β-GLUCAN AS A PROMISING FOOD ADDITIVE AND IMMUNOSTIMULANT IN AQUACULTURE INDUSTRY – A REVIEW

Mohammad Hossein Khanjani^{1*}, Moslem Sharifinia², Gholamreza Ghaedi³

¹Department of Fisheries Sciences and Engineering, Faculty of Natural Resources, University of Jiroft, Jiroft, Kerman, Iran

²Shrimp Research Center, Iranian Fisheries Sciences Research Institute, Agricultural Research, Education and Extension Organization (AREEO), Bushehr 75169-89177, Iran

³Ph.D. in Aquaculture, Graduated from Khorramshahr University of Marine Science and Technology, Khorramshahr, Iran

*Corresponding author: m.h.khanjani@ujiroft.ac.ir, m.h.khanjani@gmail.com

Abstract

The use of antibiotics in aquatic feed reduces the incidence of disease and enhances growth performance, although it presents harmful effects, such as development of resistant bacteria and accumulation in the natural environment. A variety of immune stimulants including probiotics, prebiotics, synbiotics, phytobiotics, organic acids, nucleotides, antioxidants, microalgae, yeast and enzymes have been used in the aquaculture industry. In recent decades, much attention has been paid to find a variety of immunostimulants with lower cost which also affect specific and non-specific immunity and improve fish resistance against a wide range of pathogens. These stimulants strengthen the fish's immune system by increasing the number of phagocytes, lysozyme activity and level of immunoglobulin. The use of immune stimulants as an effective tool to overcome diseases and strengthen the immune system of farmed species, leads to the promotion of cellular and humoral defense mechanisms and increases resistance to infectious diseases. Among these immunostimulants used in aquaculture, β-glucans are of particular importance. Glucans are complex polysaccharide compounds extracted from the cell wall of yeasts and fungi. These compounds can stimulate fish growth, survival, and immune function. Therefore, this review discusses the role and importance of β-glucan as a food additive in aquaculture and examines the impact of these compounds on the growth performance, immunity and biochemical parameters of farmed species.

Key words: β-glucan, nutrition, immunity, growth performance, aquaculture, food additive

In recent years, the aquaculture industry has developed rapidly and provides fish products for human consumption (Khanjani et al., 2020 a; Khanjani and Sharifinia, 2020, 2021; Pauly and Zeller, 2017). By 2030, aquaculture is expected to provide about 62% of fish for human consumption. In addition, after 2030, aquaculture is likely to continue to dominate global fish supply in the future and grow steadily (Kobayashi et al., 2015). To meet human demand, the aquaculture industry is moving towards intensification, which can lead to new challenges in the aquaculture industry. As in other farming sectors, with the intensification and expansion of aquaculture activities, the likelihood of major disease problems increases. Therefore, the aquaculture industry is full of its share of diseases and problems caused by viruses, bacteria, fungi, parasites and other pathogens that have not been detected and are emerging. There is currently intense pressure from society and consumers to find alternatives to antibiotic treatment to prevent or reduce the effects of disease on aquaculture without affecting their health and quality (Carbone and Faggio, 2016). The use of immunostimulants through dietary supplements is a major area of research for farmed aquatic species (Lee et al., 2020 a; Ma et al., 2020; Terzi et al., 2020).

Different types of immunostimulants have been studied, but few of them are suitable for aquaculture, and many of these immunostimulants are not used in aquaculture due to their high cost and low impact (Caipang and Lazado, 2015; Ringø et al., 2012). Immunostimulants are effective in increasing the growth performance, survival rate and immune system of aquatic organisms, and many of them are significant in aquaculture, including compounds such as β-glucans, alginates, nucleotides, vitamin C, aquatic and terrestrial plant extracts, and microbial accumulations (biofloc) (Dawood et al., 2018; Ghaedi et al., 2015; Khanjani et al., 2021 a, b, c; Khanjani and Sharifinia, 2020; Khanjani et al., 2020 b; Mohan et al., 2019; Wang et al., 2017 b). Among these immunostimulants used in aquaculture, β-glucans are of particular importance. Glucan is a homopolysaccharide composed of glucose molecules linked together by a glycosidic bond. In general, glucan molecules are divided into two categories based on their type of glycosidic bonds: alpha-glucan bonds include dextran and starch, and β-glucan bonds include cellulose, zymogen, laminarin, and lichen (Bagni et al., 2005; Soltanian et al., 2009). Due to their complex structure, β-glucans have an extraordinary ability to activate the immune system (Bagni et al., 2005; Soltanian

