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REVIEW

REVIEWS IN Aquaculture

Role of β-glucan on finfish and shellfish health and well-being: A systematic review and meta-analysis

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Abstract

This study aimed to conduct a systematic review and meta-analysis evaluating the inclusion of β-glucan in aquaculture animal diets and its impact on their health outcomes. Relevant studies were identified from Scopus and Web of Science databases. A total of 82 primary studies published between 1996 and 2024 were reviewed, of which 70 were included in the meta-analysis. The results revealed that the application of β-glucan to aquaculture animal's diets significantly enhanced specific growth rate (SGR; mean effect, $g = 2.71$; $p < 0.001$), feed conversion ratio (FCR; $g = -3.88$; $p < 0.0001$) and lowered mortality after exposure to pathogens. Likewise, β-glucan had a positive influence ($p < 0.0001$) on innate immune parameters (lysozyme and phagocyte activity, NBT, ACH50, and IgM). The study found that the effects of β-glucans varied among marine and freshwater fish where freshwater fishes ($g = 2.05$–6.57) exhibit better performance. This study also found a negative correlation between fish's innate immune response and trophic level, suggesting that fish with higher trophic levels may be less efficient at absorbing this bio-stimulant. Even though there were high heterogeneity ($I^2 = 73\%$–97%, $p < 0.05$) due to the diversity of tested organisms and publication bias, our model and findings are valid. The findings suggest that the dietary application of β-glucans can have beneficial effects on

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growth and immune responses especially for freshwater species. The validity of these observations needs to be confirmed by further prospective studies.

KEYWORDS

aquatic animal, growth performance, immune response, immunostimulant, meta-analysis, β-glucan

1 | INTRODUCTION

Due to evolving consumption patterns and population growth, aquaculture is projected to increase by 62% between 2010 and 2030, fulfilling over two-thirds of global fish and shellfish demand.[1–5] Approximately 100 million individuals rely on aquaculture for livelihoods, indicating its substantial socio-economic impact.[5] While some debates persist, aquaculture plays a pivotal role in addressing global food security and poverty reduction, aligning with the UN's 2030 Agenda for Sustainable Development Goals.[6] Notably, besides serving as a vital protein and income source, aquaculture offers ecosystem services like wastewater treatment and habitat restoration.[7,8] However, sustainable aquaculture practices are imperative to ensure these benefits, as inadequate practices can strain water resources, exacerbate overfishing, introduce invasive species, and foster antimicrobial resistance.[9,10]

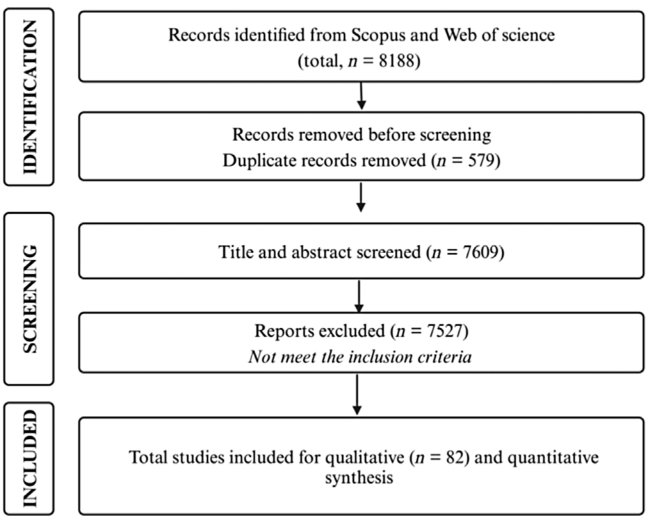

FIGURE 1 PRISMA flow chart for included studies.

Despite its significance, aquaculture faces numerous hurdles hindering its growth.[11] Aquatic animal diseases, exacerbated by global trade, system intensification, and climate change, pose a major obstacle.[12,13] High-density cultures and intensified systems facilitate pathogen evolution and disease outbreaks, compelling farmers to resort to antibiotics and disinfectants.[14,15] Nevertheless, the overuse of these chemicals compromises animal immune systems and fosters antibiotic-resistant bacteria, posing a global health hazard.[16–18] Moreover, the use of antibiotics has caused serious problems, such as the aquatic environments and the negative impacts on the aquatic ecosystem, the persistence of antibiotic residues in fish meat, and its negative impacts on human health.[19,20] In this context, alternative disease prevention strategies like functional feed supplements and vaccination have been proposed.[21–23] While vaccination reduces antibiotic usage in certain sectors, its specificity and cost limit widespread application, especially for tropical diseases.[24–26] Given the prevalence of multi-agent infections in aquaculture, a holistic approach is crucial. Functional feed supplements, including medicinal plants and probiotics, have gained traction for their potential to enhance fish performance, immune systems, and feed utilisation.[21,27,28] Incorporating such supplements into fish diets could not only improve disease prevention but also contribute to better resource utilisation, fostering sustainable aquaculture development.[29]

TABLE 1 Summary of publication bias before and after removing outliers.

Variables	Heterogeneity[1] (I^2, %)	Mean effect size[1]	Egger's regression Z	Egger's regression p-value	Study of outlier	Corrected effect size[2]	Heterogeneity[2] (I^2, %)
SGR ($n = 36$)	99.63	2.91 [2.11 to 3.7]	8.27	<0.0001	21	2.71 [2.33 to 3.08]	94.60
FCR ($n = 39$)	99.95	−4.91 [−6.33 to −2.05]	−13.43	0.0001	22	−3.88 [−6.10 to −1.67]	99.85
Lysozyme activity ($n = 46$)	99.75	3.72 [2.47 to 4.99]	7.56	<0.0001	29	4.13 [3.67 to 4.59]	90.60
Phagocytic activity ($n = 15$)	99.73	4.37 [0.620 to 8.13]	9.02	<0.0001	8	2.39 [1.49 to 3.30]	97.33
ACH50 ($n = 20$)	98.44	1.7 [1.11 to 2.28]	1.65	0.0993	8	1.20 [0.95 to 1.46]	76.21
NBT ($n = 21$)	98.76	2.11 [1.11 to 3.12]	6.39	<0.0001	11	1.69 [1.31 to 2.07]	73.65
IgM ($n = 10$)	98.5	1.89 [1.06 to 2.73]	1.49	0.1387	5	2.32 [1.82 to 2.82]	82.02
Mortality ($n = 8$)	99.78	−5.85 [−7.94 to −3.75]	−12.39	<0.0001	2	−5.75 [−6.68 to −4.82]	96.33

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β-Glucans have been used as potential prebiotics in aquaculture.[30] β-glucans comprise a group of β-D-glucose polysaccharides, naturally occurring in the cell walls of bacteria, fungi, and cereals, but with different properties dependent on the source.[31] They form a linear backbone with 1–3 β-glycosidic bonds, but vary with respect to molecular mass, solubility, viscosity, branching structure, and gelation properties, causing diverse physiological effects in animals.[32] In aquaculture, β-glucan is frequently added to feed to boost immunity, increase disease resistance, and enhance growth.[33,34] By boosting the animal's resistance to infections and stimulating immunological cells, it can strengthen the host's immune response.[35,36] β-glucan can protect aquatic animals against typical diseases like parasites, viruses, and bacterial infections.[37,38] Furthermore, through increasing the number of helpful intestinal microbes, acidifying the digestive system, and lowering the amount of toxic intestinal metabolites, β-glucan contributes significantly to the improvement of the intestinal environment.[39–41] Based on the literature, it is known that a β-glucan may have one or more modes of action, including the production of inhibitory compounds, enhancement of immune responses, improving water quality, competition for adhesion sites in the intestine, creation of proper interaction with phytoplankton, which is nutritionally important for fish and contains natural enzymes, helping digestive system of fish.[33,42] However, the efficiency of β-glucans may change depending on breeding conditions, methods of consumption, dosage, and fish species.[43] Therefore, we are faced with a wealth of information on the therapeutic effect of β-glucans, which are sometimes contradictory. Meta-analysis is the use of specific statistical methods to summarise the results of independent studies to find the most accurate form of relationship between the variables.[44] Therefore, we conducted a systematic review and meta-analysis to investigate the effect of β-glucans on finfish and shellfish health and well-being.

2 | METHODS

2.1 | Literature search

The relevant literature search was conducted using the Scopus and Web of Science databases published from 1996 to 2024 and the combined keywords were used: (β-glucan*) AND (fish* OR crustacean*) AND (growth* OR immune*) AND (supplement* OR oral*). Article selection was based on the following criteria: (i) focused on aquatic animals; (ii) one of the following parameters was reported for both fish fed a β-glucan-free diet and fish fed with β-glucan-enriched diet: specific growth rate (SGR, %/day), feed conversion ratio (FCR), immunoglobulin (mg/mL), lysozyme activity (U/mL), phagocytic activity (%), complement activity (ACH_{50}, U/mL), respiratory burst activity (NBT, OD 630 nm), immunoglobulin M (IgM, mg/dL) or mortality after infected (%); (iii) mean, number of replicates and standard deviation or standard error were reported for each of the parameters; and (iv) effects of

TABLE 2 Summary of correlation between effect size and explanatory variables.

Variables	Lysozyme activity			Phagocytic activity			ACH50			NBT			IgM			Mortality			SGR	FCR
	n	*k*	*p*	*n*	*k*	*p*	*n*	*k*	*p*	*n*	*k*	*p*	*n*	*k*	*p*	*n*	*k*	*p*	*p*	*p*
β-Glucan	43	81	0.893	15	30	0.183	19	40	0.638	18	39	0.578	10	20	0.336	8	29	0.301	0.735	0.602
Duration			**0.006**			0.135			**0.007**			**0.004**			0.262			0.262	0.461	0.865
Trophic level			0.383			**0.001**			0.473			**0.033**			0.761			0.066	0.331	0.415
Interaction[a]												0.348								

Abbreviations: ACH50, complement activity; IgM, immunoglobulin M; *k*, number of comparisons; *n*, number of studies; NBT, respiratory burst activity; *p*, *p*-value.
[a]Between duration and trophic level while both are significantly correlated with effect size.

