Sci 171:105204. https://doi.org/10.1016/j.rvsc.2024.105204

Eissa ESH, Ahmed NH, El Badawi AA, Munir MB, Abd Al Kareem OM, Eissa MEH, Hussien EHM, Sakr SSE (2022) Assessing the influence of the inclusion of *Bacillus subtilis* AQUA GROW® as a feed additive on the growth performance, feed utilization, immunological responses and body composition of the Pacific white shrimp, *Litopenaeus vannamei*. Aquac Res 00:1–10. https://doi.org/10.1111/are.16129

Eissa ESH, Ahmed RA, Abd Elghany NA, Elfeky A, Saadony S, Ahmed NH, Sakr SES, Dayrit GB, Tolenada CPS, Atienza AAC, Mabrok M, Ayoub HF (2023) Potential synbiotic effects of β-1,3 glucan and fructooligosaccharides on the growth performance, immune response, redox status, and resistance of Pacific white shrimp, *Litopenaeus vannamei*, to *Fusarium solani* infection. Fishes 8:105. https://doi.org/10.3390/fishes802010

Eissa ESH, Dowidar HA, Al-Hoshani N, Baazaoui N, Alshammari NM, Bahshwan SMA, Kari ZA, Ibrahin S, Munir MB, Al-Farga A, Eissa MEH, El-Aziz YMA (2025) Dietary supplementation with fermented prebiotics and probiotics can increase growth, immunity, and histological alterations in Pacific whiteleg shrimp (*Litopenaeus vannamei*) challenged with *Vibrio parahaemolyticus*. Aquac Int 33:62. https://doi.org/10.1007/s10499-024-01704-z

Elias NA, Hassan MSA, Yusoff NAH, Abu Hassan MS, Hassan M (2024) Antibacterial properties of synthesized *Melaleuca cajuputi*-leaf gold nanoparticles against *Vibrio parahaemolyticus*. Mater Lett 366:136565. https://doi.org/10.1016/j.matlet.2024.136565

Escobedo-Fregoso C, Quiroz-Guzmán E, Mendoza-Carrion G, Peña-Rodríguez A (2021) Effect of dietary prebiotic inulin and probiotic *Bacillus subtilis* and *Lactobacillus* sp. on the intestinal microbiota of white shrimp (*Litopenaeus vannamei*). Revista de Ciencias Biológicas y de la Salud (Biotecnia) 23(3):50–57

Ferreira V, Elosegi A, Tiegs SD, von Schiller D, Young R (2021) Organic matter decomposition and ecosystem metabolism as tools to assess the functional integrity of streams and rivers-a systematic review. Water 12(12):3523. https://doi.org/10.3390/w12123523

Gainza O, Romero J (2020) Effect of mannan oligosaccharides on the microbiota and productivity parameters of *Litopenaeus vannamei* shrimp under intensive cultivation in Ecuador. Sci Rep 10(1):2719. https://doi.org/10.1038/s41598-020-59587-y

Genc E, Kaya D, Genc MA, Keskin E, Yavuzcan H, Guroy D, Aktas M (2024) Effect of dietary mannan oligosaccharide inclusion on production parameters of *Farfantepenaeus aztecus* cultured in a biofloc system. J World Aquac Soc 55(5):e13086. https://doi.org/10.1111/jwas.13086

Glencross BD (2001) Feeding lupins to fish: A review of the nutritional and biological value of lupins in aquaculture feeds. Department of fisheries, research division, government of Western Australia

Goh JXH, Tan LT-H, Law JW-F, Ser H-L, Khaw K-Y, Letchumanan V, Lee L-H, Goh B-H (2022) Harnessing the potentialities of probiotics, prebiotics, synbiotics, paraprobiotics and postbiotics for shrimp farming. Rev Aquac 14(3):1478-1557**.** https://doi.org/10.1111/raq.12659

Hernández-Cabanyero C, Carrascosa E, Jiménez S, Fouz B (2023) Exploring the effect of functional diets containing phytobiotic compounds in whiteleg shrimp health: Resistance to acute hepatopancreatic necrotic disease caused by *Vibrio parahaemolyticus*. Animals 13(8):1354. https://doi.org/10.3390/ani13081354

Huang Z, Zeng S, Xiong J, Hou D, Zhou R, Xing C, Wei D, Deng X, Yu L, Wang H, Deng Z, Weng S, Sataporvanit K, Ning D, Zhou J, He J (2020) Microecological Koch's postulates reveal that intestinal microbiota dysbiosis contributes to shrimp white feces syndrome. Microbiome 8:32. https://doi.org/10.1186/s40168-020-00802-3