et al., 2009). It is an important cell wall compound of a number of plants, fungi, bacteria, yeasts and seaweeds (Sonck et al., 2010). Various studies on fish have shown that β -glucan is a valuable immunostimulant for improving immune status and disease control in farmed aquatic animals (Bricknell and Dalmo, 2005; Medina-Gali et al., 2018; Meena et al., 2013; Russo et al., 2006; Selim and Reda, 2015; Sherif and Mahfouz, 2019).

In nature, β -glucans are abundant in the cell wall of many plants (such as wheat, rye, barley and oats), yeast (*Saccharomyces*) and genera of the Echinacea family (Sirimanapong et al., 2015; Thompson, 2017). Other sources of β -glucan are seaweed of the genus *Laminaria*, and fungi (Rop et al., 2009; Thompson, 2017). Common sources of β -glucans are derived from the cell wall of bread yeast, the most important of which are β -1-3 glucans and β -1-6 glucans (Morales-López et al., 2009). β -glucans derived from different sources have differences in their structure (Ringø et al., 2012). Barley and oat β -glucans are linear with beta 1-4 and beta 1-3 bindings. Fungal β -glucans have beta 1-6 as short branches attached to the 1-3 beta strand. Yeast β -glucans have beta 1-6 branches that bind to beta 1-3. These structural differences can cause differences in their extraction and performance. Higher molecular weight glucans activate leukocytes, stimulate their phagocytic, cytotoxic and antimicrobial activities, and produce oxygen free radicals. Lower molecular weight glucans have fewer cellular effects, and very short glucans are virtually inactive (Akramienė et al., 2007; Zhu et al., 2016). Studies have shown that insoluble β -glucans (1-3/1-6) have more biological activity than their soluble counterparts (1-3/1-4) (Ooi and Liu, 2000). Considering the multifaceted role of β -glucans in aquatic species this review investigates the importance of β -glucan as a food additive and immunostimulant in the aquaculture industry with emphasis on growth performance, immunity and biochemical parameters.

β -glucan

β -glucans are major bioactive compounds with anti-cancer, anti-inflammatory, and immune-modulating properties (Meena et al., 2013; Zhu et al., 2016). This compound has been increasingly used by different industries due to its specific physical properties, such as water solubility, viscosity, and gelation (Meena et al., 2013; Zhu et al., 2016). β -glucans play an important role in activating innate and acquired immunity. The innate immune responses stimulated by β -glucans not only act on invading microorganisms but also complement the activation and function of acquired immunity (Montoya et al., 2018; Sakai, 1999; Velazquez-Carriles et al., 2018). The induction of the cellular response by β -glucan depends on the specific reactions of one or more cell surface receptors. Glucans are believed to enhance innate immunity by binding to specific receptors on monocytes/macrophages, neutrophils, and natural killer cells (Muellet et al., 2000).

Because of their ability to bind directly to macrophages and other white blood cells, such as neutrophils and natural killer cells, and activate them, they provide good resistance to any invader (Gantner et al., 2003; Herre et al., 2004). When β -glucan receptors are involved with β -1-3/1-6 glucan, there is a general improvement in immune parameters, such as phagocytosis, release of specific cytokines (intracellular hormones), interferons, and antigen preparation. Cytokines can stimulate the formation of new white blood cells (Raa, 2000). Phagocytic cells and activated white blood cells produce cytokines and antibodies, respectively, and increase the effectiveness of vaccines (Raa, 2000). Specific properties of glucans such as stimulating the immune system without over-activating it (Liu et al., 2020) and its ability to reduce high cholesterol levels (Joyce et al., 2019; Wang et al., 2017 c) make it a unique immunostimulant.