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β-glucan as feed supplement. Studies that evaluated the effect of mixed immunostimulants along with β-glucan at a time were not included. When the data were presented graphically, ImageJ (National Institutes of Health, Bethesda, Maryland, USA) was used to extract.

2.2 | Data analyses

A random-effects model was utilised to account for potential variability in effect sizes across studies. This is a standard approach to handle heterogeneity and is appropriate for meta-analyses where the true effect size may vary between studies.[45] Hedges' *g* effect size (*g*) was calculated as previously described.[46] The magnitude of standardised mean difference of *g* value was interpreted as follows: small effect = 0.2, medium effect = 0.5, and large effect = 0.8. A *g* value of zero indicated no significant difference in the tested parameter with the administration of β-glucan. All statistical analyses were performed using the *metafor* package in R version 1.4.1103. The influence of explanatory variables (trophic level, experimental duration, β-glucan level) on Hedges' *g* effect size was performed with multiple linear regression under the ANCOVA framework.

2.3 | Heterogeneity and publication bias

Among-study heterogeneity was determined via I^2 index. Heterogeneity is considered high and low if I^2 index is ≤50% and >50%, respectively.[47] Egger's tests were used to assess publication bias. When publication bias was detected ($p < 0.05$) by Egger's test, we removed outliers and reported results from an outlier-free test according to the previous description.[48] Statistical significance was assumed with a *p*-value <0.05.

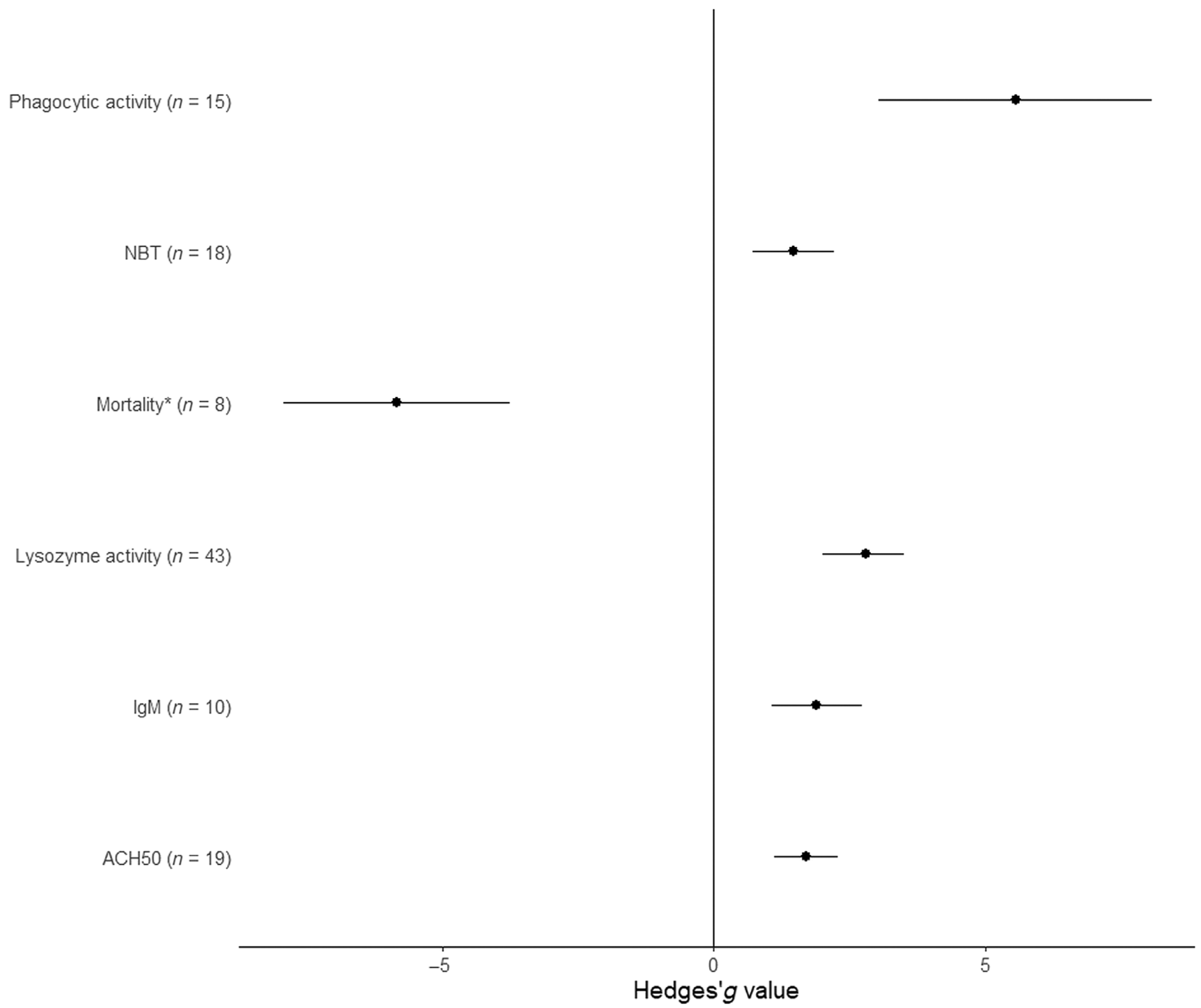

FIGURE 2 Forest plot for Hedge's effect size (mean and 95% confidential interval) of immune response indices. ACH50, complement activity; IgM, immunoglobulin M; NBT, respiratory burst activity.

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3 | RESULTS

3.1 | Included studies and overview of dataset

We used the Scopus and Web of Science databases to collect relevant articles, resulting in 8188 records compiled into a single EndNote library. After removing duplicate articles, 7609 remained. Following careful screening of titles and abstracts, 7527 articles were excluded. Finally, 82 articles were selected for review, with 70 studies utilised in the meta-analysis. Please refer to Figure 1 for a visual representation of this process. From the 70 compiled studies investigating the effect of β-glucan on the immune response of fish and shrimp, a total of 33 fish species was investigated, in which two-thirds (70%) of all studies focused on freshwater fish (70% of the dataset), while the rest of 30% considered marine fish (Table S1). The trophic level (2.5–4.1, IR) and β-glucan levels (0%–0.1%) were found in the dataset. Most of β-glucan from the literature were extracted from yeast (*Saccharomyces cerevisiae*) (93% of total studies) and other sources (such as *Laminarina digitata*, *Euglena gracilis*) (7%). β-Glucan was mainly obtained from commercial sources (94% of total studies), while laboratory extraction accounted for 6%. The administration duration of β-glucan on fed organisms ranged from 28 to 60 days (IR), with a mean value of 48.18 days (Table S1).

3.2 | Effect on β-glucan enrichment on growth production

Our findings indicated that the application of β-glucan on aquatic animal fish significantly enhanced growth performance (mean effect, $g = 2.71$; 95% CI = 2.33, 3.08; $p < 0.001$; $n = 36$). All β-glucan-fed organisms showed positive SGR compared to β-glucan-free addition (Table 1). Feed efficiency, as indicated by the FCR index, exhibited negative effects by supplementation of β-glucan (mean effect, $g = -3.88$; 95% CI = −6.10, −1.67; $p < 0.001$; $n = 39$) (Table 1).