Hussain AS, Mohamad DA, Sallam WS, Shoukry NM, Davis DA (2021) Effects of culturing the Pacific white shrimp *Penaeus vannamei* in 'biofloc'vs 'synbiotic' systems on the growth and immune system. Aquaculture 542:736905. https://doi.org/10.1016/j.aquaculture.2021.736905

Ilham IS, Sucipto, Fujaya Y (2024) Effects of fermented herbal extract as a phytobiotic on growth indices, moulting performance, and feed utilization of juvenile tiger shrimp (*Penaeus monodon* Fabr.). Fishes 9(9):352. https://doi.org/10.3390/fishes9090352

Jasmin MY, Syukri F, Kamarudin MS, Karim M (2020) Potential of bioremediation in treating aquaculture sludge: Review article. Aquaculture 519:734905. https://doi.org/10.1016/j.aquaculture.2019.734905

Jastaniah SDS, Hafsan H, Tseng CJ, Karim YS, Hamza MU, Hameed NM, Al Zubaidi SH, Almotlaq SSK, Yasin G, Iswanto AH, Dadras M, Chorehi MM (2022) Effects of dietary pectin and *Lactobacillus salivarius* ATCC 11741 on growth performance, immunocompetence, gut microbiota, antioxidant capacity, and disease resistance in narrow-clawed crayfish, *Pontastacus leptodactylus*. Aquac Nutr 2022:1861761. https://doi.org/10.1155/2022/1861761

Jastaniah SD, Alaidaroos BA, Shafi ME, Aljarari RM, Abd El-Aziz YM, Munir MB, Eissa MEH, Al-Farga A, Eissa ESH, Said RM (2024) Dietary *Pediococcus acidilactici* improved the growth performance, feed utilization, gut microbiota and disease resistance against *Fusarium solani* in Pacific white shrimp, *Litopenaeus vannamei*. Aquac Int 32(3):3195–3215. https://doi.org/10.1007/s10499-023-01318-x

Kaushik P, Khandelwal R, Jain N, Keelka S, Jain P (2022) Prospectives of prebiotics, probiotics, and synbiotics for sustainable development of aquaculture. In: K. K. Behera, R. Bist, S. Mohanty and M. Bhattacharya (eds.). Prebiotics, Probiotics and Nutraceuticals. Springer, Singapore. p. 301–340

Kaya D (2025) Improvement of brown shrimp (*Penaeus aztecus*) culture parameters through dietary enriched synbiotic in a biofloc system. Aquac Int 33:232. https://doi.org/10.1007/s10499-025-01909-w

Kewcharoen W, Srisapoome P (2019) Probiotic effects of *Bacillus* spp. from Pacific white shrimp (*Litopenaeus vannamei*) on water quality and shrimp growth, immune responses and resistance to *Vibrio parahaemolyticus* (AHPND strains). Fish Shellfish Immunol 94:175–189. https://doi.org/10.1016/j.fsi.2019.09.013

Kim S, Jeon H, Han HS, Hur JW (2021) Evaluation of *Bacillus albus* SMG 1 and *B. safensis* SMG 2 isolated from Saemangeum Lake as probiotics for aquaculture of white shrimp (*Litopenaeus vannamei*). Aquac Rep 20:100743. https://doi.org/10.1016/j.aqrep.2021.100743

Knipe H, Temperton B, Lange A, Bass D, Tyler CR (2021) Probiotics and competitive exclusion of pathogens in shrimp aquaculture. Rev Aquac 13:324–352. https://doi.org/10.1111/raq.12477

Knipe H, Chaput D, Basak SK, Lange A, Tyler CR (2024) Contaminants in shrimp probiotics: A potential emerging threat to food security. Aquaculture 593:741338. https://doi.org/10.1016/j.aquaculture.2024.741338

Li Z, Chen J, Liu M, Liu B, Zhou Q, Liu S, Sun C, Liu S, Zheng X, Wang A (2024) Synbiotic effects of *Lactobacillus rhamnosus* fermented with different prebiotics on the digestive enzyme activities, SCFAs and intestinal flora of *Macrobrachium rosenbergii in vitro*. Aquac Rep 38:102303. https://doi.org/10.1016/j.aqrep.2024.102303