The function of β -glucan in improving immunity

β -glucan plays an important role in activating the innate and acquired immune system. The presence of glucan receptors on macrophages and other white blood cells (neutrophils and natural killer cells) has been reported (Gantner et al., 2003; Herre et al., 2004). When glucan binds to these cells with its receptors, it activates macrophages directly (Sakai, 1999) and then all immune mechanisms, including phagocytosis, release of specific cytokines such as interleukin-1, interleukin-6, GM-CSF and interferons are activated. These cytokines stimulate the production of new white blood cells and thus increase β -glucan receptors (Meena et al., 2013). The results of immune indices in the serum show that lysozyme, immunoglobulin M (IgM), total immunoglobulin and alternative pathway (ACH50) were improved in rainbow trout (*Oncorhynchus mykiss*) broodstocks fed with 0.2% β -glucan (Ghaedi et al., 2015). The effect of β -glucan on increasing lysozyme levels has also been reported in other studies, including Atlantic salmon (*Salmo salar*) (Engstad et al., 1992), large yellow croaker (*Pseudosciaena crocea*) (Ai et al., 2007) and Indian carp (*Labeo rohita*) (Misra et al., 2006). Increased lysozyme activity is probably due to increased white blood cell counts and macrophage activity. When β -glucan binds to macrophages and other white blood cells, such as neutrophils, with its receptors, it activates macrophages and forms white blood cells (Meena et al., 2013). As a result, this increase in the number of macrophages increases lysozyme secretion (Sahoo et al., 2005).

Complement (C), among them C3, is a main component of the innate immune system that plays an important role in the acquired immune system (Morgan et al., 2005). Complement contains about 30 to 35 soluble and membrane proteins that perform different functions and protect embryos and larvae before the completion of immune system (Ogundele, 2001; Wang et al., 2008) and they are given the ability to fight against pathogens (Løvoll et al., 2006). Complement proteins are activated in three overlapping ways: the classical, secondary,

and lectin methods (Holland and Lambris, 2002; Nonaka and Smith, 2000). The amount of C3 in rainbow trout broodstocks (*O. mykiss*), as a representative of the classical method, was not affected by different amounts of β -glucan, but the alternative pathway (ACH50) was increased (Ghaedi et al., 2015). Some studies have reported that β -glucan injection activates the alternative pathway (Engstad et al., 1992; Travassos and Taborda, 2017) but β -glucan nutritional supplementation does not promote the same effect (Ai et al., 2007; Ortuño et al., 2002). They stated that the injection of β -glucan causes inflammatory reactions resulting in the synthesis of acute phase proteins including complement factors from the liver, but nutrition with β -glucan does not cause this type of reaction. Furthermore, Dalmo and Bøgvold (2008) reported that non-specific immune indices such as ACH50 and lysozyme increase under the influence of β -glucan. Nevertheless, Verlhac et al. (1998) reported that the use of β -glucan in the diet of rainbow trout had no effect on respiratory burst, pinocytosis, lysozyme activity, and alternative pathway of complement. In addition, Ogier de Baulny et al. (1996) stated that long-term feeding of turbot (*Scophthalmus maximus*) with glucan had no effect on complement and lysozyme activity. These conflicting reports on the effects of β -glucan can be due to reasons such as the dose, the duration of feeding, or the life stage of the species. In addition, commercial β -glucans that have different manufacturing processes, as well as the type of species, which can cause differences in test results and immune system reactions (Ai et al., 2007; Bridle et al., 2005).

Studies that have examined the effects of immunostimulants have reported an increase in immunoglobulin M. For example, the use of immunostimulants such as vitamin A, chitin, yeast and levamisole in seabream (*Sparus aurata*) has increased immunoglobulin M level (Cuesta et al., 2004), as well as feeding 0.1% glucan in rohu (*Labeo rohita*) increased specific and non-specific immune factors (Sahoo and Mukherjee, 2001). Nutrition with glucan raises the production of white blood cells (Meena et al., 2013) which in turn increases lymphocytes B and the production and secretion of immunoglobulin M (Ross et al., 1998). Immunoglobulin M transfer process is from broodstocks to the eggs through the blood to the follicle, which depends on the difference in immunoglobulin (Ig) concentration. The presence of immunoglobulin M in plasma and blood during ovarian maturation and the increase in serum Ig concentration during the reproductive period in many fish confirm the oocyte transfer (Kanlis et al., 1995; Picchitti et al., 2001; Scapigliati et al., 1999).

β -glucan function in biochemical indicators

Misra et al. (2006) investigated the effects of multiple injections of β -glucan on non-specific immune response and disease resistance in *Labeo rohita* fingerlings and reported an increase in total protein, globulin and albumin/globulin percentage after feeding with 0.025% β -glucan.