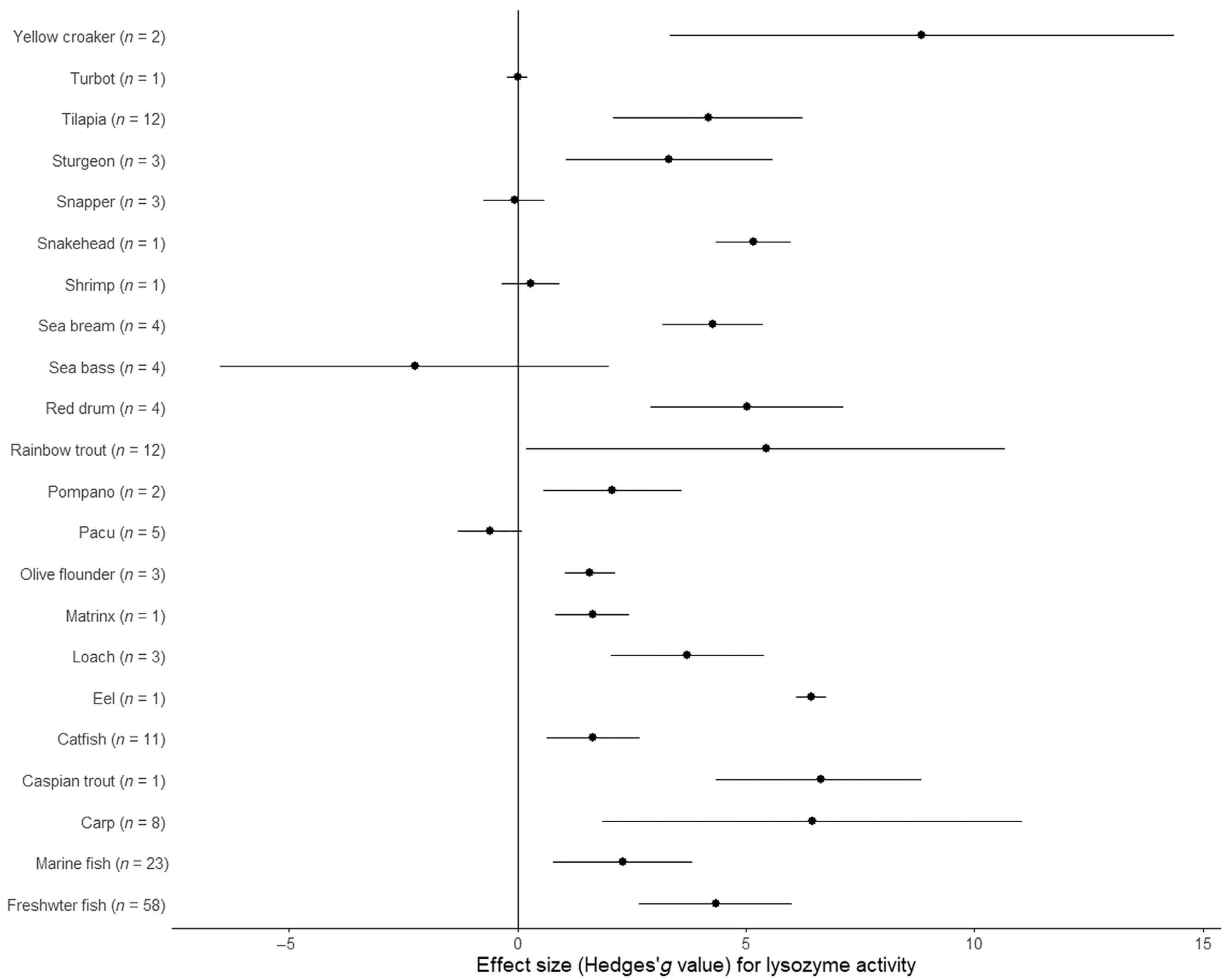

FIGURE 3 Hedge's effect size of lysozyme activity. '*n*' indicates number of comparisons.

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No significant association of explanatory variables was found for SGR and FCR (Table 2).

3.3 | Effects of β-glucan enrichment on immune parameters

The meta-analysis indicated that administration of β-glucan displayed positive results on Hedges' *g* effect size of lysozyme activity, phagocytic activity, ACH50, NBT, IgM ($p < 0.001$), while negative mortality was observed ($p < 0.001$), indicated better survival rate after exposed to the pathogen (Figure 2).

From 43 studies, the meta-analysis results confirmed the positive effect of β-glucan on lysozyme activities of aquatic animals as categorised in habitat groups, in which freshwater habitats (mean, 4.34) responded more significantly than marine ones did (2.30). Among fish species, carp, Caspian trout, and yellow croaker displayed the largest effect size of 6.45, 6.65, and 8.85, respectively, while snapper, turbot, shrimp, sea bass, and pacu remained non-significant by multiple comparison results ($p = 0.848$, 0.992, 0.300, and 0.056, respectively) (Figure 3).

The result of analysis from 15 publications showed a high phagocyte activity effect size of freshwater (6.57) compared to marine (1.85) habitats by β-glucan addition. Tilapia, pompano, flounder, and carp were positively affected by β-glucan supplement ($p < 0.001$) (Figure 4).

Most of fish species showed positive ACH50 effect size by administration of β-glucan, except for turbot ($p = 0.325$), tilapia ($p = 0.471$), and olive flounder ($p = 0.077$). Freshwater habitats also exhibited a larger effect size than did marine ones (Figure 5).

Supplementing β-glucan positively affected the effect size of NBT for carp ($p < 0.001$), pacu ($p < 0.0001$), sea bream ($p < 0.001$), shrimp ($p = 0.010$), tilapia ($p = 0.001$). In consistency with previous immune indicators, the effect size of NBT of marine and freshwater species is positive, while the latter was larger than the former (Figure 6).

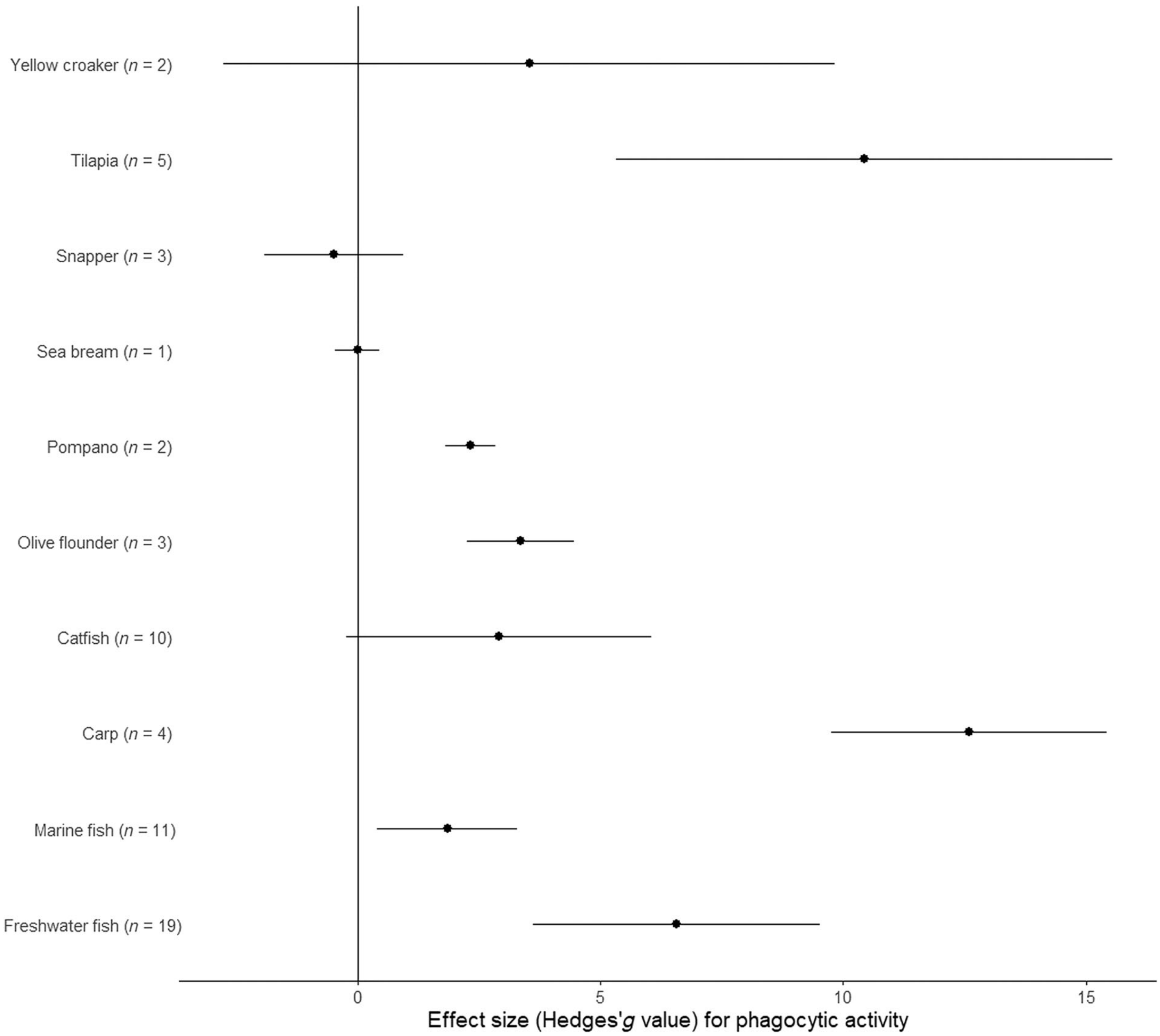

FIGURE 4 Hedge's effect size of phagocytic activity. '*n*' indicates the number of comparisons.

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Freshwater fish had a positive response of immunoglobin M at the addition of β-glucan (2.05), except for sturgeon (−0.41, $p = 0.060$), whereas marine fish showed an inverted response (−0.99) (Figure 7).

All species showed significantly lower mortality at the application of β-glucan after being infected with the pathogen in comparison with β-glucan-free diet (Figure 8).

3.4 | Meta-regression analysis

When considering the correlation between explanatory variables of β-glucan level, duration of the experiment, and trophic level with immune response effect size, there was no significant relationship between β-glucan level and effect size ($p > 0.05$). Experimental duration significantly correlated with lysozyme activity, ACH50, and NBT ($p < 0.05$), while trophic level had a significant relationship with phagocytic activity and NBT (Table 2, Figure 9).

3.5 | Heterogeneity and publication bias

The analysis indicated that all immune response indices had a remarkably high I^2 index (lysozyme activity, 99.37%; phagocytic activity, 99.73%; ACH50, 98.44%; NBT, 97.8%; IgM, 98.5%; and mortality after infected, 99.78%), suggesting high between-study heterogeneity.

The results from Begg's and Egger's tests showed no significant publication bias for ACH50 and IgM, while there was publication bias for the other four immune indices as indicated by the tests and asymmetrical funnel plots (Table 1, Figure 10).

