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BETA-GLUCANS AS FUNCTIONAL FEED ADDITIVES IN MODERN AQUACULTURE

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Beta-glucans are naturally occurring polysaccharides found in fungi, yeast, cereals and algae. They have gained considerable attention as potent immunostimulants and functional feed additives in aquaculture. This review summarises the current knowledge of the mechanisms of action, efficacy and practical applications of beta-glucans in the culture of fish and shellfish. These compounds modulate innate and adaptive immune responses by activating macrophages, neutrophils and other immune cells, enhancing antioxidant defence systems and engaging molecular receptors such as Dectin-1 and Toll-like receptors. Supplementing feed with beta-glucans has been shown to improve growth performance, feed utilisation and disease resistance against bacterial, viral and parasitic infections. Beta-glucans also demonstrate synergistic effects when combined with vaccines, probiotics and other nutraceuticals, thereby supporting holistic health management and reducing dependence on antibiotics in aquaculture systems. However, their bioactivity is influenced by multiple factors, including molecular structure, source, extraction method, dosage, and environmental conditions. Current challenges include variability among commercial preparations, a lack of long-term studies, and the need for species-specific optimisation. Future research should therefore focus on identifying novel, cost-effective sources, such as microalgae and genetically modified yeast; elucidating receptor-mediated molecular mechanisms; and integrating β -glucans into precision aquaculture and functional feed strategies. Thus, β -glucans are a cornerstone of sustainable aquaculture development, providing a biologically safe and environmentally sound way to enhance the health, performance, and resilience of fish and shellfish.

Keywords: beta-glucans; aquaculture; immunostimulation; antioxidant defense; disease resistance; functional feeds; fish health; shellfish; sustainable aquaculture

БЕТА-ГЛЮКАНИ ЯК ФУНКЦІОНАЛЬНІ КОРМОВІ ДОБАВКИ В СУЧАСНІЙ АКВАКУЛЬТУРІ

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Бета-глюкани – це природні полісахариди, що містяться у грибах, дріжджах, злаках та водоростях. Вони привертають значну увагу як потужні імуностимулятори та функціональні кормові добавки в аквакультурі. У цьому



огляді узагальнено сучасні знання щодо механізмів дії, ефективності та практичного застосування бета-глюканів у вирощуванні риб і молюсків. Ці сполуки модулюють вроджену та набуту імунну відповідь шляхом активації макрофагів, нейтрофілів та інших імунних клітин, підсилюють антиоксидантні системи захисту та взаємодіють із молекулярними рецепторами, такими як *Dectin-1* і *Toll*-подібні рецептори. Додавання бета-глюканів до корму покращує ріст, ефективність використання корму та стійкість до бактеріальних, вірусних і паразитарних інфекцій. Бета-глюкани також демонструють синергічний ефект при поєднанні з вакцинами, пробіотиками та іншими нутрицевтиками, сприяючи комплексному збереженню здоров'я та зменшенню залежності від антибіотиків у системах аквакультури. Однак їх біологічна активність залежить від багатьох факторів, зокрема від молекулярної структури, джерела, методу екстракції, дози та умов середовища. Сучасні виклики включають варіабельність між комерційними препаратами, відсутність довгострокових досліджень та необхідність видоспецифічної оптимізації. Тому подальші дослідження повинні бути спрямовані на ідентифікацію нових, економічно ефективних джерел, таких як мікроводорості та генетично модифіковані дріжджі; з'ясування рецептор-опосередкованих молекулярних механізмів; а також інтеграцію β -глюканів у системи точної аквакультури та стратегії функціонального годування. Таким чином, β -глюкани є наріжним каменем сталого розвитку аквакультури, забезпечуючи біологічно безпечний і екологічно збалансований спосіб підвищення здоров'я, продуктивності та стійкості риб і молюсків.

Ключові слова: бета-глюкани; аквакультура; імуностимуляція; антиоксидантний захист; стійкість до хвороб; функціональні корми; здоров'я риб; молюски; сталий розвиток аквакультури.

Introduction. Aquaculture has emerged as one of the fastest-growing sectors of global food production. It plays a critical role in meeting the increasing demand for high-quality protein and essential nutrients (Ahmad A. et al., 2021). However, despite its rapid growth, the industry is confronted with several challenges, such as frequent disease outbreaks, high stocking densities and the extensive use of antibiotics, all of which can lead to antimicrobial resistance and environmental contamination. These issues highlight the urgent need for sustainable strategies to enhance fish health and productivity (Okeke E. S. et al., 2022).

In response to these challenges, there has been growing interest in recent years in using immunostimulants and functional feed additives as environmentally friendly alternatives to antibiotics. These compounds enhance the innate immune responses of fish, increasing disease resistance and promoting overall health and growth performance (Kolygas M. N. et al., 2025; Banu M. S. et al., 2025). Beta-glucans, in particular, have attracted considerable attention due to their potent immunomodulatory properties and suitability for long-term use in aquaculture species (Hadiuzzaman M. et al., 2022; Machuca C. et al., 2022). Numerous studies have demonstrated that dietary supplementation with beta-glucans can significantly improve survival rates and reduce the load of pathogens in fish exposed to bacterial, viral and parasitic infections (Vetvicka V. et al., 2013; Kong Y. et al., 2025).

Beta-glucans are naturally occurring polysaccharides composed of glucose units that are predominantly linked by β -(1 \rightarrow 3) and β -(1 \rightarrow 6) glycosidic bonds. They are widely found in the cell walls of fungi, yeast and grains such as oats and barley (Du B. et al., 2019). The structure, molecular weight and branching pattern of beta-glucans largely determine their biological activity, including their ability to stimulate immune cells,



modulate inflammatory responses and improve resistance to pathogens (Caseiro C. et al., 2022; Zhong X. et al., 2023). It is important to note that the immunological effects of beta-glucans are dose-dependent and can vary depending on the species of fish, their developmental stage, and the environmental conditions (Rodrigues M. V. et al., 2020). This necessitates further research to optimise their use in commercial aquaculture.

Aim. This review is based on the promising potential of beta-glucans as functional feed additives in aquaculture. By enhancing the innate immune system of fish and reducing reliance on antibiotics, beta-glucans offer a sustainable approach to disease management, supporting the economic and environmental sustainability of aquaculture operations. This review aims to summarise current knowledge on the sources, chemical characteristics, and immunomodulatory effects of beta-glucans, highlighting their role in promoting fish health and productivity.

Materials and methods. This review was developed based on a systematic literature survey covering the period between 1985 and 2025. The following keywords were used in combinations to search scientific databases including Web of Science, Scopus, PubMed, and Google Scholar: 'β-glucans', 'fish', 'aquaculture', 'immunostimulants', 'disease resistance', 'feed additives', 'growth performance', and 'antioxidant response'. Boolean operators ('AND', 'OR') were applied to refine the search results and filters were used to select peer-reviewed research articles, reviews and conference proceedings published in English. The initial search yielded approximately 550 references, which were screened for relevance based on titles and abstracts. After applying inclusion and exclusion criteria, 70 publications were selected for detailed analysis and synthesis in this review.

Studies were included based on the following criteria: they had to be experimental or review papers investigating the biological activity of β-glucans in fish or shellfish species; they had to assess immunological, antioxidant, or growth performance parameters following the dietary, injected, or immersion administration of β-glucans; and they had to provide quantitative data on immune biomarkers, growth indices, or disease resistance outcomes. Only articles published in peer-reviewed journals or official institutional reports were considered. Studies were excluded if they lacked experimental validation (e.g., theoretical or anecdotal reports), focused on mammals, birds, or terrestrial invertebrates, did not provide accessible full text or sufficient methodological detail, or presented duplicate data from the same research group or experiment.

The extracted data were categorised according to the following thematic sections, which correspond to the structure of this review: (1) sources and structural types of β-glucans; (2) mechanisms of action in fish and shellfish; (3) effects on growth performance and feed utilisation; (4) role in disease resistance and health management; and (5) factors affecting efficacy.

Results and discussion.

3.1. Sources and types of beta-glucans

Beta-glucans are widely distributed in nature and are categorised by their source as fungal, cereal or microbial (Edo G. I. et al., 2024). Those of fungal origin are among the most extensively studied for their immunomodulatory properties. Examples of species rich in β-(1→3)-glucans with β-(1→6) branching include *Saccharomyces cerevisiae* (baker's yeast) and various medicinal mushrooms such as *Lentinula edodes* (shiitake) and *Grifola frondosa* (maitake) (Zhong X. et al., 2023; Amirinia F. et al., 2025). These structures are particularly effective in stimulating innate immune responses, enhancing macrophage activity and promoting cytokine production, which is critical for defending against pathogens in fish (Amirinia F. et al., 2025). Numerous *in vivo* studies have demonstrated that dietary supplementation with fungal beta-glucans significantly



improves survival rates and immune gene expression in aquaculture species, including rainbow trout and carp (Ji L. et al., 2017; Cao H. et al., 2019; Khanjani M. H. et al., 2021).

In contrast, cereal-derived beta-glucans are primarily obtained from oats and barley, where they consist mainly of linear β -(1 \rightarrow 3) and β -(1 \rightarrow 4)-linked glucose residues. Unlike their fungal counterparts, cereal beta-glucans are more soluble and viscous, which has beneficial effects on gut health and nutrient absorption (Henrion M. et al., 2019). Although their immunostimulatory potential is generally lower than that of fungal beta-glucans, cereal beta-glucans have been shown to improve intestinal barrier function and modulate the gut microbiota, thereby indirectly supporting immune competence in aquaculture species (Petit J. et al., 2022). This prebiotic effect has been linked to increased populations of beneficial bacteria, such as *Lactobacillus* and *Bifidobacterium*, that play a role in maintaining mucosal immunity (Shoukat M. and Sorrentino A., 2021).