Furthermore, Ghaedi et al. (2015) found that biochemical parameters including protein, albumin and globulin in β -glucan-fed rainbow trout broodstocks were higher than control-fed broodstocks. Given that these parameters are important compounds in the immune system and are associated with nonspecific immunity (Kumar et al., 2005), their increase indicates the proper function of β -glucan as an immunostimulant. Total protein and globulin are needed to keep the immune system healthy, and these parameters are usually higher in fish fed with immunostimulant (Choudhury et al., 2005). Abdel-Tawwab et al. (2008) concluded that as the yeast in the feed of the Nile tilapia (*Oreochromis niloticus*) increased, the levels of these indices increased. In addition, Amparyup et al. (2012) also stated that pattern recognition proteins [including lipopolysaccharide and β -1,3-glucan binding protein (LGBP)] could raise the phenoloxidase activity in black tiger shrimp (*Penaeus monodon*).

β -glucan function in growth performance

The effects of β -glucan alone or in combination with other immunostimulants on growth performance and survival have been examined by several researchers. For instance, Nile tilapia (*Oreochromis niloticus*) fed with different concentrations of β -glucan indicated no difference in growth and survival rate after 10 weeks (Whittington et al., 2005). β -glucan at a dose of 250 mg/kg diet was recommended for enhancing immunity, growth, and survival against opportunistic pathogens such as *Aeromonas hydrophila* and *Edwardsiella tarda* in rohu (*Labeo rohita*). Oral administration of three different quantities of β -glucan, low (38 g/kg), average (52 g/kg) and high (82 g/kg) in *Oncorhynchus mykiss* showed decrease in the growth rate but enhanced survival against IHNV (infectious hematopoietic necrosis virus) (Sealey et al., 2008). Pacific white shrimp (*Litopenaeus vannamei*) fed with diet containing inactive yeast cell wall (β -glucan) 1 and 2 g/kg feed showed no significant differences in final weight, survival, and growth rate, but indicated better effects on immune parameters compared to the control group (Chotikachinda et al., 2008). These differences in results are due to different types of β -glucan, dosage, route and duration of administration, as well as aquatic animal species.

Growth indices in rainbow trout larvae fed β -glucan were higher than the control group (Ghaedi et al., 2015). In *Pseudosciaena crocea*, an increase in growth due to feeding with β -glucan at a 0.09% supplementation level was reported, but the 0.18% level had no effects (Ai et al., 2007). These results are also consistent with those obtained from hybrid bass (*Morone chrysops* $\times$ *M. saxatilis*) (Li and Gatlin III, 2003, 2004, 2005), Indian carp (Misra et al., 2006), *Penaeus monodon* (Chang et al., 2003) and Nile tilapia. Some studies have also reported that adding yeast to the diet improves diet and protein digestion (Lara-Flores et al., 2003; Tovar et al., 2002; Waché et al., 2006). Increased survival and growth under β -glucan is probably due to increased disease resistance as a result

of enhanced immunity (Itami et al., 1989) or improved digestive function (Abdel-Tawwab et al., 2008). Another explanation could be the selective fermentation of the polysaccharide by probiotic bacteria. This, in turn, would provide health benefits to the host (Lam and Cheung, 2013).

Large yellow croakers fed with β -glucan at 0.09% reduced the mortality rate compared to the control group (Ai et al., 2007). The increase in relative survival in juveniles is possibly due to increased immunity, which has been reported in other studies on glucan (Castro et al., 1999; Chen and Ainsworth, 1992; Cook et al., 2001). An adequate amount of glucan can improve immunity and increase disease resistance in fish.

Review of studies

Table 1 lists some of the studies performed with β -glucan. Ai et al. (2007) examined the effects of β -glucan on growth and innate immunity indices in *Pseudosciaena crocea*. Three diets (0, 0.09 and 0.18%) were used and growth indices, lysozyme activity, alternative pathway of complement, phagocytosis percentage and respiratory burst activity were measured. The results of their study showed that 0.09% of glucan in the diet has the best effect on increasing immunity and immune parameters were not significantly different when comparing the control group and the 0.18% supplementation.

Bagni et al. (2005) investigated the effects of Macroguard β -glucan and an alginic acid-containing algae extract called Ergosan on immune parameters including complement, lysozyme, total protein and heat shock proteins (HSP) in seabass (*Dicentrarchus labrax*). The results of the study showed that Macroguard and Ergosan promote the innate immunity of fish.