4 | DISCUSSION

The role of β-glucans as an immunomodulatory additive on fish immunity has been extensively investigated in aquaculture nutrition research.[35,38,49–51] Due to its ability to regulate cellular and humoral responses, restore cell homeostasis, and aid in the formation of

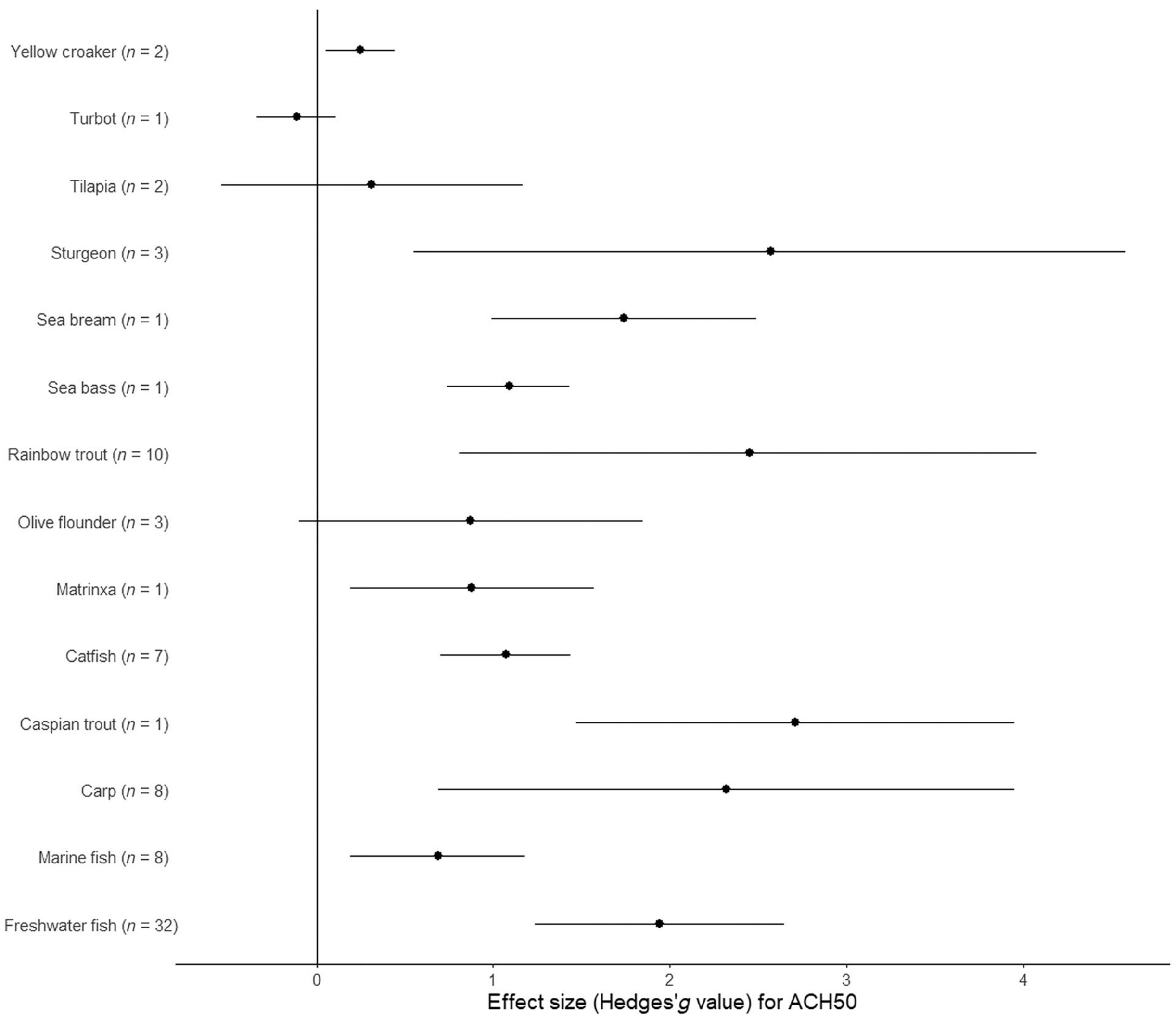

FIGURE 5 Hedge's effect size of complement activity (ACH50). '*n*' indicates the number of comparisons.

immunity training, β-glucan has been widely utilised to boost the non-specific immune system.[42,52,53] Pattern recognition receptors (PRRs) and β-glucans interact to initiate intracellular signalling that in turn activates humoral and cellular responses.[54,55] Moreover, β-glucans can 'train' non-specific immunity by boosting the immune system and improving defence versus infections in the future.[56] Our meta-analysis provided a quantitative assessment of the effect of oral β-glucans administration on the immune response in aquatic animals. Overall, supplementing this immunostimulant improved growth performance and immune parameters while reducing FCR and mortality after exposure to various pathogens and ammonia stress. Although β-glucan significantly enhanced immune effect size in general, other explanatory variables–duration of the trial and trophic levels–were found to be significant covariances.

The high heterogeneity (>97%) across all immune parameters could be attributed to the diversity of tested organisms in the literature. Indeed, the compiled dataset covered 20 fish species from either marine or freshwater habitats. In the present study, publication bias was found in all investigated indices by Egger's tests (Table 1). By removing strong outliers from the dataset, all effect sizes were still significant differences between β-glucans-supplemented and β-glucans-free applications (Table 1). Therefore, the findings from the present meta-analysis are valid even with publication bias.

Although the elimination of outlier studies reduced the heterogeneity of ACH50 and NBT, this value remained particularly high (>50%) across effect sizes. It is therefore apparent that the diversity of investigated fish in our study strongly affects between-study heterogeneity.

The growth and feed efficiency of aquatic animals at the supplementation of β-glucans fed were reported.[57–60] β-glucan supplementation led to increased activity levels of important digestive enzymes and gut microbiota, which implies enhanced nutrient utilisation and digestion efficiency in aquatic farmed species.[61–63] Supplementation of dietary β-glucan at concentrations ranging from 0.02% to 0.04% resulted in improved digestive capacity,[62] antioxidant activity, and immune response of different freshwater fishes, river prawn, banana shrimp, and white shrimp.[61,64–70] Adding β-glucans at concentrations between 0.4% and 0.6% to the diets of *Atractosteus tropicus* larvae

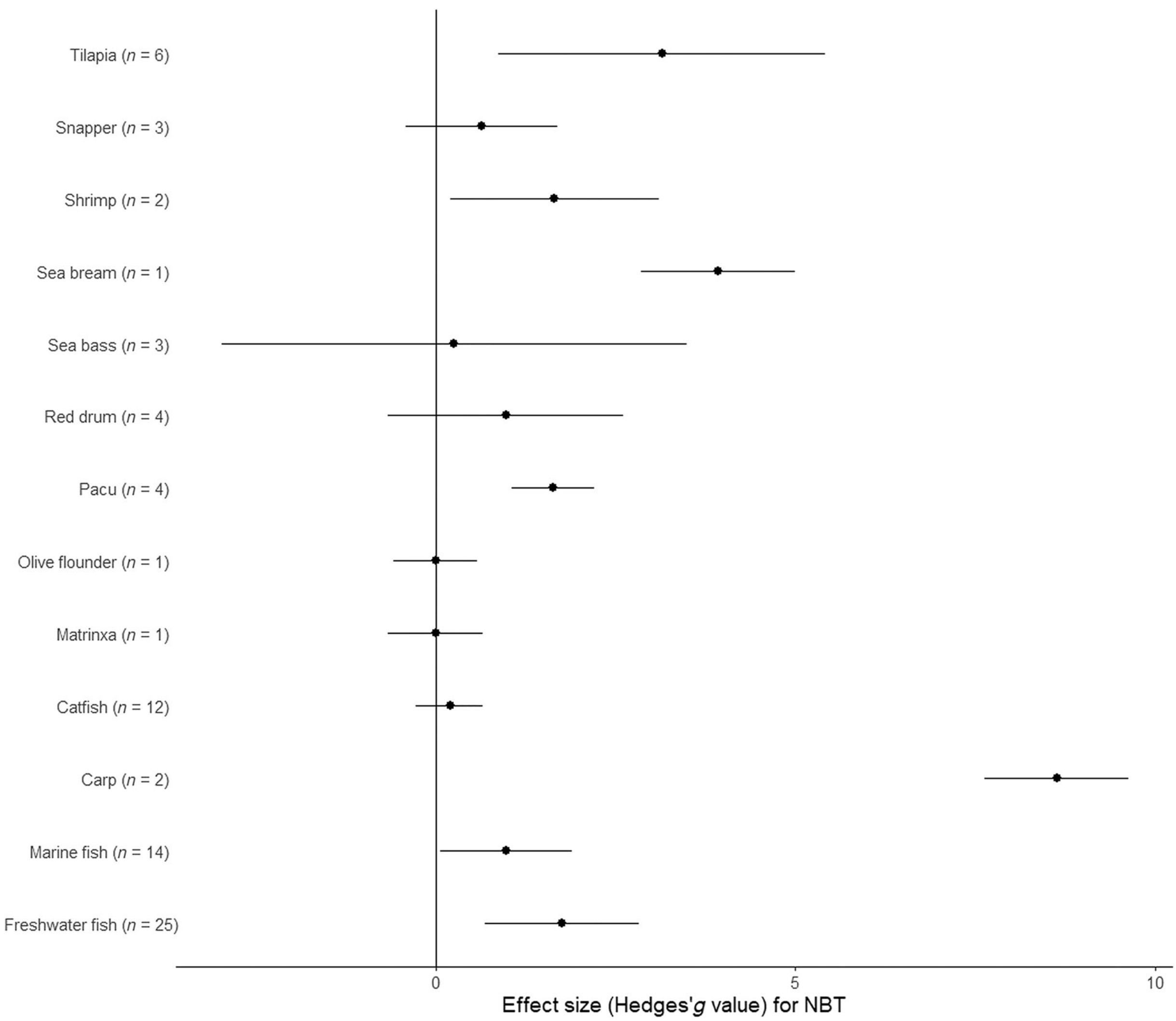

FIGURE 6 Hedge's effect size of respiratory burst activity (NBT). '*n*' indicates the number of comparisons.