Microalgae and bacteria are emerging and unconventional sources of beta-glucans. Certain species of microalgae produce β -glucans with unique branching patterns that may confer novel biological activities, including antioxidant and antiviral effects (Li C. et al., 2025). Similarly, preliminary studies have shown that bacterial exopolysaccharides with β -(1 \rightarrow 3) and β -(1 \rightarrow 6) linkages have promising immunostimulatory potential, suggesting that these sources could be developed as sustainable feed additives for aquaculture (Nguyen H. T. et al., 2024). While these alternative sources are still under-explored, they may offer advantages in terms of scalability, environmental impact and compatibility with specific aquafeed formulations.

Table 1

Sources of beta-glucans, types of bonds, and main bioactive effects in the context of aquaculture

Source	Main β -glucan linkages	Key bioactive effects	Applications in aquaculture
Fungi (<i>Saccharomyces cerevisiae</i> , <i>Lentinula edodes</i> , <i>Grifola frondosa</i>)	β -(1 \rightarrow 3) backbone with β -(1 \rightarrow 6) branches	Strong immunostimulation, activation of macrophages, cytokine production, enhanced disease resistance	Widely used as feed additive to boost innate immunity and pathogen defense
Cereals (oats, barley)	Linear β -(1 \rightarrow 3)/ β -(1 \rightarrow 4)	Prebiotic effects, improved gut health, nutrient absorption, modulation of gut microbiota	Supports intestinal barrier function and overall growth; lower direct immunostimulatory activity
Microalgae (e.g., <i>Chlorella</i> , <i>Phaeodactylum</i>)	β -(1 \rightarrow 3) with variable branching	Antioxidant, antiviral, immunomodulatory potential	Emerging source; may offer novel functional benefits and sustainable production
Bacteria (exopolysaccharides from certain strains)	β -(1 \rightarrow 3), β -(1 \rightarrow 6)	Immunostimulation, pathogen resistance, potential anti-inflammatory effects	Less studied; promising for development of novel functional feeds



The structural diversity of beta-glucans is a key determinant of their bioactivity. The linkages between glucose monomers – β -(1 \rightarrow 3), β -(1 \rightarrow 4) and β -(1 \rightarrow 6) – affect solubility, molecular weight and receptor recognition by immune cells (Caseiro C. et al., 2022). For example, β -(1 \rightarrow 3/1 \rightarrow 6)-glucans from fungi are highly effective at activating pattern recognition receptors such as dectin-1 and complement receptor 3, triggering a cascade of immune responses (Caseiro C. et al., 2022; Singla A. et al., 2024). Conversely, linear β -(1 \rightarrow 3/1 \rightarrow 4)-glucans derived from cereals are more effective as prebiotics, promoting the growth of beneficial gut microbiota rather than directly stimulating immune cells (Lante A. et al., 2023). Understanding these molecular interactions is essential for optimising the immunonutritional value of beta-glucans in aquaculture diets.

The source and structural characteristics of beta-glucans determine their suitability for specific aquaculture applications. Fungal beta-glucans are generally favoured for enhancing systemic immunity and disease resistance, whereas cereal-derived beta-glucans are more appropriate for promoting gut health and improving growth performance (Vetvicka V. et al., 2013; Caseiro C. et al., 2022). Furthermore, combining beta-glucans with other functional ingredients, such as probiotics, vitamins or omega-3 fatty acids, has been shown to have additive or even synergistic effects on fish immunity and resilience to stress (Edo G. I. et al., 2024). Understanding these differences is therefore essential for selecting the appropriate beta-glucan type for targeted functional feed formulations.

Thus, the diversity of beta-glucan sources provides aquaculture nutritionists with a versatile toolbox for improving fish health and productivity. Matching the source, structure and bioactivity of beta-glucans to specific species and husbandry conditions enables the development of feed strategies that maximise immunostimulatory effects and overall welfare in aquaculture systems. Future research should focus on dose optimisation, long-term safety and species-specific responses to different beta-glucan types, in order to fully harness their potential in sustainable aquaculture.

3.2. Mechanisms of action in fish and shellfish

The immunomodulatory effects of β -glucans in aquatic organisms are primarily mediated by modulation of innate and adaptive immune responses. In fish and shellfish, for example, β -glucans act as pathogen-associated molecular patterns (PAMPs), which are recognised by pattern recognition receptors (PRRs) found on immune cells (Zhong X. et al., 2023; Machuca C. et al., 2026). This recognition triggers a cascade of signalling events that enhance non-specific immunity and indirectly activate adaptive immune mechanisms. Stimulating these pathways improves disease resistance, accelerates wound healing and enhances vaccine efficacy, all of which are of considerable interest in aquaculture health management (Vetvicka V. et al., 2013; Hadiuzzaman M. et al., 2022). These effects have been documented in various species, including rainbow trout, tilapia and shrimp (El-Boshy M. E. et al., 2010; Porter D. et al., 2023; Uengwetwanit T. et al., 2025), demonstrating the broad applicability of β -glucans in aquafeed formulations.

One key mechanism involves activating macrophages, neutrophils and other phagocytic cells. Upon exposure to β -glucans, these immune cells exhibit increased phagocytic and bactericidal activity, accompanied by enhanced production of reactive oxygen species (ROS) and nitric oxide (NO) (Stothers C. L. et al., 2021). In teleost fish, for example, macrophage activation leads to the upregulation of cytokines such as interleukin-1 β (IL-1 β), tumour necrosis factor-alpha (TNF- α) and interferon-gamma (IFN- γ), which coordinate innate and adaptive immune interactions (Mokhtar D. M. et al., 2023). Similarly, in crustaceans, β -glucans stimulate hemocytes, resulting in increased encapsulation, melanisation, and prophenoloxidase (proPO) activity. These cellular responses contribute to improved pathogen clearance and enhanced survival



under infectious challenge conditions (Guluarte C. et al., 2023).

In addition to activating immune cells, β -glucans enhance the antioxidant defence system in fish and shellfish. By modulating the activities of antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), β -glucans mitigate the oxidative damage associated with environmental stressors and infection (Kim Y. S. et al., 2009; Song L. et al., 2020). Improving antioxidant capacity supports cellular integrity and reduces lipid peroxidation, which is essential for maintaining homeostasis during immune responses and under intensive aquaculture production conditions. This dual role in immune stimulation and oxidative stress mitigation establishes β -glucans as multifunctional agents in the management of fish health (Tkachenko H. et al., 2022-2024; Kurhaluk N. et al., 2024).

At the molecular level, β -glucans exert their effects through specific receptor-mediated pathways. In vertebrate species, the C-type lectin receptor dectin-1 and various Toll-like receptors (TLRs) are among the most important for recognising β -glucans. Engagement of dectin-1 activates downstream signalling pathways such as NF- κ B and MAPK, leading to the transcription of immune-related genes (Adachi Y. et al., 2004; Petit J. et al., 2019). While dectin-1 homologues in fish are not well characterised, there is evidence to suggest that TLRs 2 and 6, as well as complement receptor 3 (CR3), are involved in β -glucan recognition and signalling in teleosts. These receptors enable β -glucans to modulate cytokine expression, antigen presentation and antibody production (Rodrigues M. V. et al., 2020). Further genomic and transcriptomic studies are needed to fully elucidate the receptor repertoire and signalling dynamics in different aquaculture species.

In invertebrates such as shrimp and molluscs, which lack adaptive immunity, β -glucans primarily function through pattern recognition receptors, including β -glucan-binding proteins (BGBPs) and lipopolysaccharide- and β -1,3-glucan-binding proteins (LGBPs) (Amparyup P. et al., 2012). Activation of these receptors triggers immune signalling cascades involving the proPO system and transcription factors such as Relish, which regulate the synthesis of antimicrobial peptides. This receptor-mediated mechanism enhances resistance to bacterial, viral and fungal pathogens (Amparyup P. et al., 2012). Notably, β -glucan supplementation has been shown to improve survival and immune gene expression in shrimp challenged with *Vibrio* spp., highlighting its importance in crustacean aquaculture (Uengwetwanit T. et al., 2025).

The mechanisms of β -glucan action in fish and shellfish are shown in Fig. 1.

Thus, β -glucans act as potent immunostimulants in fish and shellfish by engaging conserved immune recognition systems, amplifying cellular defence mechanisms and maintaining redox balance. Their ability to modulate both immune and antioxidant pathways highlights their potential as functional feed additives in aquaculture, promoting health and growth performance while reducing reliance on antibiotics and chemical treatments (Vetvicka V. et al., 2013; Rodrigues M. V. et al., 2020). Integrating them into feed strategies represents a promising approach to sustainable aquaculture, particularly when tailored to species-specific immune profiles and environmental conditions.

3.3. Effects on growth performance and feed utilisation

Numerous studies have demonstrated that supplementing the diet with β -glucans has a positive influence on growth performance, feed utilisation and overall health in various species of fish and shellfish. Including β -glucans in aquafeeds has been shown to improve weight gain, specific growth rate (SGR) and feed conversion ratio (FCR), often accompanied by increased survival rates in normal and stressful conditions (Kühlwein H. et al., 2014; Pilarski F. et al., 2017; Hao X. et al., 2024). These improvements are attributed to the immunostimulatory and antioxidant properties of β -glucans, which



enhance metabolic efficiency and reduce the physiological costs associated with immune challenges and oxidative stress (Doan H. V. et al., 2024). These benefits are particularly valuable in intensive aquaculture systems, where fish are frequently exposed to environmental and pathogenic stressors.