The IgM levels of seabream (*Sparus aurata*) under the influence of various immunomodulators were examined by Cuesta et al. (2004). In this study, they investigated several substances including vitamin A, chitin, yeast or levamisole as immunostimulants and in high stocking density conditions, hypoxia and anesthetics as stressors. Immunostimulants increased serum IgM but density and hypoxia had no effect on IgM levels. Anesthetics including benzocaine and phenoxyethanol decreased IgM but quinaldine increased IgM. Sahoo and Mukherjee (2001) studied the effects of glucan on rohu (*Labeo rohita*), arguing that feeding healthy fish with glucan increased specific, non-specific immunity and resistance to *Aeromonas hydrophila*. Verlhac et al. (1998) by studying vitamin C and glucan alone or in combination on the immune indices of rainbow trout, reported that vitamin C and glucan alone or in combination significantly increased innate immune indicators such as phagocytic activity and lysozyme.

Siwicki et al. (1994) investigated the effects of immunostimulants including Macroguard, *Candida utilis*, *Saccharomyces cerevisiae*, Evetsel, Chitosan, and Finnstim on the immune parameters of 200 g rainbow trout and observed an increase in the release of oxidative radicals,

myeloperoxidase activity, phagocytosis and the lethal activity of phagocytic cells such as neutrophils. Total plasma protein and total immunoglobulin rose under the influence of these stimuli. Bacterial challenge with *Aeromonas salmonicida* also showed that fish fed these stimuli were more resistant to infection.

The effects of dietary β -glucan in silver catfish (*Rhamdia quelen*) were investigated by Domenico et al. (2017). They stated that β -glucan had no effect on growth performance and blood cells, serum bacterial agglutination and serum myeloperoxidase activity. However, the natural hemolytic activity of complement in β -glucan treatment increased significantly compared to the control group. In addition, fish of the β -glucan treatment were challenged with *A. hydrophila* and showed fewer bacteria in blood and presented a significantly higher survival rate compared to the control group.

Tayyab et al. (2019) evaluated the effects of β -glucan, the plant extract, Vitabio A, and the plant extract with probiotic *Lactobacillus* spp. (Vitabio B) on the growth, histology and immune response of rohu (*Labeo rohita*). They concluded that the plant extracts and β -glucan can be used without any adverse effects on growth, total serum proteins, hematology and fish body composition.

Effect of glucan on growth, survival, digestive enzyme activity, immune system and intestinal barrier gene expression for tropical gar (*Atractosteus tropicus*) juveniles was experimented by Nieves-Rodríguez et al. (2018). Their results indicated that 0.5% to 1.5% of β -glucans in the diet had no adverse effects. They also expressed that β -glucan 1,3/1,6 at 1.0% and 1.5% in the diet significantly increases chymotrypsin activity.

Sirimanapong et al. (2015) investigated the effects of β -glucan on the immune response of pangasius (*Pangasianodon hypophthalmus*) and concluded that both the innate humoral and cellular immune responses of pangasius were differentially stimulated by different concentrations of β -glucan, with doses of 0.1 or 0.2% fungal-derived β -glucan giving optimal immunostimulation compared with the basal diet, and these performed equally well as fish fed 0.1% commercial yeast-derived β -glucan.

Adloo et al. (2015) studied the effect of different levels of β -glucan on the growth performance, survival and physiological responses in juvenile pangasius (*Pangasianodon hypophthalmus*). They stated that different levels of β -glucan had no significant effect on the growth, survival and glucose value of fish. However, highest serum lysozyme activity was measured in fish fed on a diet containing 0.5% of β -glucan. Furthermore, the protein content was significantly enhanced in all β -glucan treatments compared to the control group.

Ghaedi et al. (2015) examined the effect of β -glucan on broodstocks, larvae and maternal immunity in rainbow trout and reported that the immune parameters of female broodstocks at 0.2% glucan were significantly higher than the control group. They also stated that some immune parameters were transferred to oocytes.