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may enhance larval rearing.[61] This is evidenced by the elevated activity levels of various digestive enzymes (such as lipase and trypsin) and the upregulation of immune system genes. Our findings indicate that the effect of β-glucans on innate immune indices varied widely among marine and freshwater fish. For example, Del Rio-Zaragoza et al.,[71] and Ogier de Baulny et al.[72] found no significant difference in lysozyme activities of turbot and snapper fed with enriched glucan relative to the control diet, while carp and trout showed a strong positive response to this supplementation.[59,73,74] The phenomenon could likely be explained by the difference in the digestive tract system, nutritional requirement, and gut microbiota-driven immune response. Therefore, the use of β-glucan for some marine fish, such as sea bass, with the target of enhancing immune response should be carefully considered. The use of β-glucan in combination with other immunostimulants in marine fish could be an effective strategy.[49]

Given that the immune response of aquatic animals is known to primarily rely on the duration of treatment, this relationship remains controversial in the literature. Douxfils et al.[75] reported a higher immune-related gene expression of rainbow trout fed β-glucan for 15 days than do 30 days. Similarly, lysozyme activity and ACH50 of tilapia were found to increase after 1 and 2 weeks of administrated β-glucans and to follow a slight decrease by the end of the 8-week experiment. A prolonged administration of β-glucan could lead to the immunity fatigue phenomenon found in fish.[38] In contrast, recent findings have developed a new term 'trained immunity' referring to the longer supplementation of β-glucan for enhancing the immune response in fish.[76] Our meta-regression models indicated that a relatively short feeding period (8 weeks for lysozyme activity and ACH50, and 3 weeks for NBT) was suitable for fish. This could hint at important information for further investigation at laboratory or commercial purposes to reduce treatment duration, thereby related costs. Moreover, our study found that all species exhibited significantly lower mortality rates when fed with β-glucan compared to those on a β-glucan-free diet after being infected with the pathogen. Some studies have also indicated that the dietary intake of β-glucan improved resistance to toxic stress (such as ammonia, fipronil, trichlorfon, and lead) to a certain extent, possibly by activating the antioxidative system in golden mahseer (*Tor putitora*), Nile tilapia, and African catfish (*Clarias gariepinus*).[65,77,78]

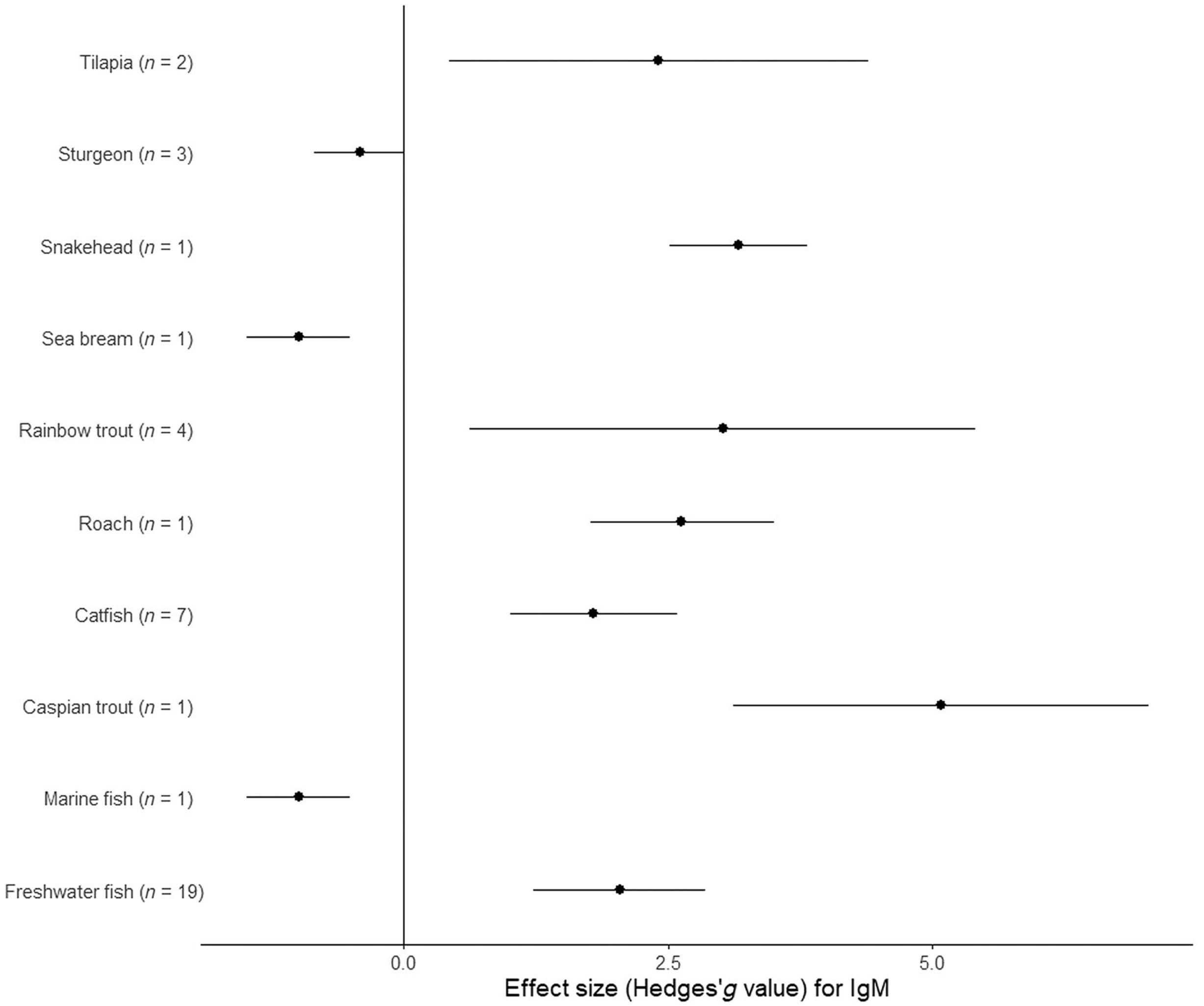

FIGURE 7 Hedge's effect size of immunoglobin M (IgM) activity. '*n*' indicates the number of comparisons.

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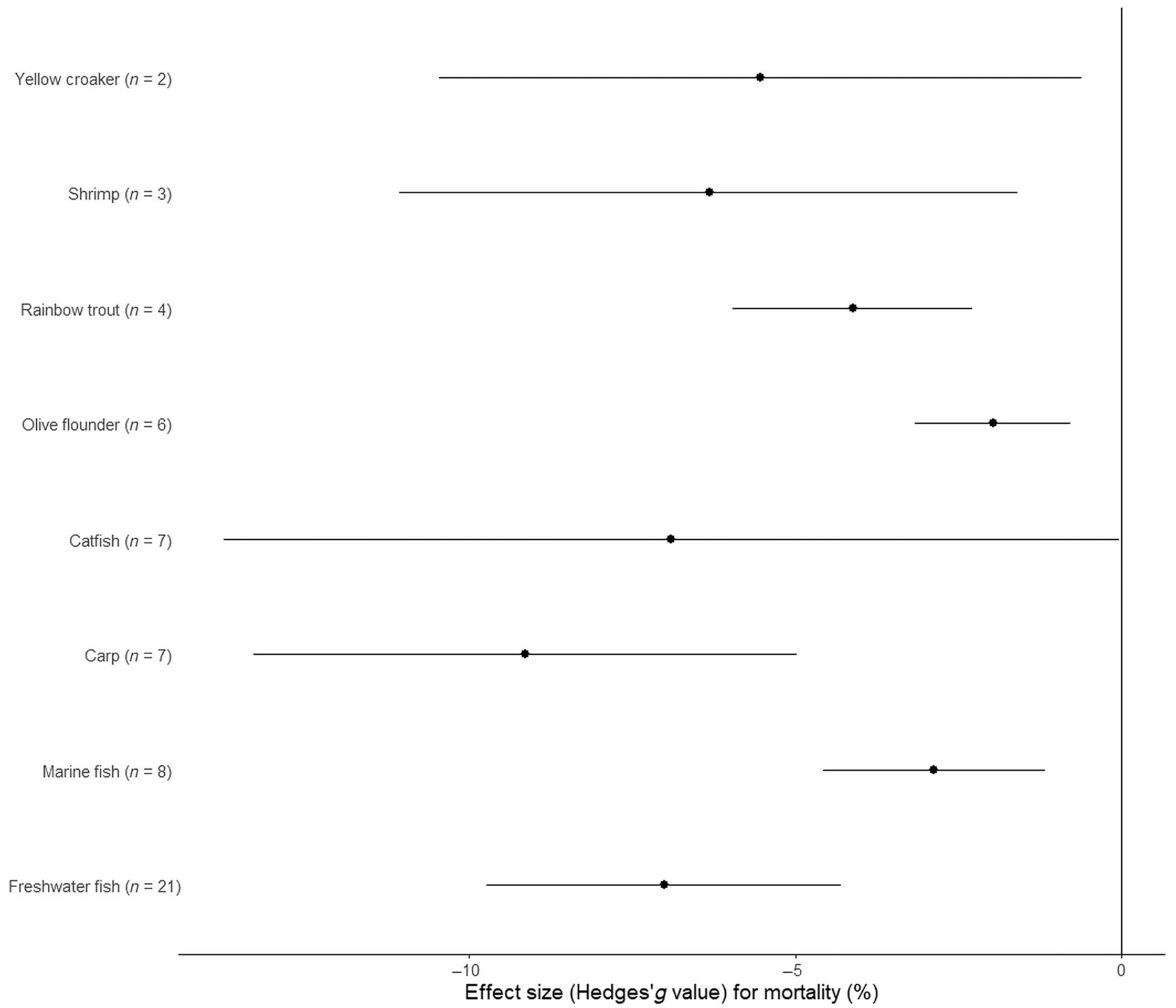

FIGURE 8 Hedge's effect size of mortality after exposure to pathogens. '*n*' indicates the number of comparisons.

Recent studies have evidenced the influence of trophic levels on growth performance, immunity, and disease tolerance in fish.[79] The meta-regression analysis showed a negative correlation between the innate immune response of fish (phagocytic activity and NBT) and trophic level (Figure 8). The absorption of β-glucans has ultimately occurred in the intestine,[38] whose length has a negative relationship with trophic level. Therefore, the higher trophic level fish could be less effective in absorbing this bio-stimulant, thereby immune response.