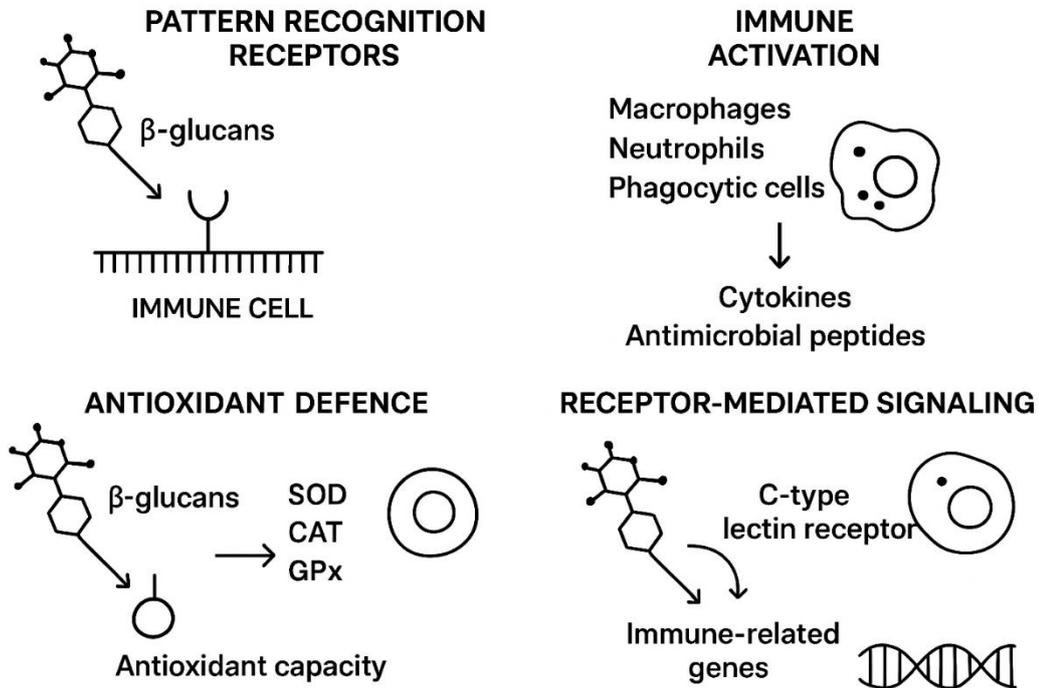


Fig. 1. Mechanisms of β -glucan action in fish and shellfish

The enhanced feed efficiency observed in fish supplemented with β -glucans is often linked to improved intestinal health and nutrient absorption. β -glucans may modulate gut morphology by increasing villus height and mucosal surface area, thereby promoting better feed digestibility (Singh R. P. and Bhardwaj A., 2023). Furthermore, their prebiotic-like activity stimulates the growth of beneficial gut microbiota such as *Lactobacillus* and *Bacillus* species, contributing to improved digestion and nutrient assimilation (Shoukat M. and Sorrentino A., 2021). Similar benefits have been reported in crustaceans, including increased protein retention and enhanced digestive enzyme activities, particularly amylase and protease, which support efficient feed utilisation (Vargas-Albores F. and Yepiz-Plascencia G., 2000). These effects collectively contribute to improved feed conversion efficiency and reduced production costs.

The effects of β -glucans on growth and survival are also dose-dependent. The optimal level of supplementation varies between species and is influenced by factors such as the molecular weight, source and structural linkage of the β -glucans (e.g. β -1,3/1,6 versus β -1,3/1,4) (Caseiro C. et al., 2022). For most teleost fish, effective dosages range from 0.05% to 0.2% dietary inclusion; higher levels may result in immune overstimulation and reduced growth performance (Doan H. V. et al., 2024). In shellfish such as shrimp, dietary inclusion levels of 0.1-0.5% are generally associated with improved growth and resistance to pathogens. However, excessive supplementation can cause metabolic imbalances, reduced palatability or altered energy partitioning, highlighting the importance of optimising dosages for each species (Uengwetwanit T. et al., 2025).

Various administration methods of β -glucans have also been explored in



aquaculture. Oral supplementation via feed is the most practical and widely applied approach, providing a continuous and non-invasive means of immune stimulation (Vetvicka V. et al., 2013). However, injection-based administration has been shown to elicit a rapid and pronounced immune response, which is especially useful in vaccination or disease-challenge experiments. Immersion treatments, though less common, may be suitable for early life stages or larvae (Rodrigues M. V. et al., 2020). Each method has its own advantages and limitations in terms of efficacy, labour intensity and stress induction, and the most suitable method should be selected based on the production context and target outcomes.

There have been many reports of species-specific responses to β -glucan supplementation. For example, salmonids and cyprinids typically demonstrate significant improvements in growth and immune function (Waikhom D. et al., 2022; Stangroom J. et al., 2025), whereas carnivorous marine fish such as sea bass and grouper tend to exhibit more modest responses (Bagni M. et al., 2005; Krishnan R. et al., 2022). In crustaceans, particularly *Litopenaeus vannamei* and *Penaeus monodon*, β -glucans consistently enhance survival and feed efficiency in the presence of bacteria or viruses (Wilson W. et al., 2015; Medina Félix D. et al., 2022; Shen K. et al., 2023). These interspecies differences are likely driven by variations in gut physiology, immune system complexity and microbiota composition, all of which influence the bioavailability and functional outcomes of β -glucan supplementation (Vetvicka V. et al., 2013; Doan H. V. et al., 2024).

Thus, β -glucan supplementation is an effective strategy for enhancing growth performance and feed utilisation in aquaculture species. By improving nutrient absorption, intestinal integrity and systemic resilience, β -glucans can contribute to sustainable, antibiotic-free production systems. Integrating them into functional feed formulations aligns with modern aquaculture's goals of reducing environmental impact, improving animal welfare, and ensuring food safety (Doan H. V. et al., 2024; Machuca C. et al., 2025). Continued optimisation of dosage, source selection and administration methods across different species will further strengthen their application in modern aquafeed formulations and support the development of resilient aquaculture systems.

3.4. Role of β -glucans in disease resistance and health management

β -glucans play a crucial role in improving the disease resistance and overall health of aquaculture species by stimulating their innate immune defences and making them more resilient to bacterial, viral and parasitic infections (Meena D. K. et al., 2013). As natural immunostimulants, they activate macrophages, neutrophils and other immune cells, leading to increased production of lysozyme, complement proteins and antimicrobial peptides (Doan H. V. et al., 2024). These effects improve survival following exposure to pathogens such as *Aeromonas hydrophila*, *Vibrio anguillarum*, *Streptococcus iniae* and the White Spot Syndrome Virus (WSSV) (Lokesh J. et al., 2012; Salah A. S. et al., 2017; Duman S. and Şahan A., 2023; Valladares A. et al., 2024). In the case of parasitic infections, fish supplemented with β -glucans often exhibit reduced parasite loads and enhanced tissue repair mechanisms, highlighting their broad-spectrum protective capacity (Meena D. K. et al., 2013). These outcomes are particularly valuable in high-density aquaculture systems, where pathogen transmission and stress levels are high.

The synergistic interaction between β -glucans and vaccines is a promising strategy for improving vaccine efficacy in aquaculture. Pre-treatment or co-administration of β -glucans can enhance antigen presentation, elevate antibody titres, and promote a more sustained immune response following vaccination (Rodrigues M. V. et al., 2020). Not only do β -glucans strengthen non-specific immune defences, they also potentiate vaccine efficacy, providing a promising strategy for disease prevention in salmon aquaculture. Dietary supplementation with β -1,3/1,6-glucans (MacroGard[®]) has



been shown to significantly improve the survival rate of Atlantic salmon when challenged with *Moritella viscosa* and the infectious salmon anaemia (ISA) virus. (Roberti Filho, F. de O. et al., 2019). Similarly, in tilapia, β -glucans have been shown to enhance the efficacy of vaccines against bacterial and viral pathogens by stimulating both humoral and cellular immunity (Reis I. C. D. et al., 2021). This immunopotentiality improves protection and reduces the time required to establish effective immunity, which is critical during early life stages and disease outbreaks.

In addition to their synergistic effects with vaccines, β -glucans also work in conjunction with probiotics to promote fish health. Using β -glucans alongside probiotic bacteria, such as *Bacillus subtilis* or *Lactobacillus plantarum*, has been shown to improve the balance of gut microbiota, mucosal immunity and resistance to enteric infections. This functional synergy arises from the ability of β -glucans to prime innate immune cells and the role of probiotics in maintaining a beneficial intestinal environment. The result is additive or even synergistic effects on disease resistance, feed efficiency, and overall performance (Dawood M. A. O. et al., 2020; do Carmo Alves A. P. et al., 2023). Recent studies also suggest that these combinations may reduce inflammation and improve stress tolerance, providing further support for their use in integrated health management strategies (Dawood M. A. et al., 2015; Jami, M. J. et al., 2019).

One of the most significant implications of using β -glucans in aquaculture is reducing antibiotic dependence (Vetvicka V. et al., 2013; Doan H. V. et al., 2024). The overuse of antibiotics in fish farming has led to growing concerns about antimicrobial resistance, environmental contamination and food safety (Ljubojević Pelić D. et al., 2024). Incorporating β -glucans into feed provides a sustainable alternative by enhancing the animal's natural immune competence and decreasing the need for chemotherapeutic interventions. This approach is in line with the global shift towards more sustainable aquaculture practices and supports regulatory initiatives aimed at minimising antibiotic use in food production systems (Doan H. V. et al., 2024; Kong Y. et al., 2025). Furthermore, β -glucan-based strategies can contribute to increased consumer confidence and market access, particularly in regions with stringent residue regulations.

Several case studies involving commercially important species further demonstrate the practical benefits of applying β -glucan. For example, in Atlantic salmon (*Salmo salar*), diets enriched with β -glucans have improved resistance to *Vibrio* and *Aeromonas* infections, while reducing mortality during stressful production phases (Robertsen B. et al., 1990; Jørgensen J. B. and Robertsen B., 1995). In Nile tilapia (*Oreochromis niloticus*), β -glucan supplementation enhanced survival following a *Streptococcus* challenge and improved haematological and immune parameters (Salah A. S. et al., 2017). In shrimp species such as *Litopenaeus vannamei* and *Penaeus monodon*, β -glucans have provided protection against WSSV and *Vibrio* infections, significantly increasing survival rates and growth performance (Rodríguez J. et al., 2007; Yang C.-C. et al., 2014; Vega-Carranza A. S. et al., 2024). Similarly, in common carp (*Cyprinus carpio*), dietary β -glucans increased resistance to *Aeromonas hydrophila* infection and improved antioxidant enzyme activities (Jung-Schroers V. et al., 2018; Mohammadian T. et al., 2019). These findings highlight the versatility of β -glucans across taxonomic groups and production environments.