Luo K, Liu Y, Qin G, Wang S, Wei C, Pan M, Guo Z, Liu Q, Tian X (2023) A comparative study on effects of dietary three strains of lactic acid bacteria on the growth performance, immune responses, disease resistance and intestinal microbiota of Pacific white shrimp, *Penaeus vannamei.* Fish Shellfish Immunol 138:108707. https://doi.org/10.1016/j.fsi.2023.108707

Miyasaka H, Koga A, Maki TA (2023) Recent progress in the use of purple non-sulfur bacteria as probiotics in aquaculture. World J Microbiol Biotechnol 39(6):145. https://doi.org/10.1007/s11274-023-03592-6

Monier MN, Kabary H, Elfeky A, Saadony S, Abd ElHamed NNB, Eissa MEH, Eissa EH (2023) The effects of *Bacillus* species probiotics (*Bacillus subtilis* and *Bacillus licheniformis*) on the water quality, immune responses, and resistance of whiteleg shrimp (*Litopenaeus vannamei*) against *Fusarium solani* infection. Aquac Int 31:3437–3455. https://doi.org/10.1007/s10499-023-01136-1

Monzón-Atienza L, Bravo J, Torrecillas S, Gómez Mercader A, Montero D, Ramos Vivas J, Galindo Villegas J, Acosta F (2024) An in-depth study on the inhibition of quorum sensing by *Bacillus velezensis* D18: Its significant impact on *Vibrio* biofilm formation in aquaculture. Microorganisms 12(5):890. https://doi.org/10.3390/microorganisms12050890

Moreno-Gámez S, Hochberg ME, van Doorn GS (2023) Quorum sensing as a mechanism to harness the wisdom of the crowds. Nat Commun 14:3415. https://doi.org/10.1038/s41467-023-39134-0

Muharrama ARW, Widanarni W, Alimuddin A, Yuhana M (2021) Gene expression and immune response of Pacific white shrimp given *Bacillus* NP5 probiotic and honey prebiotic and *Vibrio parahaemolyticus* infection. J Appl Aquac 33(1):58–70. https://doi.org/10.1080/10454438.2020.1811221

Mustafa A, Buentello A, Gatlin III D, Lightner D, Hume M, Lawrence A (2020) Effects of fructooligosaccharides (FOS) on growth, survival, gut microflora, stress and immune response in Pacific white shrimp, *Litopenaeus vannamei*, cultured in a recirculating system. J Immunoassay Immunochem 41:45–59

Nababan YI, Alimuddin A, Yuhana M, Penataseputro T, Widanarni W (2022) Dietary supplementation of *Pseudoalteromonas piscicida* 1UB and fructooligosaccharide enhance growth performance and protect the whiteleg shrimp (*Litopenaeus vannamei*) against WSSV and *Vibrio harveyi* coinfection. Fish Shellfish Immunol 131:746–756. https://doi.org/10.1016/j.fsi.2022.07.023

Ochoa-Romo JP, Cornejo-Granados F, Lopez-Zavala AA, Viana MT, Sánchez F, Gallardo-Becerra L, Luque-Villegas M, Valdez-López Y, Sotelo-Mundo RR, Cota-Huízar A, López-Munguia A, Ochoa-Leyva A (2022) Agavin induces beneficial microbes in the shrimp microbiota under farming conditions. Sci Rep 12:6392. https://doi.org/10.1038/s41598-022-10392-8

Pan MV, Ferriols VMEN, Traifalgar RFM (2024) Synergistic influence of hydrolyzed squid processing by-products and *Bacillus* probiotics as dietary supplements on growth performance, immunological responses, and gut health of juvenile black tiger shrimp fed fishmeal-free diets. Aquac Int 32:4551–4580. https://doi.org/10.1007/s10499-024-01390-x

Panigrahi A, Kiron V, Puangkaew J, Kobayashi T, Satoh S, Sugita H (2005) The viability of probiotic bacteria as a factor influencing the immune response in rainbow trout (*Oncorhynchus mykiss*). Aquaculture 243(1–4):241–254. https://doi.org/10.1016/j.aquaculture.2004.09.032

Park J, Lv H, Cho C, Lim HK, Yin X, Gao Y, Hur J (2025) Influence of dietary inulin on growth and intestinal ecology in Pacific white shrimp (*Litopenaeus vannamei*). J World Aquac Soc 56:e70006. https://doi.org/10.1111/jwas.70006