5 | CONCLUDING REMARKS AND RESEARCH GAPS

The majority of the studies included in this review summarise that β-glucan supplementation improved the immunological properties (lysozyme activity, phagocyte activity, complement activity, respiratory burst activity, and immunoglobin M) as well as reduced mortality among aquaculture species infected with the pathogen. It was found that a number of species, including carp, Caspian trout, yellow croaker, tilapia, pompano, and flounder, responded strongly to the previously mentioned properties when provided with β-glucan supplement. Moreover, our findings concluded that results vary depending on fish species, environment, trophic level, and diet concentration. However, based on the results of this meta-analysis, adding β-glucan has a significant positive effect on the growth performance and immune responses of freshwater fish rather than marine fish. For β-glucan application, our meta-regression models suggest a short feeding period of 8 weeks for lysozyme activity and ACH50, and 3 weeks for NBT, which could provide valuable insights for further research to reduce treatment duration and associated costs. Moreover, there are limited studies examining the effects of adding dietary β-glucans on digestive enzyme activities in aquatic species.[61,63] The findings indicate that β-glucans can modulate digestive enzyme activity in aquatic species, suggesting potential implications for nutrient absorption and overall digestive health in this species. Based on the fact that no information is available about the effect of immunostimulants on the '*good*' gut microbiota with antagonistic activity against fish pathogenic bacteria, this should be a topic of further research, as

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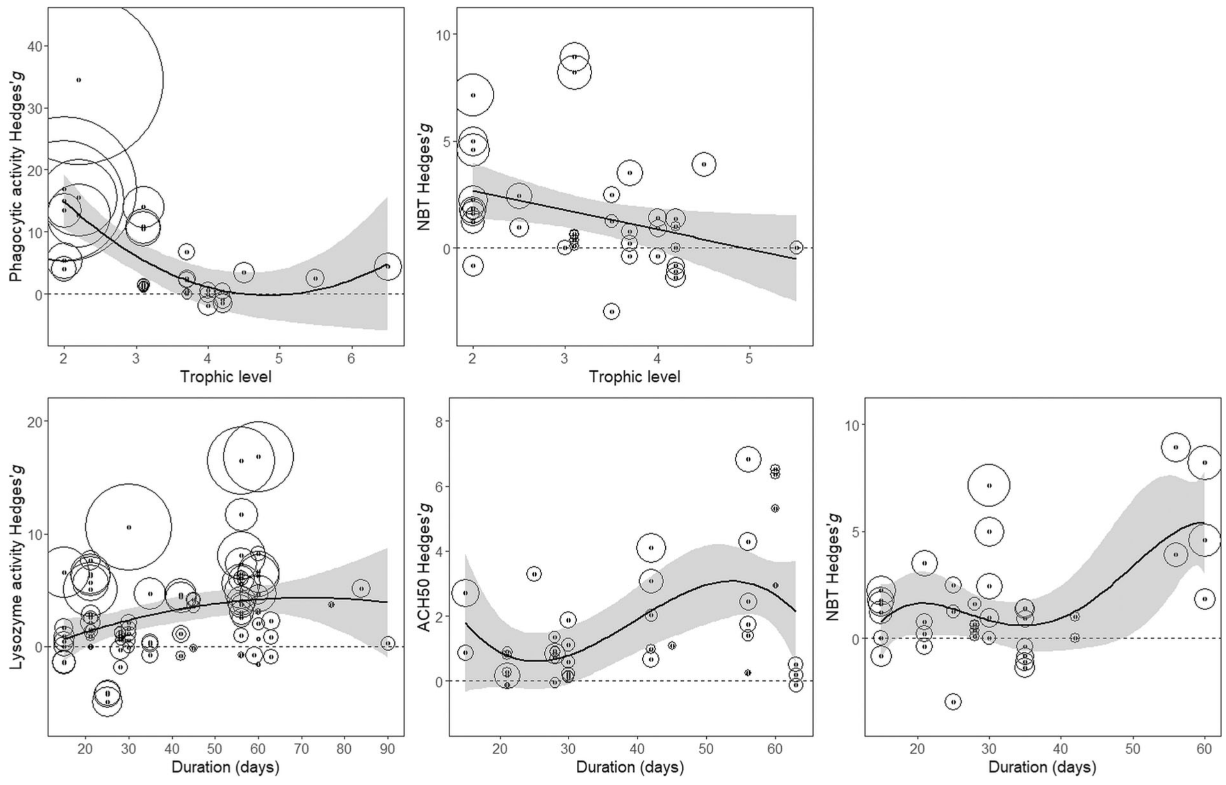

FIGURE 9 Significant correlation between explanatory variables and effect size. The centre and diameter of the circle represent the mean and the 95% confidential interval of effect size.

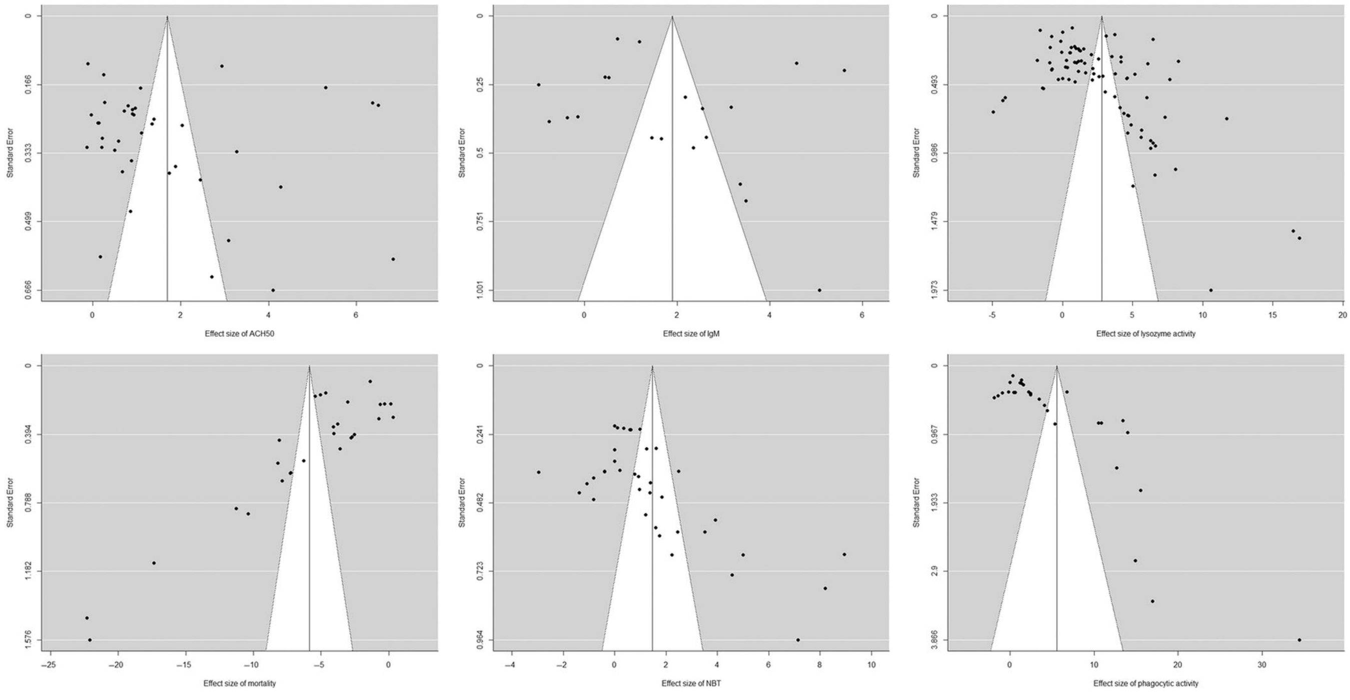

FIGURE 10 Funnel plots to assess the publication bias.

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the gastrointestinal tract in fish is a potential port of entry for pathogenic bacteria.[80]

AUTHOR CONTRIBUTIONS

Hien Van Doan: Conceptualization; investigation; funding acquisition; writing – original draft; validation; visualization; writing – review and editing; software; formal analysis; project administration; data curation; resources. **Md Afsar Ahmed Sumon:** Conceptualization; investigation; writing – original draft; methodology; validation; visualization; writing – review and editing; formal analysis; software; data curation; resources. **Hung Quang Tran:** Conceptualization; investigation; writing – original draft; methodology; validation; visualization; writing – review and editing; software; formal analysis; data curation; resources. **Chinh Xuan Le:** Conceptualization; investigation; writing – original draft; methodology; validation; visualization; writing – review and editing; software; formal analysis; data curation; resources. **Eman Y. Mohammady:** Conceptualization; investigation; writing – original draft; methodology; validation; visualization; writing – review and editing; formal analysis; software; data curation; resources. **Ehab R. El-Haroun:** Conceptualization; investigation; writing – original draft; visualization; writing – review and editing; formal analysis; supervision. **Seyed Hossein Hoseinifar:** Conceptualization; investigation; writing – original draft; methodology; validation; visualization; writing – review and editing; software; formal analysis; supervision. **Einar Ringo:** Conceptualization; investigation; writing – original draft; methodology; validation; visualization; writing – review and editing; software; project administration; supervision; data curation. **Stejskal Vlastimil:** Conceptualization; investigation; writing – original draft; methodology; validation; visualization; writing – review and editing; software; project administration; formal analysis; data curation; supervision. **Mahmoud A. O. Dawood:** Conceptualization; investigation; writing – original draft; writing – review and editing; visualization; project administration; supervision; data curation.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the authors up on request.