Fig. 2 shows the role of β -glucans in disease resistance and health management.

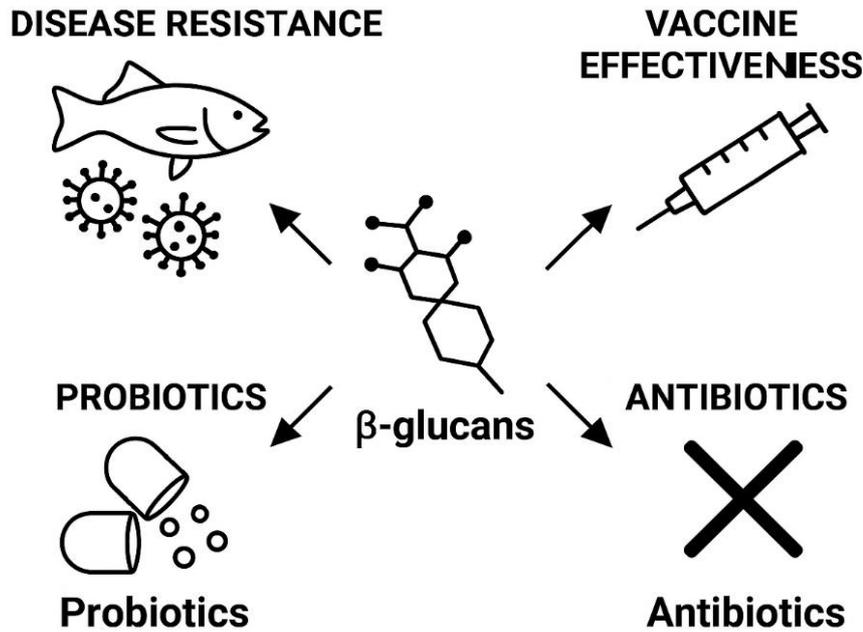


Fig. 2. Role of β -glucans in disease resistance and health management

Thus, β -glucans are a cornerstone of modern aquaculture health management, reinforcing disease resistance, promoting vaccine effectiveness and reducing reliance on antibiotics. Integrating them into feed and health programmes improves productivity, sustainability and biosecurity in diverse aquaculture systems (Vetvicka V. et al., 2013; Doan H. V. et al., 2024). Future research should focus on optimising delivery methods, understanding species-specific responses and exploring synergistic combinations with other functional ingredients, in order to fully harness the potential of β -glucans in precision aquaculture.

3.5. Factors affecting efficacy of β -glucans in fish and shellfish

The biological efficacy of β -glucans in fish and shellfish is influenced by various factors, including their chemical structure, source, dosage, administration route and environmental conditions. Understanding these factors is crucial for optimising the use of β -glucans in aquaculture and achieving consistent immunostimulatory and growth-promoting results across species and production systems (Rodrigues M. V. et al., 2020; Machuca C. et al., 2025). This complexity underscores the necessity of integrative approaches that consider biological and operational variables when designing functional feed strategies.

One of the most critical factors affecting β -glucan activity is its molecular structure and origin. Those derived from yeast (*Saccharomyces cerevisiae*), fungi, cereals or algae differ in their degree of branching, solubility and linkage patterns (β -1,3-, β -1,6- or β -1,4-linkages), which strongly influence recognition by immune receptors such as Dectin-1 and Toll-like receptors (Zhong X. et al., 2023). Yeast-derived β -1,3/1,6-glucans generally exhibit the highest immunostimulatory activity, whereas cereal β -1,3/1,4-glucans are more effective as dietary fibres and modulators of gut physiology (Edo G. I. et al., 2025). Structural characteristics such as molecular weight, tertiary conformation and degree of purification also affect bioavailability and receptor binding efficiency, thereby modulating the intensity of the biological response (Rodrigues M. V. et al., 2020). Recent studies suggest that highly purified, low-molecular-weight β -glucans may offer



improved solubility and absorption, thereby enhancing their immunological impact in aquatic species (Ishimoto Y. et al., 2018).

The dose, duration and route of administration of β -glucan also significantly impact its effectiveness. Optimal immune enhancement is typically achieved with low to moderate inclusion levels (0.05-0.2% in fish and 0.1-0.5% in crustaceans), while excessive dosages may result in immune tolerance or metabolic burden (Vetvicka V. et al., 2013; Hadiuzzaman M. et al., 2022). Short-term administration can trigger transient immune activation, whereas continuous supplementation supports prolonged immunocompetence, though this can reduce responsiveness over time. In terms of delivery methods, oral administration via feed is favoured for regular use, whereas injection or immersion methods may be used in experimental or emergency situations that require rapid immune stimulation (Zhong X. et al., 2023). Tailoring the delivery strategy to the species, life stage and production context is essential for maximising efficacy and minimising stress.

Environmental factors and stress conditions play a crucial role in determining β -glucan efficacy. Temperature, salinity, dissolved oxygen and water quality can all affect the immune status of fish and their responsiveness to immunostimulants (Vetvicka V. et al., 2013). For example, at suboptimal temperatures or under hypoxic conditions, β -glucan-mediated immune activation may be reduced due to lower metabolic activity (Murphy E. J. et al., 2020; Zhong X. et al., 2023). Conversely, β -glucan supplementation can mitigate the negative effects of stress on immunity and oxidative balance during periods of stress, such as handling, transport or crowding, thereby improving overall resilience and survival (Zhong X. et al., 2023). Therefore, the timing of β -glucan administration relative to stressful events is a key consideration in aquaculture management. Strategic supplementation during periods of known stress may enhance recovery and reduce mortality.

The biological activity of β -glucans can also be influenced by interactions with other feed components. The presence of lipids, proteins, vitamins and minerals can affect the solubility, absorption and stability of β -glucans in the gastrointestinal tract (Singh R. P. and Bhardwaj A., 2023). For instance, high levels of dietary lipids can prevent β -glucans from binding to intestinal receptors, whereas certain micronutrients, such as vitamins C and E, selenium, and zinc, can enhance their antioxidant and immune-boosting effects (Singh R. P. and Bhardwaj A., 2023; Edo G. I. et al., 2024). Similarly, combining β -glucans with probiotics or prebiotics can enhance the activity of beneficial gut microbiota, thereby improving intestinal health and disease resistance (Marcharla E. et al., 2025). These combinations are a promising approach to developing multifunctional aquafeeds that support immunity and digestion.

In summary, the efficacy of β -glucans in aquaculture depends on a complex interplay of molecular, physiological and environmental factors. Optimising these parameters – particularly the source, structure, dosage and feeding strategy – will maximise their potential as sustainable immunostimulants and performance enhancers in fish and shellfish farming (Meena D. K. et al., 2013; Vetvicka V. et al., 2013). Future research should focus on species-specific receptor interactions, long-term safety and synergistic formulations, with the aim of advancing precision nutrition in aquaculture. A better mechanistic understanding of these interactions will contribute to the development of more targeted, species-specific β -glucan applications in modern aquafeed formulations.

3.6. Challenges and limitations

Despite the well-documented benefits of β -glucans in aquaculture, their large-scale application and consistent performance across species are still constrained by



several challenges and limitations. One of the most significant obstacles is the variability in bioactivity among different β -glucan preparations (Singla A. et al., 2024). Structural heterogeneity arising from the source organism (e.g. yeast, fungi, cereals or algae), the extraction method and the purification process can lead to substantial differences in molecular weight, degree of branching, solubility and receptor-binding affinity (Singh R. P. and Bhardwaj A., 2023). For example, β -1,3/1,6-glucans derived from yeast typically exhibit higher immunostimulatory potency than β -1,3/1,4-glucans derived from cereals, yet their efficacy can vary depending on the methods used to disrupt the cell wall and the presence of residual impurities. Such variability complicates standardisation and makes it difficult to compare results across studies or predict biological outcomes in commercial settings (De Marco Castro E. et al., 2021). Therefore, establishing standardised characterisation protocols and bioactivity benchmarks is essential to ensure reproducibility and comparability across research and industry applications.

Another key limitation is the cost and scalability of producing β -glucans for widespread use in aquaculture. High-quality, purified β -glucans that are suitable for inclusion in feed are relatively expensive due to the complex extraction and refinement procedures required (Kong Y. et al., 2025). Although industrial by-products and fermentation waste offer potential as alternative sources, achieving consistent purity and activity on a large scale remains technically challenging. Furthermore, when incorporating them into aquafeeds, a balance must be struck between cost-effectiveness and biological efficacy, particularly for low-margin species such as carp or tilapia (Estevão-Rodrigues T. et al., 2025). Innovative approaches, such as enzymatic extraction, biotechnological synthesis and the valorisation of agro-industrial residues, could help to reduce production costs and improve accessibility. Therefore, the development of more efficient extraction technologies and the identification of novel, low-cost sources, such as marine fungi or microalgae, are essential for making β -glucan supplementation more economically viable (Mishra B. et al., 2023).

Another limitation is the scarcity of long-term, species-specific studies that evaluate the effects of β -glucans under practical farming conditions. Most of the available data comes from short-term laboratory trials which often focus on a single immune or antioxidant marker rather than providing a comprehensive assessment of growth, health and disease resistance throughout the production cycle (Hadiuzzaman M. et al., 2022). Additionally, differences in digestive physiology, microbiota composition, and immune architecture among fish and shellfish species mean that findings from one species cannot always be extrapolated to others. To address this, future studies should incorporate multi-parameter assessments, field trials and life-stage-specific evaluations, in order to better reflect real-world aquaculture scenarios (Wang F. et al., 2024). There is an urgent need for standardised protocols and longer-term studies that address chronic exposure, cumulative effects and interactions with environmental stressors, such as temperature fluctuations, salinity changes and pathogen load (Nieves-Rodríguez K. N. et al., 2018).