Phan TCT, Nguyen TKL, Pham TTN, Truong QP, Huynh TG, Tran TTH (2025) Synbiotic effects of *Lactobacillus plantarum* CMT1 and *Morinda citrifolia* on the growth performance and disease resistance of whiteleg shrimp. Comparat Biochem Physiol 275:111037

Platel K, Srinivasan K (2000) Influence of dietary spices and their active principles on pancreatic digestive enzymes in albino rats. Nahrung 44(1):42–46. https://doi.org/10.1002/(SICI)1521-3803(20000101)44:1

Prabawati E, Hu S-Y, Chiu S-T, Balantyne R, Risjani Y, Liu C-H (2022) A synbiotic containing prebiotic prepared from a by-product of king oyster mushroom, *Pleurotus eryngii* and probiotic, *Lactobacillus plantarum* incorporated in diet to improve the growth performance and health status of white shrimp, *Litopenaeus vannamei*. Fish Shellfish Immunol 120:155–165. https://doi.org/10.1016/j.fsi.2021.10.037

Pudota BA, Tambireddy N, Chennu R, Chethurajupalli L, Shaik H, Nadella RK, Chatterjee NS, Paturi AP (2025) Exploring the perspectives of phytobiotics and their role in aquaculture: Present status and future trends. The Microbe 8:100496. https://doi.org/10.1016/j.microb.2025.100496

Quiroz-Guzmán E, Morreeuw ZP, Peña-Rodríguez A, Barajas-Sandoval DR, Magallón-Servín P, Mejía A, Reyes AG (2023) Flavonoid-enriched extract of *Agave lechuguilla* bagasse as a feed supplement to prevent vibriosis in Pacific white shrimp *Penaeus vannamei*. Aquaculture 562:738867. https://doi.org/10.1016/j.aquaculture.2022.738867

Romano N, Dauda AB, Ikhsan N, Karim M, Kamarudin MS (2018) Fermenting rice bran as a carbon source for biofloc technology improved the water quality, growth, feeding efficiencies and biochemical composition of African catfish *Clarias gariepinus* juve-