Table 1. A summary of the effects of β -glucan on cultured aquatic animals in different studies

Species	Findings	Reference
1	2	3
African catfish (<i>Clarias gariepinus</i>)	In exposure to chlorpyrifos, the algae <i>Spirulina platensis</i> and β -glucan inhibit the effects of chlorpyrifos on health status, immunity, and antioxidative responses of African catfish	Mokhbatly et al. (2020)
Atlantic salmon (<i>Salmo salar</i>)	Atlantic salmon are more resistant to a vaccine against pathogens when diets rich in β -glucans are consumed	Roberti Filho et al. (2019)
Atlantic salmon	β -1,3/1,6 glucan-containing diets increased the levels of transcripts of key genes involved in the immune response of salmon, allowing it to respond more strongly to a vaccine, as well as decreasing the effect of hypoxia	Rodríguez et al. (2016)
Blue swimmer crab (<i>Portunus pelagicus</i>)	The functional aspects of b-GBP purified from <i>P. pelagicus</i> and its vital role in triggering prophenoloxidase during pathogenic infection were described	Anjugam et al. (2016)
Common carp (<i>Cyprinus carpio</i>)	A diet based on plant oils did not significantly impair the immunomodulatory effects of β -glucans, proving that these oils are suitable for sustaining a high level of immunity in common carp	Nguyen et al. (2019)
Gilthead seabream (<i>Sparus aurata</i>)	In a Mediterranean aquaculture system, the β -1,3/1,6-glucan and Pdp 11 (<i>Shewanella putrefaciens</i> , a probiotic isolated from gilthead seabream skin) modulated immunity and promoted the growth of gilthead seabream	Guzmán-Villanueva et al. (2014 b)
Hybrid giant tiger groupers (<i>Epinephelus fuscoguttatus</i> $\times$ <i>Epinephelus lanceolatus</i>)	β -glucan can alleviate the immunosuppressive effects mediated by oxytetracycline (OTC) <i>in vitro</i> . Dietary β -glucan in combination with OTC improves the parameters of innate immunity. A combination of β -glucan and OTC provides better protection against bacterial infection than either alone	Lee et al. (2020 b)
Hybrid striped bass (<i>Morone chrysops</i> $\times$ <i>M. saxatilis</i>)	During feeding trials, a synergistic effect between β -1,3 glucan paramylon and vitamin C was most noticeable <i>in vitro</i> in terms of reactive oxygen species, and a limited enhancement of immune responses was observed <i>in vivo</i>	Yamamoto et al. (2020)
Koi carp (<i>Cyprinus carpio koi</i>)	Koi's immune responses were improved and they were less susceptible to infection from <i>Aeromonas veronii</i> when given immunostimulants through dietary intake. In particular, supplementing the kois with β -1,3 glucan for 56 days resulted in significant improvements in growth, survival, and immune response	Lin et al. (2011)
Large yellow croaker (<i>Pseudosciaena crocea</i>)	β -glucan was able to reduce hypoxia-induced oxidative stress in large yellow croaker through enhancing anaerobic glycolysis capacity, highlighting HIF-1 α 's role in this process	Zeng et al. (2016)
Marron (<i>Cherax tenuimanus</i>)	Marron's immune system may be improved by increasing dietary β -1,3 glucan concentrations to a minimum of 0.1–0.2%	Sang and Fotedar (2010)
Mozambique tilapia (<i>Oreochromis mossambicus</i>)	A dietary supplementation of 0.004% β -1,3 glucan binding protein based zinc oxide nanoparticles may have a positive effect on the immune system and survival of <i>O. mossambicus</i> .	Anjugam et al. (2018)
Mozambique tilapia	Acquiring stress tolerance and improving aquaculture growth performance of Mozambique tilapia can be accomplished with β -glucan out of yeast, <i>Saccharomyces cerevisiae</i>	Divya et al. (2020)
Nile tilapia (<i>Oreochromis niloticus</i>)	The fish immune status and relative level of protection were significantly improved by β -glucan. To achieve better fish growth and disease resistance, new feeding practices in fish farming should include various additives	Sherif and Mahfouz (2019)
Nile tilapia	The results show that the concentration of 0.1 mg L ⁻¹ increased tolerance to hypoxia, increased survival rates, and regulated glucose levels of Nile tilapia. Before hypoxic challenge, a concentration of 0.3 mg L ⁻¹ modulates the hematological responses under stress and increases the lymphocyte count	de Souza et al. (2020)
Nile tilapia	The β -glucan diet can improve the growth, intestinal morphometry, stress resistance, and immunity of Nile tilapia aquaculture by counteracting the negative effects of crowding stress	Dawood et al. (2020)
Nile tilapia	Dietary α -lipoic acid, β -glucan, and L-carnitine have varying protective mechanisms and different effectiveness against <i>A. hydrophila</i> infections in Nile tilapia	Lu et al. (2019)
Nile tilapia	β -glucan supplementation alleviated the immune-toxic and antioxidant effects of fipronil in tilapia	Abd El Hakim et al. (2019)
Nile tilapia	Atrazine negatively impacts immune responses, antioxidant balance, and genes related to them for Nile tilapia. It is possible that supplementing with β -glucan before exposure to atrazine can help counteract the damage caused by atrazine water pollution compared to its simultaneous treatment with atrazine.	Neamat-Allah et al. (2020)
Nile tilapia	Further evidence of β -glucans' use in aquaculture, specifically Nile tilapia, is provided by these findings. In addition, they provide more evidence of the compound's growth promoting properties	Pilarski et al. (2017)