Additionally, the mechanisms underlying β -glucan recognition and signalling in many aquatic species are only partially understood. The identification and functional characterisation of receptors analogous to dectin-1 or Toll-like receptors in teleosts and invertebrates is ongoing (Petit J. et al., 2019). Knowledge gaps currently limit our ability to tailor β -glucan formulations for maximum efficacy. Without a deeper molecular understanding, optimising structure–function relationships and predicting immunological outcomes will remain challenging. However, advances in omics technologies, such as transcriptomics, proteomics and metabolomics, could accelerate the discovery of key immune pathways and receptor interactions, enabling more precise, species-specific β -glucan applications (Rodrigues M. V. et al., 2020).



Thus, although β -glucans show great potential as sustainable immunostimulants in aquaculture, their practical application is hindered by inconsistent product quality, cost limitations, and a lack of mechanistic and long-term data. Overcoming these challenges through standardisation, technological innovation and targeted research is essential to realise their full potential in disease management and productivity enhancement across diverse aquaculture systems. Collaborative efforts between academia, industry and regulatory bodies are essential for translating laboratory findings into scalable, cost-effective solutions that will support the future of sustainable aquaculture.

3.7. Future perspectives and research directions

The future of β -glucan applications in aquaculture depends on utilising new sources, improving production technologies, and incorporating them into modern precision aquaculture systems. Emerging research highlights the potential of alternative sources such as microalgae, marine fungi and genetically engineered yeast strains that can produce β -glucans with optimised structures and enhanced bioactivity (Li C. et al., 2025). For example, β -glucans derived from microalgae may be more soluble and can deliver bioactive compounds such as carotenoids and polyunsaturated fatty acids alongside them, providing multifunctional benefits for managing fish health (Martínez-Ruiz F. E. et al., 2025; Prates J. A. M., 2025). Meanwhile, advances in biotechnology allow yeast to be genetically modified to produce specific β -glucan linkages or to co-produce synergistic molecules such as mannans and chitin. This paves the way for next-generation immunostimulants that are more consistent and potent (Hadiuzzaman M. et al., 2022).

Integrating β -glucans into precision aquaculture and functional feed strategies is another important development. As aquaculture increasingly adopts data-driven management, β -glucans could be administered in response to real-time environmental and physiological indicators, such as temperature fluctuations, pathogen exposure or oxidative stress levels (Ghaedi G. et al., 2022; Onomu A. J. and Okuthe, G. E., 2024). Combining β -glucans with other nutraceuticals, including probiotics, prebiotics, phytogenics and omega-3 fatty acids, may further enhance resilience, disease resistance and feed efficiency. This approach aligns with the broader concept of functional feeds, which support growth and actively promote animal health and welfare in an environmentally sustainable manner (Marcharla E. et al., 2025).

Despite these advances, there are still several research gaps that must be addressed before β -glucans can reach their full potential in commercial aquaculture. The optimal dosage, duration and timing of administration are poorly defined and are likely to vary by species, developmental stage and production system (Hadiuzzaman M. et al., 2022; Hao X. et al., 2024). Furthermore, the molecular mechanisms underlying β -glucan recognition and signalling in fish and shellfish need to be better understood. Identifying receptor homologues, downstream signalling pathways, and transcriptional networks will be essential for designing more targeted and efficient formulations. Long-term studies assessing chronic exposure, immune memory and the potential trade-offs between immune activation and growth are also needed to ensure the safe and effective application of β -glucans under commercial farming conditions (Petit J. et al., 2019).

Standardisation and quality control of β -glucan products are another critical area for future research. Variability in source material, extraction methods, and structural characteristics can lead to inconsistent bioactivity across batches. Establishing global guidelines for characterisation, purity assessment and bioactivity testing would facilitate regulatory approval and broader industry adoption. In parallel, advances in omics technologies, such as transcriptomics, proteomics and metabolomics, will be instrumental in uncovering the complex interactions between β -glucans, host metabolism and



microbiota. This will support evidence-based feed formulation and precision nutrition (Li X. et al., 2024).

In conclusion, β -glucans are a key component of the future of sustainable aquaculture, combining nutrition, immunology, and biotechnology. Continued innovation in source development, molecular understanding and precision feeding strategies holds great promise for enhancing the health of fish and shellfish, improving productivity and reducing the global aquaculture industry's dependence on antibiotics and chemical therapeutics.

Conclusions. β -glucans have emerged as some of the most effective natural immunostimulants and functional feed additives in modern aquaculture. Extensive research has demonstrated their ability to boost innate and adaptive immune responses, activate phagocytic cells and strengthen antioxidant defences in fish and shellfish. These biological effects result in improved disease resistance, growth performance and feed utilisation in a variety of aquaculture species. Through receptor-mediated pathways involving dectin-1 and Toll-like receptors, β -glucans modulate immune signalling and contribute to greater resilience in the face of environmental and pathogenic stress. Taken together, these findings highlight their multifunctional role in promoting health, welfare and sustainability in the production of aquatic animals.

Beyond immune enhancement, the practical benefits of β -glucan supplementation include improved intestinal health, enhanced nutrient absorption and reduced mortality under routine and stressful conditions. When appropriately dosed and formulated, β -glucans support mucosal integrity and stimulate beneficial gut microbiota, contributing to better digestion and metabolic efficiency. Their interactions with vaccines, probiotics and other bioactive feed components strengthen host defence mechanisms synergistically, offering a viable alternative to antibiotic use. Consequently, β -glucans are in line with global efforts to minimise antimicrobial resistance and promote eco-friendly aquaculture practices that prioritise food safety and environmental stewardship.

Despite these advantages, several challenges remain. Variability in product quality, limited species-specific data and the absence of standardised dosage and administration protocols continue to constrain their widespread application. Future research should focus on elucidating the molecular mechanisms of action, optimising supplementation strategies and exploring novel sources, such as microalgae and genetically engineered yeast. Long-term field trials conducted in a variety of aquaculture environments are essential for validating laboratory findings and establishing practical guidelines for commercial use.

In conclusion, β -glucans are a powerful tool for advancing sustainable aquaculture by improving health management, growth efficiency and disease prevention. Continued interdisciplinary research integrating molecular biology, nutrition and aquaculture technology will refine their application further, enabling precise, species-specific use and enhancing the overall productivity and resilience of aquaculture systems worldwide.

References

- Adachi, Y., Ishii, T., Ikeda, Y., Hoshino, A., Tamura, H., Aketagawa, J., Tanaka, S., & Ohno, N. (2004). Characterization of beta-glucan recognition site on C-type lectin, dectin 1. *Infection and immunity*, 72(7), 4159–4171. <https://doi.org/10.1128/IAI.72.7.4159-4171.2004>.
- Ahmad, A., Sheikh Abdullah, S. R., Abu Hasan, H., Othman, A. R., & Ismail, N. I. (2021). Aquaculture industry: Supply and demand, best practices, effluent and its current issues and treatment technology. *Journal of Environmental Management*, 287, 112271. <https://doi.org/10.1016/j.jenvman.2021.112271>.



- Amirinia, F., Jabrodi, A., Morovati, H., Ardi, P., & Motamedi, M. (2025). Fungal β -Glucans: Biological Properties, Immunomodulatory Effects, Diagnostic and Therapeutic Applications. *Infectious diseases & clinical microbiology*, 7(1), 1–16. <https://doi.org/10.36519/idcm.2025.448>.
- Amparyup, P., Sutthangkul, J., Charoensapsri, W., & Tassanakajon, A. (2012). Pattern recognition protein binds to lipopolysaccharide and β -1,3-glucan and activates shrimp prophenoloxidase system. *The Journal of biological chemistry*, 287(13), 10060–10069. <https://doi.org/10.1074/jbc.M111.294744>.
- Bagni, M., Romano, N., Finioia, M. G., Abelli, L., Scapigliati, G., Tiscar, P. G., Sarti, M., & Marino, G. (2005). Short- and long-term effects of a dietary yeast beta-glucan (Macrogard) and alginic acid (Ergosan) preparation on immune response in sea bass (*Dicentrarchus labrax*). *Fish & shellfish immunology*, 18(4), 311–325. <https://doi.org/10.1016/j.fsi.2004.08.003>.
- Banu, M. S., Yadav, N. K., Saha, H., & Patel, A. B. (2025). Culinary spices as functional feed additives in aquaculture: Growth, immunity, and health perspectives. *Comparative Immunology Reports*, 9, 200256. <https://doi.org/10.1016/j.cirep.2025.200256>.
- Cao, H., Yu, R., Zhang, Y., Hu, B., Jian, S., Wen, C., Kajbaf, K., Kumar, V., & Yang, G. (2019). Effects of dietary supplementation with β -glucan and *Bacillus subtilis* on growth, fillet quality, immune capacity, and antioxidant status of Pengze crucian carp (*Carassius auratus* var. Pengze). *Aquaculture*, 508, 106–112. <https://doi.org/10.1016/j.aquaculture.2019.04.064>.
- Caseiro, C., Dias, J. N. R., de Andrade Fontes, C. M. G., & Bule, P. (2022). From Cancer Therapy to Winemaking: The Molecular Structure and Applications of β -Glucans and β -1, 3-Glucanases. *International journal of molecular sciences*, 23(6), 3156. <https://doi.org/10.3390/ijms23063156>.
- Dawood, M. A. O., Magouz, F. I., Salem, M. F. I., Elbially, Z. I., & Abdel-Daim, H. A. (2020). Synergetic Effects of *Lactobacillus plantarum* and β -Glucan on Digestive Enzyme Activity, Intestinal Morphology, Growth, Fatty Acid, and Glucose-Related Gene Expression of Genetically Improved Farmed Tilapia. *Probiotics and antimicrobial proteins*, 12(2), 389–399. <https://doi.org/10.1007/s12602-019-09552-7>.
- Dawood, M. A., Koshio, S., Ishikawa, M., & Yokoyama, S. (2015). Interaction effects of dietary supplementation of heat-killed *Lactobacillus plantarum* and β -glucan on growth performance, digestibility and immune response of juvenile red sea bream, *Pagrus major*. *Fish & shellfish immunology*, 45(1), 33–42. <https://doi.org/10.1016/j.fsi.2015.01.033>.
- De Marco Castro, E., Calder, P. C., & Roche, H. M. (2021). β -1,3/1,6-Glucans and Immunity: State of the Art and Future Directions. *Molecular nutrition & food research*, 65(1), e1901071. <https://doi.org/10.1002/mnfr.201901071>.
- do Carmo Alves, A. P., do Carmo Alves, A., Ferreira Rodrigues, R. A., da Silva Cerozi, B., & Possebon Cyrino, J. E. (2023). Microencapsulation of *Bacillus subtilis* and oat β -glucan and their application as a synbiotic in fish feed. *Journal of microencapsulation*, 40(7), 491–501. <https://doi.org/10.1080/02652048.2023.2220394>.
- Doan, H. V., Sumon, M. A. A., Tran, H. Q., Le, C. X., Mohammady, E. Y., El-Haroun, E. R., Hoseinifar, S. H., Ringo, E., Stejskal, V., & Dawood, M. A. O. (2024). Role of β -glucan on finfish and shellfish health and well-being: A systematic review and meta-analysis. *Reviews in Aquaculture*, 16(4), 1996–2009. <https://doi.org/10.1111/raq.12944>.