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REFERENCES

1. Sumon MAA, Sumon TA, Hussain MA, et al. Single and multi-strain probiotics supplementation in commercially prominent finfish aquaculture: review of the current knowledge. *J Microbiol Biotechnol*. 2022;32(6):681-698. doi:10.4014/jmb.2202.02032
2. Van Doan H, Lumsangkul C, Sringarm K, et al. Impacts of Amla (*Phyllanthus emblica*) fruit extract on growth, skin mucosal and serum immunities, and disease resistance of Nile tilapia (*Oreochromis niloticus*) raised under biofloc system. *Aquac Rep*. 2022;22:100953.
3. Afewerki S, Asche F, Misund B, Thorvaldsen T, Tveteras R. Innovation in the Norwegian aquaculture industry. *Rev Aquac*. 2023;15(2):759-771. doi:10.1111/raq.12755
4. Bu X, Li Y, Lai W, et al. Innovation and development of the aquaculture nutrition research and feed industry in China. *Rev Aquac*. 2024;16(2):759-774. doi:10.1111/raq.12865
5. Verdegem M, Buschmann AH, Latt UW, Dalsgaard AJT, Lovatelli A. The contribution of aquaculture systems to global aquaculture production. *J World Aquac Soc*. 2023;54(2):206-250. doi:10.1111/jwas.12963
6. Fanzo J, Miachon L. Harnessing the connectivity of climate change, food systems and diets: taking action to improve human and planetary health. *Anthropocene*. 2023;42:100381. doi:10.1016/j.ancene.2023.100381
7. Troell M, Costa-Pierce B, Stead S, et al. Perspectives on aquaculture's contribution to the sustainable development goals for improved human and planetary health. *J World Aquac Soc*. 2023;54(2):251-342. doi:10.1111/jwas.12946
8. Rodrigues-Filho JL, Macêdo RL, Sarmento H, et al. From ecological functions to ecosystem services: linking coastal lagoons biodiversity with human well-being. *Hydrobiologia*. 2023;850(12):2611-2653. doi:10.1007/s10750-023-05171-0
9. Naylor RL, Hardy RW, Buschmann AH, et al. A 20-year retrospective review of global aquaculture. *Nature*. 2021;591(7851):551-563. doi:10.1038/s41586-021-03308-6
10. Gonzalez TJ. 'Positive' animal welfare in aquaculture as a cardinal principle for sustainable development. *Front Anim Sci*. 2023;4:1206035. doi:10.3389/fanim.2023.1206035
11. Yue K, Shen Y. An overview of disruptive technologies for aquaculture. *Aquac Fish*. 2022;7(2):111-120. doi:10.1016/j.aaf.2021.04.009
12. Singh BK, Delgado-Baquerizo M, Egidi E, et al. Climate change impacts on plant pathogens, food security and paths forward. *Nat Rev Microbiol*. 2023;21(10):640-656. doi:10.1038/s41579-023-00900-7
13. Mičúchová A, Piačková V, Frébort I, Korytář T. Molecular farming: expanding the field of edible vaccines for sustainable fish aquaculture. *Rev Aquac*. 2022;14(4):1978-2001. doi:10.1111/raq.12683
14. Brunton LA, Desbois AP, Garza M, et al. Identifying hotspots for antibiotic resistance emergence and selection, and elucidating pathways to human exposure: application of a systems-thinking approach to aquaculture systems. *Sci Total Environ*. 2019;687:1344-1356. doi:10.1016/j.scitotenv.2019.06.134
15. Li W, Zeng J, Li Y, Ge C, Su J, Yao H. A fascinating finding: the application of traditional Chinese medicine in aquaculture prevents the spread and diffusion of antibiotic resistance genes among gut microbes. *Aquaculture*. 2024;583:740573. doi:10.1016/j.aquaculture.2024.740573
16. Suyamud B, Chen Y, Quyen DTT, Dong Z, Zhao C, Hu J. Antimicrobial resistance in aquaculture: occurrence and strategies in Southeast Asia. *Sci Total Environ*. 2024;907:167942. doi:10.1016/j.scitotenv.2023.167942
17. Caputo A, Bondad-Reantaso MG, Karunasagar I, et al. Antimicrobial resistance in aquaculture: a global analysis of literature and national action plans. *Rev Aquac*. 2023;15(2):568-578. doi:10.1111/raq.12741
18. Devadas S, Zakaria Z, Shariff M, Bhassu S, Karim M, Natrah I. Methodologies and standards for monitoring antimicrobial use and antimicrobial resistance in shrimp aquaculture. *Aquaculture*. 2024;579:740216. doi:10.1016/j.aquaculture.2023.740216
19. Okeke ES, Chukwudozie KI, Nyaruaba R, et al. Antibiotic resistance in aquaculture and aquatic organisms: a review of current

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nanotechnology applications for sustainable management. *Environ Sci Pollut Res Int*. 2022;29(46):69241-69274. doi:10.1007/s11356-022-22319-y
20. Sumon MAA, Molla MHR, Hakeem IJ, et al. Epigenetics and probiotics application toward the modulation of fish reproductive performance. *Fishes*. 2022;7(4):189.
21. Noman M, Kazmi SSUH, Saqib HSA, et al. Harnessing probiotics and prebiotics as eco-friendly solution for cleaner shrimp aquaculture production: a state of the art scientific consensus. *Sci Total Environ*. 2024;915:169921. doi:10.1016/j.scitotenv.2024.169921
22. Dien LT, Ngo TPH, Nguyen TV, et al. Non-antibiotic approaches to combat motile Aeromonas infections in aquaculture: current state of knowledge and future perspectives. *Rev Aquac*. 2023;15(1):333-366. doi:10.1111/raq.12721
23. Bondad-Reantaso MG, MacKinnon B, Karunasagar I, et al. Review of alternatives to antibiotic use in aquaculture. *Rev Aquac*. 2023;15(4):1421-1451. doi:10.1111/raq.12786
24. Mondal H, Thomas J. A review on the recent advances and application of vaccines against fish pathogens in aquaculture. *Aquac Int*. 2022;30(4):1971-2000. doi:10.1007/s10499-022-00884-w
25. Du Y, Hu X, Miao L, Chen J. Current status and development prospects of aquatic vaccines. *Front Immunol*. 2022;13:1040336. doi:10.3389/fimmu.2022.1040336
26. Hoseinifar SH, Ashouri G, Marisaldi L, et al. Reducing the use of antibiotics in European aquaculture with vaccines, functional feed additives and optimization of the gut microbiota. *J Mar Sci Eng*. 2024;12(2):204.
27. Wei LS, Goh KW, Abdul Hamid NK, Abdul Kari Z, Wee W, Van Doan H. A mini-review on co-supplementation of probiotics and medicinal herbs: application in aquaculture. *Front Vet Sci*. 2022;9:869564. doi:10.3389/fvets.2022.869564
28. Van Doan H, Prakash P, Hoseinifar SH, et al. Marine-derived products as functional feed additives in aquaculture: a review. *Aquac Rep*. 2023;31:101679. doi:10.1016/j.aqrep.2023.101679
29. Mathan Muthu CM, Vickram AS, Bhavani Sowndharya B, Saravanan A, Kamalesh R, Dinakarkumar Y. A comprehensive review on the utilization of probiotics in aquaculture towards sustainable shrimp farming. *Fish Shellfish Immunol*. 2024;147:109459. doi:10.1016/j.fsi.2024.109459
30. Wee W, Abdul Hamid NK, Mat K, et al. The effects of mixed prebiotics in aquaculture: a review. *Aquac Fish*. 2024;9(1):28-34. doi:10.1016/j.aaf.2022.02.005
31. Rahar S, Swami G, Nagpal N, Nagpal MA, Singh GS. Preparation, characterization, and biological properties of β-glucans. *J Adv Pharm Technol Res*. 2011;2(2):94-103. doi:10.4103/2231-4040.82953
32. Caseiro C, Dias JNR, de Andrade Fontes CMG, Bule P. From cancer therapy to winemaking: the molecular structure and applications of β-glucans and β-1,3-glucanases. *Int J Mol Sci*. 2022;23(6):3156.
33. Tian J, Yang Y, Xu W, et al. Effects of β-1,3-glucan on growth, immune responses, and intestinal microflora of the river prawn (*Macrobrachium nipponense*) and its resistance against *Vibrio parahaemolyticus*. *Fish Shellfish Immunol*. 2023;142:109142. doi:10.1016/j.fsi.2023.109142
34. Arciuch-Rutkowska M, Nowosad J, Łuczyński MK, Jasiński S, Kucharczyk D. Effects of the diet enrichment with β-glucan, sodium salt of butyric acid and vitamins on growth parameters and the profile of the gut microbiome of juvenile African catfish (*Clarias gariepinus*). *Anim Feed Sci Technol*. 2024;310:115941. doi:10.1016/j.anifeedsci.2024.115941
35. Rodrigues MV, Zanuzzo FS, Koch JFA, de Oliveira CAF, Sima P, Vetvicka V. Development of fish immunity and the role of β-glucan in immune responses. *Molecules*. 2020;25(22):5378. doi:10.3390/MOLECULES25225378
36. Liu Y, Wu Q, Wu X, et al. Structure, preparation, modification, and bioactivities of β-glucan and mannan from yeast cell wall: a review. *Int J Biol Macromol*. 2021;173:445-456. doi:10.1016/j.ijbiomac.2021.01.125
37. Huo X, Wang P, Zhao F, et al. Revitalizing pond culture system: harnessing the power of composite nanopeptide CI20, 1,3-1,6-β-glucan, and anthocyanidin biotherapy as an antibiotic substitute for efficient management of bacterial diseases in bullfrogs. *Aquaculture*. 2024;581:740394. doi:10.1016/j.aquaculture.2023.740394
38. Ching JJ, Shuib AS, Abdul Majid N, Mohd TN. Immunomodulatory activity of β-glucans in fish: relationship between β-glucan administration parameters and immune response induced. *Aquac Res*. 2021;52(5):1824-1845. doi:10.1111/are.15086
39. Singh RP, Bhardwaj A. β-Glucans: a potential source for maintaining gut microbiota and the immune system. *Front Nutr*. 2023;10:1143682. doi:10.3389/fnut.2023.1143682
40. Jang HY, Jung SJ, Park EO, et al. TBG-136, a Schizophyllum commune-derived β-glucan benefits gut microbiota and intestinal health: a randomized, double-blind, and placebo-controlled clinical trial. *J Funct Foods*. 2023;107:107105668. doi:10.1016/j.jff.2023.105668
41. Zhang Y, Guo M, Li N, et al. New insights into β-glucan-enhanced immunity in largemouth bass *Micropterus salmoides* by transcriptome and intestinal microbial composition. *Front Immunol*. 2022;13:1086103. doi:10.3389/fimmu.2022.1086103
42. Hadiuzzaman M, Moniruzzaman M, Shahjahan M, Bai SC, Min T, Hossain Z. β-Glucan: mode of action and its uses in fish immunomodulation. *Front Mar Sci*. 2022;9:905986. doi:10.3389/fmars.2022.905986
43. Machuca C, Méndez-Martínez Y, Reyes-Becerril M, Angulo C. Yeast β-glucans as fish immunomodulators: a review. *Animals*. 2022;12(16):2154.
44. Deeks JJ, Higgins JP, Altman DG, Cochrane CSM. Analysing data and undertaking meta-analyses. In: Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA, eds. *Cochrane Handbook for Systematic Reviews of Interventions*. 2019. doi:10.1002/9781119536604.ch10
45. Eng C, Kramer CK, Zinman B, Retnakaran R. Glucagon-like peptide-1 receptor agonist and basal insulin combination treatment for the management of type 2 diabetes: a systematic review and meta-analysis. *Lancet*. 2014;384(9961):2228-2234. doi:10.1016/s0140-6736(14)61335-0
46. Guo J, Bao Y, Davis R, Abebe A, Wilson AE, Davis DA. Application of meta-analysis towards understanding the effect of adding a methionine hydroxy analogue in the diet on growth performance and feed utilization of fish and shrimp. *Rev Aquac*. 2020;12(4):2316-2332. doi:10.1111/raq.12436
47. Higgins JPT, Thompson SG. Quantifying heterogeneity in a meta-analysis. *Stat Med*. 2002;21(11):1539-1558. doi:10.1002/sim.1186
48. Anton A, Geraldi NR, Lovelock CE, et al. Global ecological impacts of marine exotic species. *Nat Ecol Evol*. 2019;3(5):787-800. doi:10.1038/s41559-019-0851-0
49. Meena DK, Das P, Kumar S, et al. Beta-glucan: an ideal immunostimulant in aquaculture (a review). *Fish Physiol Biochem*. 2013;39(3):431-457. doi:10.1007/s10695-012-9710-5
50. Rojo-Cebreros AH, Ibarra-Castro L, Martínez-Brown JM. Immunostimulation and trained immunity in marine fish larvae. *Fish Shellfish Immunol*. 2018;80:15-21. doi:10.1016/j.fsi.2018.05.044
51. Song SK, Beck BR, Kim D, et al. Prebiotics as immunostimulants in aquaculture: a review. *Fish Shellfish Immunol*. 2014;40(1):40-48. doi:10.1016/j.fsi.2014.06.016
52. Guluarte C, Pereyra A, Ramírez-Hernández E, Zenteno E, Luis S-SJ. The immunomodulatory and antioxidant effects of β-glucans in invertebrates. *J Invertebr Pathol*. 2023;201:108022. doi:10.1016/j.jip.2023.108022
53. Renke G, Baesso T, Paes R, Renke A. β-Glucan "trained immunity" immunomodulatory properties potentiate tissue wound management