Table 1 – contd.

1	2	3
Nile tilapia	The combination of <i>Chlorella vulgaris</i> and β -glucan is a potential feed additive for improving immunity, prevention against oxidative damage, growth performance, and hematobiochemical alterations induced by diazinon toxicity in Nile tilapia	Abdelhamid et al. (2020)
Nile tilapia	A study conducted on Nile tilapia showed that β -glucan administration alleviated the negative effects of chlorpyrifos on immunity, anti-inflammatory response, and histopathology	Dawood et al. (2020)
Nile tilapia	As a result of the β -glucan treatment, Nile tilapia larvae were 20% heavier and 8.5% longer compared to controls	de Jesus et al. (2019)
Olive flounder (<i>Paralichthys olivaceus</i>)	Olive flounder mortality from bacterial and viral infections was reduced as a result of innate immune function activation by β -1,3-glucan. Scuticociliatosis-related death, however, did not appear to be protected by the same level of immunity. This pronounced response against bacterial infection suggests bacterial pathogens are dealt with by factors other than innate immunity	Lee et al. (2018)
Pacific red snapper (<i>Lutjanus peru</i>)	The addition of 1,3/1,6-glucan to Pacific red snapper feed increased growth, antioxidant activity, and digestive enzyme activity	Guzmán-Villanueva et al. (2014 a)
Pacific white shrimp (<i>Litopenaeus vannamei</i>)	In <i>L. vannamei</i> , dietary β -glucan supplements at 0.02%–0.04% can significantly boost digestibility, antioxidant capacity, and immunity, thus improving growth performance and survival under low salinity conditions. The beneficial effects of β -glucan probably result from probiotics dominating potential pathogens in the intestine	Li et al. (2019)
Pacific white shrimp	Based on the evidence, β -1,3/1,6-glucan and vitamin C were shown to induce nonspecific immune responses in Pacific white shrimp in an additive manner	Wu et al. (2016)
Pacific white shrimp	<i>Pediococcus acidilactici</i> combined with β -glucan or β -glucan alone influenced shrimp growth and protein composition in meat. The concentration of haemolymph glucose and osmoregulation were also increased by dietary β -glucan. Adding a synbiotic supplement had more impact on intestinal morphometry and microbiota than consuming β -glucan on its own	Boonanuntanasarn et al. (2016)
Pacific white shrimp	β -glucans obtained from marine yeasts living in the shrimp pond provided extra protection against the mortalities caused by this pathogenic virus	Ochoa-Álvarez et al. (2021)
Pacu (<i>Piaractus mesopotamicus</i>)	The results of this study support the benefits of feeding strategies that integrate both mannans and 1,3–1,6 glucans as dietary supplements prior to intensive management. In the 30-day period, growth performance was increased, nutrient utilization was improved, stress responses were minimized, and immunity responses were modulated for pacu fed the dietary supplements	Soares et al. (2018)
Pacu	β -glucans and mannanoligosaccharides in a 0.2% composition promoted the best responses to feed, feed efficiency, and intestinal morphology in juvenile pacu, without detrimental effects on hematological parameters	Hisano et al. (2018)
Pacu	In addition to reducing the activity of leukocytes after stress and the bacterial challenge, β -glucan increased the level of baseline glucose in the blood of pacu. Glucan is confirmed to have immunomodulatory effects and may be involved in stress response	Sabioni et al. (2020)
Pacu	The β -glucan modulated the bidirectional interaction between stress and immunity. As the levels of cortisol and the immune system were modulated at various times in their study, this suggests that the compound is protective by preventing high levels of the hormone and enhancing immunity to bacterial infection in pacu	de Mello et al. (2019)
Pengze crucian carp (<i>Carassius auratus</i>)	Supplementation with β -glucan and <i>Bacillus subtilis</i> significantly increased the antioxidant status, immune response, and fillet quality of Pengze crucian carp	Cao et al. (2019)
Persian sturgeon (<i>Acipenser persicus</i>)	Persian sturgeon can benefit from β -glucan as a dietary supplement to improve their immune response and growth performance	Aramli et al. (2015)
Pompano (<i>Trachinotus ovatus</i>)	By supplementing β -glucans, the pompano fish <i>T. ovatus</i> grew faster, had higher <i>Vibrio</i> counts, and was more resistant to stress	Do Huu et al. (2016)
Rainbow trout (<i>Oncorhynchus mykiss</i>)	Based on the results of this study, dietary β -glucans at 0.1% and 0.2% are beneficial for increasing growth in rainbow trout and improving resistance to <i>Aeromonas salmonicida</i> . Furthermore, β -glucan may play a critical role in the regulation of stress- and immune-related factors in rainbow trout, making it more effective in fighting bacterial infection	Ji et al. (2017)
Rainbow trout	The effects of β -glucan at concentrations of 0.1% and 0.2% were dose-dependently ameliorated in rainbow trout from trinitrobenzene sulfonic acid-induced enteritis. This study provides evidence supporting the use of β -glucan in treating or protecting fish enteritis	Ji et al. (2019)