- Du, B., Meenu, M., Liu, H., & Xu, B. (2019). A Concise Review on the Molecular Structure and Function Relationship of β -Glucan. *International journal of molecular sciences*, 20(16), 4032. <https://doi.org/10.3390/ijms20164032>.
- Duman, S., & Şahan, A. (2023). Effects of β -1,3/1,6 glucan dietary supplements on some immunological and hematological health markers in Siberian sturgeon (*Acipenser baerii*) infected with *Aeromonas hydrophila*. *Polish journal of veterinary sciences*, 26(1), 109–118. <https://doi.org/10.24425/pjvs.2023.145012>.
- Edo, G. I., Mafe, A. N., Ali, A. B. M., Akpogheli, P. O., Yousif, E., Isoje, E. F., Igbuku, U. A., Zainulabdeen, K., Owheruo, J. O., Essaghah, A. E. A., Umar, H., Ahmed, D. S., & Alamiery, A. A. (2025). A critical review on the impacts of β -glucans on gut microbiota and human health. *The Microbe*, 7, 100394. <https://doi.org/10.1016/j.microb.2025.100394>.
- Edo, G. I., Ndudi, W., Makia, R. S., Ainyanbhor, I. E., Yousif, E., Gaaz, T. S., Zainulabdeen, K., Jikah, A. N., Opiti, R. A., Akpogheli, P. O., Owheruo, J. O., Essaghah, A. E. A., & Umar, H. (2024). Beta-glucan: An overview in biological activities, derivatives, properties, modifications and current advancements in food, health and industrial applications. *Process Biochemistry*, 147, 347–370. <https://doi.org/10.1016/j.procbio.2024.09.011>.
- El-Boshy, M. E., El-Ashram, A. M., Abdelhamid, F. M., & Gadalla, H. A. (2010). Immunomodulatory effect of dietary *Saccharomyces cerevisiae*, beta-glucan and laminaran in mercuric chloride treated Nile tilapia (*Oreochromis niloticus*) and experimentally infected with *Aeromonas hydrophila*. *Fish & shellfish immunology*, 28(5-6), 802–808. <https://doi.org/10.1016/j.fsi.2010.01.017>.
- Estevão-Rodrigues, T., Fernandes, H., Moutinho, S., Ferreira, M., Castro, C., Belo, I., Salgado, J. M., Oliva-Teles, A., & Peres, H. (2025). Effect of Solid-Fermented Brewer's Spent Grain on Growth, Metabolism, and Oxidative Status of European Seabass (*Dicentrarchus labrax*). *Fishes*, 10(2), 49. <https://doi.org/10.3390/fishes10020049>.
- Ghaedi, G., Sharifinia, M., & Khanjani, M. H. (2022). Beta-glucan as a promising food additive and immunostimulant in aquaculture industry. *Annals of Animal Science*, 22(3), 817–827. <https://doi.org/10.2478/aoas-2021-0083>.
- Guluarte, C., Pereyra, A., Ramírez-Hernández, E., Zenteno, E., & Luis Sánchez-Salgado, J. (2023). The immunomodulatory and antioxidant effects of β -glucans in invertebrates. *Journal of invertebrate pathology*, 201, 108022. <https://doi.org/10.1016/j.jip.2023.108022>.
- Hadiuzzaman, M., Moniruzzaman, M., Shahjahan, M., Bai, S. C., Min, T., & Hossain, Z. (2022). β -Glucan: Mode of action and its uses in fish immunomodulation. *Frontiers in Marine Science*, 9, 905986. <https://doi.org/10.3389/fmars.2022.905986>.
- Hao, X., Lin, Z., Ma, Z., Yang, Y., Zhou, C., Hu, J., Yu, W., & Lin, H. (2024). Effect of Dietary β -Glucan on Growth Performance, Antioxidant Responses, and Immunological Parameters of Coral Trout (*Plectropomus leopardus*). *Fishes*, 9(8), 298. <https://doi.org/10.3390/fishes9080298>.
- Henrion, M., Francey, C., Lê, K. A., & Lamothe, L. (2019). Cereal B-Glucans: The Impact of Processing and How It Affects Physiological Responses. *Nutrients*, 11(8), 1729. <https://doi.org/10.3390/nu11081729>.
- Ishimoto, Y., Ishibashi, K.-I., Yamanaka, D., Adachi, Y., Kanzaki, K., Iwakura, Y., & Ohno, N. (2018). Production of low-molecular weight soluble yeast β -glucan by an acid degradation method. *International Journal of Biological Macromolecules*, 107(Part B), 2269–2278. <https://doi.org/10.1016/j.ijbiomac.2017.10.094>.



- Jami, M. J., Abedian Kenari, A., Paknejad, H., & Mohseni, M. (2019). Effects of dietary β -glucan, mannan oligosaccharide, *Lactobacillus plantarum* and their combinations on growth performance, immunity and immune related gene expression of Caspian trout, *Salmo trutta caspius* (Kessler, 1877). *Fish & shellfish immunology*, 91, 202–208. <https://doi.org/10.1016/j.fsi.2019.05.024>.
- Ji, L., Sun, G., Li, J., Wang, Y., Du, Y., Li, X., & Liu, Y. (2017). Effect of dietary β -glucan on growth, survival and regulation of immune processes in rainbow trout (*Oncorhynchus mykiss*) infected by *Aeromonas salmonicida*. *Fish & shellfish immunology*, 64, 56–67. <https://doi.org/10.1016/j.fsi.2017.03.015>.
- Jørgensen, J. B., & Robertsen, B. (1995). Yeast beta-glucan stimulates respiratory burst activity of Atlantic salmon (*Salmo salar* L.) macrophages. *Developmental and comparative immunology*, 19(1), 43–57. [https://doi.org/10.1016/0145-305x\(94\)00045-h](https://doi.org/10.1016/0145-305x(94)00045-h).
- Jung-Schroers, V., Adamek, M., Harris, S., Syakuri, H., Jung, A., Irnazarow, I., & Steinhagen, D. (2018). Response of the intestinal mucosal barrier of carp (*Cyprinus carpio*) to a bacterial challenge by *Aeromonas hydrophila* intubation after feeding with β -1,3/1,6-glucan. *Journal of Fish Diseases*, 41(7), 1077–1092. <https://doi.org/10.1111/jfd.12799>.
- Khanjani, M. H., Ghaedi, G., & Sharifinia, M. (2021). Effects of diets containing β -glucan on survival, growth performance, haematological, immunity and biochemical parameters of rainbow trout (*Oncorhynchus mykiss*) fingerlings. *Aquaculture Research*, 52(12), 6012–6024. <https://doi.org/10.1111/are.15712>.
- Kim, Y. S., Ke, F., & Zhang, Q. Y. (2009). Effect of beta-glucan on activity of antioxidant enzymes and Mx gene expression in virus infected grass carp. *Fish & shellfish immunology*, 27(2), 336–340. <https://doi.org/10.1016/j.fsi.2009.06.006>.
- Kolygas, M. N., Bitchava, K., Nathanailides, C., & Athanassopoulou, F. (2025). Phytochemicals: Essential Oils and Other Extracts for Disease Prevention and Growth Enhancement in Aquaculture: Challenges and Opportunities. *Animals*, 15(18), 2653. <https://doi.org/10.3390/ani15182653>.
- Kong, Y., Pan, S., & Wu, S. (2025). Advances in the use of dietary β -glucan in aquaculture: Structural insights, immunological benefits, and feed applications. *Developmental & Comparative Immunology*, 172, 105476. <https://doi.org/10.1016/j.dci.2025.105476>.
- Krishnan, R., Jang, Y. S., & Oh, M. J. (2022). Beta glucan induced immune priming protects against nervous necrosis virus infection in sevenband grouper. *Fish & shellfish immunology*, 121, 163–171. <https://doi.org/10.1016/j.fsi.2022.01.005>.
- Kühlwein, H., Merrifield, D. L., Rawling, M. D., Foey, A. D., & Davies, S. J. (2014). Effects of dietary β -(1,3)(1,6)-D-glucan supplementation on growth performance, intestinal morphology and haemato-immunological profile of mirror carp (*Cyprinus carpio* L.). *Journal of animal physiology and animal nutrition*, 98(2), 279–289. <https://doi.org/10.1111/jpn.12078>.
- Kurhaluk, N., Grudniewska, J., & Tkaczenko, H. (2024). Modulation of oxidative stress biomarkers and lysosomal functioning in gills and liver of rainbow trout (*Oncorhynchus mykiss* Walbaum) fed a diet supplemented with yeast β -glucans. *Fisheries & Aquatic Life*, 32(1), 44–62. <https://doi.org/10.2478/aopf-2024-0005>.
- Lante, A., Canazza, E., & Tessari, P. (2023). Beta-Glucans of Cereals: Functional and Technological Properties. *Nutrients*, 15(9), 2124. <https://doi.org/10.3390/nu15092124>.
- Li, C., Du, M., Han, Y., Sun, W., Chen, Z., Liu, Q., Zhu, H., Zhao, L., Li, S., & Wang, J. (2025). Microalgae in health care and functional foods: β -glucan applications,