niles. Aquac Res 49(12):3691–3701. https://doi.org/10.1111/are.13837
Rosales-Leija M, Gatlin III DM, Holt JP, Lawrence AL (2025) Effect of prebiotics added to the culture water on the bacterial profiles of biofloc and the gills, hepatopancreas and intestine of *Penaeus vannamei*. Comparat Biochem Physiol B: Biochem Mol Biol 278:111097. https://doi.org/10.1016/j.cbpb.2025.111097
Rowley AF, Pope EC (2012) Vaccines and crustacean aquaculture - A mechanistic exploration. Aquaculture 334–337:1–11. https://doi.org/10.1016/j.aquaculture.2011.12.011
Sampath H, Sreenivasulu D, Udaya Shankar AC, Babu MM (2025) Harnessing *Bacillus* probiotics: An approach for *Vibrio* control and growth promotion in shrimp aquaculture. Aquac Res Econom 2767593. https://doi.org/10.1155/are/2767593
Santana TM, Farias ABS, Older CE, Romano N, Gatlin DMIII, Griffin MJ, Yamamoto FY, Gonçalves LU (2025) Black soldier fly (*Hermetia illucens*) larvae exoskeleton as a potential source of chitin in diets for juvenile channel catfish (*Ictalurus punctatus*). Fish Physiol Biochem 51:135. https://doi.org/10.1007/s10695-025-0135-x
Shaheer P, Sreejith VN, Joseph TC, Murugadas V, Lalitha KV (2021) Quorum quenching *Bacillus* spp.: An alternative biocontrol agent for *Vibrio harveyi* infection in aquaculture. Dis Aquat Org 146:117–128. https://doi.org/10.3354/dao03619
Shen K, Bao L, Liu M, Lei W, Zhou Q, Ding J, Fang P, Hu B, Wen C, Kumar V, Peng M, Yang G (2023) Dietary supplementation of β1,3glucan improves the intestinal health of white shrimp (*Litopenaeus vannamei*) by modulating intestinal microbiota and inhibiting inflammatory response. Front Immunol 14:1119902. https://doi.org/10.3389/fimmu.2023.1119902
Shin J, Yun KS, Gunathilaka BE, Hasanthi M, Ko D, Lim H, Lim J, Eom G, Kim HS (2023) Piperine supplementation in diet improves growth, feed efficiency, innate immunity, digestibility and disease resistance of Pacific white shrimp (*Litopenaeus vannamei*). Aquac Rep 29:101490. https://doi.org/10.1016/j.aqrep.2023.101490
Situmorang ML, Nurwidayanti P, Suantika G (2021) Synbiotic containing *Kappaphycus alvarezii*, *Spirulina* sp. and *Halomonas alkaliphila* improves survival, growth and vibriosis resistance in whiteleg shrimp (*Litopenaeus vannamei*) postlarval culture. Aquat Living Res 34:10. https://doi.org/10.1051/alr/2021009
Sudpraseart C, Shinn AP, Pooljun C, Sirimanapong W (2025) Efficacy of *Rhodobacter sphaeroides* TISTR 1529 on the growth performance, immune response and amino acid profile of Pacific whiteleg shrimp, *Penaeus vannamei*. Aquaculture 599:742081
Sutanti S, Sukenda S, Widanarni W, Alimuddin A, Aliah RS, Ardiansyah AR, Romadhona EI (2025) Indigenous Gram-negative bacteria as probiotics for Pacific white shrimp (*Litopenaeus vannamei*). Curr Microbiol 82:205. https://doi.org/10.1007/s00284-025-04187-0
Tammas I, Bitchava K, Gelasakis AI (2024) Transforming aquaculture through vaccination: A review on recent developments and milestones. Vaccines 12(7):732. https://doi.org/10.3390/vaccines12070732
Tran TTTH, Fagnon MS, Thy DTM, Chabrillat T, Trung NB, Kerros S (2023) Growth performance and disease resistance against *Vibrio parahaemolyticus* of whiteleg shrimp (*Litopenaeus vannamei*) fed essential oil blend (Phyto AquaBiotic). Animals 13(21):3320. https://doi.org/10.3390/ani13213320
Wang Y, Liang Y, Yu J, Li Z, Wang W, Jiang L, Liu B (2024) Effects of polysaccharide fermentation with *Bacillus coagulans* on growth, antioxidant capacity and immunity of *Macrobrachium nipponense*. Front Mar Sci 11:1514651. https://doi.org/10.3389/fmars.2024.1514651
Wei G, Tay MYF, Tay MY, Kamaja VK, ChanPark MB (2024) Synbiotic encapsulation against *Vibrio parahaemolyticus* infection in whiteleg shrimps. Aquaculture 590:741051. https://doi.org/10.1016/j.aquaculture.2024.741051
Winanti DDT, Firdausi HN, Yusup MW, Delis PC, Setyawan A, Elisdiana Y, Fidyandini HP, Amiin MK, Widodo A (2025) Evaluation of a fermented palm kernel meal as a prebiotic for enhancing immune response in Indonesian red claw crayfish (*Cherax quadricarinatus*). Vet World 18(4):896–906. https://doi.org/10.14202/vetworld.2025.896-906
Xu B, Zhang G, Wang L, Sagada G, Zhang J, Shao Q (2021) The influence of dietary β1,3glucan on growth performance, feed utilization, antioxidative and immune status of Pacific white shrimp, *Litopenaeus vannamei*. Aquac Nutr 27(5):1590–1601. https://doi.org/10.1111/anu.13299
Yao W, Li X, Zhang C, Wang J, Cai Y, Leng X (2021) Effects of dietary synbiotics supplementation methods on growth, intestinal health, nonspecific immunity and disease resistance of Pacific white shrimp, *Litopenaeus vannamei*. Fish Shellfish Immunol 112:46–55. https://doi.org/10.1016/j.fsi.2021.02.055
Yin X, Zhuang X, Luo W, Liao M, Huang L, Cui Q, Huang J, Yan C, Jiang Z, Liu Y, Wang W (2022) Andrographolide promotes the growth and immunity of *Litopenaeus vannamei*, and protects shrimp against *Vibrio alginolyticus* by regulating inflammation and apoptosis via a ROS-JNK dependent pathway. Front Immunol 13:990297. https://doi.org/10.3389/fimmu.2022.990297
Zhao Q, Zhou K, Zhang F, Wang Y, Hao J, Xie F, Yang Q (2025) Relations between core taxa and metabolic characteristics of bacterial communities in *Litopenaeus vannamei* ponds and their probiotic potential. Microorganisms 13(2):466. https://doi.org/10.3390/microorganisms13020466

Publisher's Note

IAU remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.