Table 1 – contd.

1	2	3
Rainbow trout	The findings provide basic information to understand possible mechanisms of dietary β-glucan's role in maternal immunity and the growth of rainbow trout	Ghaedi et al. (2016)
Red drum (<i>Sciaenops ocellatus</i>)	In both <i>ex vivo</i> and <i>in vivo</i> studies, algamune™ β-glucan was demonstrated to have a moderate immunostimulatory effect on red drum	Yamamoto et al. (2018)
Red seabream (<i>Pagrus major</i>)	Supplementation with β-glucan and vitamin C to the basal diet of red sea bream could boost the fish's growth, antioxidant reserves, humoral immunity, and resistance to low salinity stress	Dawood et al. (2017 b)
Red seabream	<i>P. major</i> grows faster, is more resistant to stress, and has a better immune response when its diet is supplemented with β-glucan	Dawood et al. (2017 a)
Turbot (<i>Scophthalmus maximus</i>)	As a promising therapeutic agent, β-glucans can induce trained immunity against bacterial disease, whereas viruses seem to take advantage of metabolic changes in β-glucans	Librán-Pérez et al. (2018)
Turbot	It is concluded that MacroGard administration was immunomodulatory and could be employed as a useful measure to increase survival in turbot rearing	Miest et al. (2016)
Zebrafish (<i>Danio rerio</i>)	β-glucan stimulates the production of lysozyme in eggs and offspring by the process of transferring the molecule from mothers to eggs and by stimulating the production of this molecule on oocytes of zebrafish	Wang et al. (2017 a)
Zebrafish	When female zebrafish were fed β-glucan, there was little negative effect on the number of eggs and embryogenesis. For the first time, these results show that β-glucan can help fish offspring develop non-specific immunity	Jiang et al. (2016)

Conclusion

The aquaculture industry is growing rapidly and its share in the total production of aquatic food has increased above 50%. In order to make this growth sustainable and increase the yield and quality and thus the income, feed additives should be used.

The results of studies have shown that the addition of β-glucan to the diet can improve growth performance, survival and immunity in cultured aquatic animals. Taken together, we would strongly recommend the use of β-glucan on farmed fish diet, whenever there are sufficient evidences for its benefit, aiming to improve overall health. Optimizing the dosage of β-glucan in different cultured species should be done by more studies and improving the quality of β-glucan should be performed. The possible use of β-glucan from other sources such as seaweed, terrestrial plants and bacteria, should also be examined. β-glucan is an emerging prebiotic in aquaculture, which needs far more research to explore its roles in different species of farmed fish.

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