- innovations in drug delivery and synthetic biology. *Frontiers in pharmacology*, 16, 1557298. <https://doi.org/10.3389/fphar.2025.1557298>.
- Li, X., Wu, Y., Duan, R., Yu, H., Liu, S., & Bao, Y. (2024). Research Progress in the Extraction, Structural Characteristics, Bioactivity, and Commercial Applications of Oat β -Glucan: A Review. *Foods*, 13(24), 4160. <https://doi.org/10.3390/foods13244160>.
- Ljubojević Pelić, D., Radosavljević, V., Pelić, M., Živkov Baloš, M., Puvača, N., Jug-Dujaković, J., & Gavrilović, A. (2024). Antibiotic Residues in Cultured Fish: Implications for Food Safety and Regulatory Concerns. *Fishes*, 9(12), 484. <https://doi.org/10.3390/fishes9120484>.
- Lokesh, J., Fernandes, J. M., Korsnes, K., Bergh, O., Brinchmann, M. F., & Kiron, V. (2012). Transcriptional regulation of cytokines in the intestine of Atlantic cod fed yeast derived mannan oligosaccharide or β -glucan and challenged with *Vibrio anguillarum*. *Fish & shellfish immunology*, 33(3), 626–631. <https://doi.org/10.1016/j.fsi.2012.06.017>.
- Machuca, C., Méndez-Martínez, Y., Reyes-Becerril, M., & Angulo, C. (2022). Yeast β -Glucans as Fish Immunomodulators: A Review. *Animals: an open access journal from MDPI*, 12(16), 2154. <https://doi.org/10.3390/ani12162154>.
- Machuca, C., Reyes-Becerril, M., Monreal-Escalante, E., Méndez-Martínez, Y., Vázquez-Juárez, R., Silva-Jara, J. M., & Angulo, C. (2026). Perspectives on the potential of β -glucan nanoparticles for fish aquaculture based on the current applications in biomedicine and agri-foods. *Aquaculture*, 612(Part 1), 743125. <https://doi.org/10.1016/j.aquaculture.2025.743125>.
- Marcharla, E., Vishnuprasadh, A., Gnanasekaran, L., Vinayagam, S., Sundaram, T., & Ganesan, S. (2025). The role of functional feed in modulating fish gut microbiome to enhance resistance against aquaculture pathogens. *Probiotics and Antimicrobial Proteins*. <https://doi.org/10.1007/s12602-025-10660-w>
- Martínez-Ruiz, F. E., Andrade-Bustamante, G., Holguín-Peña, R. J., Renganathan, P., Gaysina, L. A., Sukhanova, N. V., & Puente, E. O. R. (2025). Microalgae as Functional Food Ingredients: Nutritional Benefits, Challenges, and Regulatory Considerations for Safe Consumption. *Biomass*, 5(2), 25. <https://doi.org/10.3390/biomass5020025>.
- Medina Félix, D., Cortés Jacinto, E., Isidro Campa Córdova, Á., Antonio López Elías, J., Rafael Martínez Córdova, L., Luna González, A., & David Leal Soto, S. (2022). Physiological and antioxidant response of *Litopenaeus vannamei* against *Vibrio parahaemolyticus* infection after feeding supplemented diets containing *Dunaliella* sp. flour and β -glucans. *Journal of invertebrate pathology*, 187, 107702. <https://doi.org/10.1016/j.jip.2021.107702>.
- Meena, D. K., Das, P., Kumar, S., Mandal, S. C., Prusty, A. K., Singh, S. K., Akhtar, M. S., Behera, B. K., Kumar, K., Pal, A. K., & Mukherjee, S. C. (2013). Beta-glucan: an ideal immunostimulant in aquaculture (a review). *Fish physiology and biochemistry*, 39(3), 431–457. <https://doi.org/10.1007/s10695-012-9710-5>.
- Mishra, B., Mohanta, Y. K., Reddy, C. N., Reddy, S. D. M., Mandal, S. K., Yadavalli, R., & Sarma, H. (2023). Valorization of agro-industrial biowaste to biomaterials: An innovative circular bioeconomy approach. *Circular Economy*, 2(3), 100050. <https://doi.org/10.1016/j.cec.2023.100050>.
- Mohammadian, T., Nasirpour, M., Tabandeh, M. R., & Mesbah, M. (2019). Synbiotic effects of β -glucan, mannan oligosaccharide and *Lactobacillus casei* on growth performance, intestine enzymes activities, immune-hematological parameters and immune-related gene expression in common carp (*Cyprinus carpio*): An



- experimental infection with *Aeromonas hydrophila*. *Aquaculture*, 511, 634197. <https://doi.org/10.1016/j.aquaculture.2019.06.011>.
- Mokhtar, D. M., Zaccone, G., Alesci, A., Kuciel, M., Hussein, M. T., & Sayed, R. K. A. (2023). Main Components of Fish Immunity: An Overview of the Fish Immune System. *Fishes*, 8(2), 93. <https://doi.org/10.3390/fishes8020093>.
- Murphy, E. J., Rezoagli, E., Major, I., Rowan, N. J., & Laffey, J. G. (2020). β -Glucan Metabolic and Immunomodulatory Properties and Potential for Clinical Application. *Journal of fungi (Basel, Switzerland)*, 6(4), 356. <https://doi.org/10.3390/jof6040356>.
- Nguyen, H. T., Pham, T. T., Nguyen, P. T., Le-Buanec, H., Rabetafika, H. N., & Razafindralambo, H. L. (2024). Advances in Microbial Exopolysaccharides: Present and Future Applications. *Biomolecules*, 14(9), 1162. <https://doi.org/10.3390/biom14091162>.
- Nieves-Rodríguez, K. N., Álvarez-González, C. A., Peña-Marín, E. S., Vega-Villasante, F., Martínez-García, R., Camarillo-Coop, S., Tovar-Ramírez, D., Guzmán-Villanueva, L. T., Andree, K. B., & Gisbert, E. (2018). Effect of β -Glucans in Diets on Growth, Survival, Digestive Enzyme Activity, and Immune System and Intestinal Barrier Gene Expression for Tropical Gar (*Atractosteus tropicus*) Juveniles. *Fishes*, 3(3), 27. <https://doi.org/10.3390/fishes3030027>.
- Okeke, E. S., Chukwudozie, K. I., Nyaruaba, R., Ita, R. E., Oladipo, A., Ejeromedoghene, O., Atakpa, E. O., Agu, C. V., & Okoye, C. O. (2022). Antibiotic resistance in aquaculture and aquatic organisms: a review of current nanotechnology applications for sustainable management. *Environmental science and pollution research international*, 29(46), 69241–69274. <https://doi.org/10.1007/s11356-022-22319-y>.
- Onomu, A. J., & Okuthe, G. E. (2024). The Role of Functional Feed Additives in Enhancing Aquaculture Sustainability. *Fishes*, 9(5), 167. <https://doi.org/10.3390/fishes9050167>.
- Petit, J., Bailey, E. C., Wheeler, R. T., de Oliveira, C. A. F., Forlenza, M., & Wiegertjes, G. F. (2019). Studies Into β -Glucan Recognition in Fish Suggests a Key Role for the C-Type Lectin Pathway. *Frontiers in immunology*, 10, 280. <https://doi.org/10.3389/fimmu.2019.00280>.
- Petit, J., de Bruijn, I., Goldman, M. R. G., van den Brink, E., Pellikaan, W. F., Forlenza, M., & Wiegertjes, G. F. (2022). β -Glucan-Induced Immuno-Modulation: A Role for the Intestinal Microbiota and Short-Chain Fatty Acids in Common Carp. *Frontiers in immunology*, 12, 761820. <https://doi.org/10.3389/fimmu.2021.761820>.
- Pilarski, F., Ferreira de Oliveira, C. A., Darpossolo de Souza, F. P. B., & Zanuzzo, F. S. (2017). Different β -glucans improve the growth performance and bacterial resistance in Nile tilapia. *Fish & shellfish immunology*, 70, 25–29. <https://doi.org/10.1016/j.fsi.2017.06.059>.
- Porter, D., Naseer, S., Peggs, D., McGurk, C., & Martin, S. A. M. (2023). Deciphering the Immunostimulatory Effects of β -Glucan on a Rainbow Trout (*Oncorhynchus mykiss*) Macrophage-like Cell Line (RTS11) by Whole Transcriptome Analysis. *Genes*, 14(6), 1261. <https://doi.org/10.3390/genes14061261>.
- Prates, J. A. M. (2025). Applications of Bioactive Compounds from Marine Microalgae in Health, Cosmetics, and Functional Foods. *Applied Sciences*, 15(11), 6144. <https://doi.org/10.3390/app15116144>.
- Reis, I. C. D., Fierro-Castro, C., Gonçalves, G. S., Moromizato, B. S., Tort, L., & Biller, J. D. (2021). β -glucan mimics tissue damage signaling and generates a trade-off



- between head kidney and spleen to activate acquired immunity in vaccinated tilapia (*Oreochromis niloticus*). *Fish & shellfish immunology*, 117, 179–187. <https://doi.org/10.1016/j.fsi.2021.08.003>.
- Roberti Filho, F. de O., Koch, J. F. A., Wallace, C., & Leal, M. C. (2019). Dietary β -1,3/1,6-glucans improve the effect of a multivalent vaccine in Atlantic salmon infected with *Moritella viscosa* or infectious salmon anemia virus. *Aquaculture International*, 27, 1825–1834. <https://doi.org/10.1007/s10499-019-00436-9>.
- Robertsen, B., Rørstad, G., Engstad, R., & Raa, J. (1990). Enhancement of non-specific disease resistance in Atlantic salmon (*Salmo salar* L.) by a glucan from *Saccharomyces cerevisiae* cell walls. *Journal of Fish Diseases*, 13(5), 391–400. <https://doi.org/10.1111/j.1365-2761.1990.tb00798.x>.
- Rodrigues, M. V., Zanuzzo, F. S., Koch, J. F. A., de Oliveira, C. A. F., Sima, P., & Vetvicka, V. (2020). Development of Fish Immunity and the Role of β -Glucan in Immune Responses. *Molecules (Basel, Switzerland)*, 25(22), 5378. <https://doi.org/10.3390/molecules25225378>.
- Rodríguez, J., Espinosa, Y., Echeverría, F., Cárdenas, G., Román, R., & Sterna, S. (2007). Exposure to probiotics and β -1,3/1,6-glucans in larviculture modifies the immune response of *Penaeus vannamei* juveniles and both the survival to White Spot Syndrome Virus challenge and pond culture. *Aquaculture*, 273(3–4), 405–415.
- Salah, A. S., El Nahas, A. F., & Mahmoud, S. (2017). Modulatory effect of different doses of β -1,3/1,6-glucan on the expression of antioxidant, inflammatory, stress and immune-related genes of *Oreochromis niloticus* challenged with *Streptococcus iniae*. *Fish & shellfish immunology*, 70, 204–213. <https://doi.org/10.1016/j.fsi.2017.09.008>.
- 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 β -1, 3-glucan improves the intestinal health of white shrimp (*Litopenaeus vannamei*) by modulating intestinal microbiota and inhibiting inflammatory response. *Frontiers in immunology*, 14, 1119902. <https://doi.org/10.3389/fimmu.2023.1119902>.
- Shoukat, M., & Sorrentino, A. (2021). Cereal β -glucan: A promising prebiotic polysaccharide and its impact on the gut health. *International Journal of Food Science & Technology*, 56(5), 2088–2097. <https://doi.org/10.1111/ijfs.14971>.
- Singh, R. P., & Bhardwaj, A. (2023). β -glucans: a potential source for maintaining gut microbiota and the immune system. *Frontiers in nutrition*, 10, 1143682. <https://doi.org/10.3389/fnut.2023.1143682>.
- Singla, A., Gupta, O. P., Sagwal, V., Kumar, A., Patwa, N., Mohan, N., Ankush, Kumar, D., Vir, O., Singh, J., Kumar, L., Lal, C., & Singh, G. (2024). Beta-Glucan as a Soluble Dietary Fiber Source: Origins, Biosynthesis, Extraction, Purification, Structural Characteristics, Bioavailability, Biofunctional Attributes, Industrial Utilization, and Global Trade. *Nutrients*, 16(6), 900. <https://doi.org/10.3390/nu16060900>.
- Song, L., Zhou, Y., Ni, S., Wang, X., Yuan, J., Zhang, Y., & Zhang, S. (2020). Dietary Intake of β -Glucans Can Prolong Lifespan and Exert an Antioxidant Action on Aged Fish *Nothobranchius guentheri*. *Rejuvenation research*, 23(4), 293–301. <https://doi.org/10.1089/rej.2019.2223>.
- Stangroom, J., Marana, M., Booman, M., Andrew, S., Poley, J., Wilderjans, E., Ghillebert, R., & Zanuzzo, F. S. (2025). *Aspergillus niger* β -glucan, MycoFence[®], efficacy against ulcerative disease in Atlantic salmon compared to commercial yeast β -glucan. *Aquaculture*, 603, 742350. <https://doi.org/10.1016/j.aquaculture.2025.742350>.



- Stothers, C. L., Burelbach, K. R., Owen, A. M., Patil, N. K., McBride, M. A., Bohannon, J. K., Luan, L., Hernandez, A., Patil, T. K., Williams, D. L., & Sherwood, E. R. (2021). β -Glucan Induces Distinct and Protective Innate Immune Memory in Differentiated Macrophages. *Journal of immunology (Baltimore, Md.: 1950)*, 207(11), 2785–2798. <https://doi.org/10.4049/jimmunol.2100107>.
- Tkachenko, H., Grudniewska, J., & Kurhaluk, N. (2022). Effects of dietary yeast α -1.3/1.6-glucans on oxidative stress biomarkers in hearts and livers of rainbow trout (*Oncorhynchus mykiss* Walbaum), European whitefish (*Coregonus lavaretus* L.), and grayling (*Thymallus thymallus* L.). *Fisheries & Aquatic Life*, 30, 149–168. <https://doi.org/10.2478/aopf-2022-0014>.
- Tkachenko, H., Kurhaluk, N., & Grudniewska, J. (2023). Effects of dietary yeast β -1.3/1.6-glucans on lipid peroxidation in the hepatic and cardiac tissues of rainbow trout (*Oncorhynchus mykiss* Walbaum), European whitefish (*Coregonus lavaretus* L.), and grayling (*Thymallus thymallus* L.). *Scientific and Technical Bulletin of the Institute of Animal Science of the National Academy of Agrarian Science of Ukraine*, 129, 16–25. <https://doi.org/10.32900/2312-8402-2023-129-16-25>.
- Tkaczhenko, H., Kurhaluk, N., & Grudniewska, J. (2024). Activity of antioxidant enzymes in the cardiac and hepatic tissues of rainbow trout (*Oncorhynchus mykiss* Walbaum) fed a diet supplemented with β -glucans. *Scientific and Technical Bulletin of Livestock Farming Institute of NAAS*, 132, 171–182. <https://doi.org/10.32900/2312-8402-2024-132-171-182>.
- Uengwetwanit, T., Uawisetwathana, U., Angthong, P., Phanthura, M., Phromson, M., Tala, S., Thepsuwan, T., Chaiyapechara, S., Prathumpai, W., & Rungrassamee, W. (2025). Investigating a novel β -glucan source to enhance disease resistance in Pacific white shrimp (*Penaeus vannamei*). *Scientific reports*, 15(1), 15377. <https://doi.org/10.1038/s41598-025-00157-5>.
- Valladares, A., Domínguez-Borbor, C., Echeverría, F., Panchana, F., Betancourt, I., Sonnenholzner, S., Bayot, B., & Rodríguez, J. (2024). The influence of temperature and β -1,3-glucans on the occurrence of white spot syndrome virus and white spot disease in post-larvae of *Penaeus vannamei* shrimp. *Fish & shellfish immunology*, 154, 109938. <https://doi.org/10.1016/j.fsi.2024.109938>.
- Vargas-Albores, F., & Yepiz-Plascencia, G. (2000). Beta glucan binding protein and its role in shrimp immune response. *Aquaculture*, 191(1–3), 13–21. [https://doi.org/10.1016/S0044-8486\(00\)00416-6](https://doi.org/10.1016/S0044-8486(00)00416-6).
- Vega-Carranza, A. S., Escamilla-Montes, R., Luna-González, A., Fierro-Coronado, J. A., Diarte-Plata, G., & García-Gutiérrez, C. (2024). Survival, immune response, and gut microbiota in *Litopenaeus vannamei* fed with synbiotics and postbiotics and challenged with *Vibrio parahaemolyticus*. *Aquaculture International*, 32, 361–381. <https://doi.org/10.1007/s10499-023-01165-w>.
- Vetvicka, V., Vannucci, L., & Sima, P. (2013). The Effects of β - Glucan on Fish Immunity. *North American journal of medical sciences*, 5(10), 580–588. <https://doi.org/10.4103/1947-2714.120792>.
- Waikhom, D., Kezhedath, J., Krishnan, R., Varghese, T., Kurcheti, P. P., & Valappil, R. K. (2022). Beta-glucan stimulation induces trained immunity markers in common carp, *Cyprinus carpio*. *Fish & shellfish immunology*, 131, 855–861. <https://doi.org/10.1016/j.fsi.2022.10.069>.
- Wang, F., Wang, Z., Cao, J., & Lu, Y. (2024). Long- and short-term dietary β -glucan improves intestinal health and disease resistance in pearl gentian grouper



- (*Epinephelus lanceolatus*♂ × *Epinephelus fuscoguttatus*♀). *Fish physiology and biochemistry*, 50(3), 973–988. <https://doi.org/10.1007/s10695-024-01310-z>.
- Wilson, W., Lowman, D., Antony, S. P., Puthumana, J., Bright Singh, I. S., & Philip, R. (2015). Immune gene expression profile of *Penaeus monodon* in response to marine yeast glucan application and white spot syndrome virus challenge. *Fish & shellfish immunology*, 43(2), 346–356. <https://doi.org/10.1016/j.fsi.2014.12.032>.
- Yang, C.-C., Chen, S.-N., Lu, C.-L., Chen, S., Lai, K.-C., & Liao, W.-L. (2014). Effect of mushroom beta glucan (MBG) on immune and haemocyte response in Pacific white shrimp (*Litopenaeus vannamei*). *Journal of Aquaculture Research & Development*, 5(6), 275. <https://doi.org/10.4172/2155-9546.1000275>.
- Zhong, X., Wang, G., Li, F., Fang, S., Zhou, S., Ishiwata, A., Tonevitsky, A. G., Shkurnikov, M., Cai, H., & Ding, F. (2023). Immunomodulatory Effect and Biological Significance of β-Glucans. *Pharmaceutics*, 15(6), 1615. <https://doi.org/10.3390/pharmaceutics15061615>.