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and accelerate fitness recover. *Immunotargets Ther*. 2022;11:67-73. doi:10.2147/itt.S381145
54. Gu Y, Zhu L, Wang X, Li H, Hou L, Kong X. Research progress of pattern recognition receptors in red swamp crayfish (*Procambarus clarkii*). *Fish Shellfish Immunol*. 2023;141:109028. doi:10.1016/j.fsi.2023.109028
55. Han B, Baruah K, Cox E, Vanrompay D, Bossier P. Structure-functional activity relationship of β-glucans from the perspective of immunomodulation: a mini-review. *Front Immunol*. 2020;11:00658. doi:10.3389/fimmu.2020.00658
56. Netea MG, Domínguez-Andrés J, Barreiro LB, et al. Defining trained immunity and its role in health and disease. *Nat Rev Immunol*. 2020;20(6):375-388.
57. Dawood MAO, Eweedah NM, Moustafa EM, Shahin MG. Synbiotic effects of *Aspergillus oryzae* and β-glucan on growth and oxidative and immune responses of Nile Tilapia, *Oreochromis niloticus*. *Probiotics Antimicrob Proteins*. 2019;12:172-183. doi:10.1007/s12602-018-9513-9
58. Dawood MAO, Koshio S, El-Sabagh M, et al. Changes in the growth, humoral and mucosal immune responses following β-glucan and vitamin C administration in red sea bream, *Pagrus major*. *Aquaculture*. 2017;470:214-222. doi:10.1016/j.aquaculture.2016.12.036
59. Misra CK, Das BK, Mukherjee SC, Pattnaik P. Effect of long term administration of dietary β-glucan on immunity, growth and survival of *Labeo rohita* fingerlings. *Aquaculture*. 2006;255(1):82-94. doi:10.1016/j.aquaculture.2005.12.009
60. Welker TL, Lim C, Yildirim-Aksoy M, Klesius PH. Use of diet crossover to determine the effects of β-glucan supplementation on immunity and growth of Nile tilapia, *Oreochromis niloticus*. *J World Aquac Soc*. 2012;43(3):335-348. doi:10.1111/j.1749-7345.2012.00569.x
61. Cigarroa-Ruiz L, Toledo-Solís F, Frías-Gómez S, et al. Addition of β-glucans in diets for tropical gar (*Atractosteus tropicus*) larvae: effects on growth, digestive enzymes and gene expression of intestinal epithelial integrity and immune system. *Fish Physiol Biochem*. 2023;49(4):613-626.
62. Li H, Xu C, Zhou L, et al. Beneficial effects of dietary β-glucan on growth and health status of Pacific white shrimp *Litopenaeus vannamei* at low salinity. *Fish Shellfish Immunol*. 2019;91:315-324. doi:10.1016/j.fsi.2019.05.052
63. Nieves-Rodríguez KN, Álvarez-González CA, Peña-Marín ES, et al. 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*. 2018;3(3):27.
64. Bano S, Khan N, Fatima M, et al. Enhancing farmed striped catfish (*Pangasianodon hypophthalmus*) robustness through dietary β-glucan. *PLoS One*. 2024;19(3 March):e0298414. doi:10.1371/journal.pone.0298414
65. Ciji A, Tripathi PH, Pandey A, Akhtar MS. Expression of genes encoding non-specific immunity, anti-oxidative status and aquaporins in β-glucan-fed golden mahseer (*Tor putitora*) juveniles under ammonia stress. *Fish Shellfish Immunol Rep*. 2023;4:4100100. doi:10.1016/j.fsirep.2023.100100
66. De Lima ECS, De Souza FP, Furlan-Murari PJ, et al. Effects of dietary β-glucans on the productive performance, blood parameters, and intestinal microbiota of angelfish (*Pterophyllum scalare*) juveniles. *Anais Acad Bras Cienc*. 2024;96(1):e20231006. doi:10.1590/0001-3765202420231006
67. Pooljun C, Jariyapong P, Wongtawan T, Hirono I, Wuthisuthimethavee S. Effect of feeding different types of β-glucans derived from two marine diatoms (*Chaetoceros muelleri* and *Thalassiosira weissflogii*) on growth performance and immunity of banana shrimp (*Penaeus merguiensis*). *Fish Shellfish Immunol*. 2022;130:512-519. doi:10.1016/j.fsi.2022.09.047
68. Qiao Y, Han F, Lu K, Zhou L, Rombenso A, Li E. Effects of dietary β-glucan feeding strategy on the growth, physiological response, and gut microbiota of Pacific white shrimp, *Litopenaeus vannamei*, under low salinity. *Animals*. 2023;13(24):3778. doi:10.3390/ani13243778
69. Qiao Y, Zhou L, Qu Y, Lu K, Han F, Li E. Effects of different dietary β-glucan levels on antioxidant capacity and immunity, gut microbiota and transcriptome responses of white shrimp (*Litopenaeus vannamei*) under low salinity. *Antioxidants*. 2022;11(11):2282. doi:10.3390/antiox11112282
70. Tian J, Yang Y, Du X, et al. Effects of dietary soluble β-1,3-glucan on the growth performance, antioxidant status, and immune response of the river prawn (*Macrobrachium nipponense*). *Fish Shellfish Immunol*. 2023;138:138108848. doi:10.1016/j.fsi.2023.108848
71. Del Rio-Zaragoza O, Fajer-Ávila E, Almazán-Rueda P. Influence of β-glucan on innate immunity and resistance of *Lutjanus guttatus* to an experimental infection of dactylogyrid monogeneans. *Parasite Immunol*. 2011;33(9):483-494.
72. Ogier de Baulny M, Quentel C, Fournier V, Lamour F, Le Gouvello R. Effect of long-term oral administration of beta-glucan as an immunostimulant or an adjuvant on some non-specific parameters of the immune response of turbot *Scophthalmus maximus*. *Dis Aquatic Org*. 1996;26(2):139-147.
73. Jami MJ, Abedian Kenari A, Paknejad H, Mohseni M. Effects of dietary b-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 Immunol*. 2019;91:202-208. doi:10.1016/j.fsi.2019.05.024
74. Nguyen TM, Mandiki SNM, Tran TNT, et al. Growth performance and immune status in common carp *Cyprinus carpio* as affected by plant oil-based diets complemented with β-glucan. *Fish Shellfish Immunol*. 2019;92:288-299. doi:10.1016/j.fsi.2019.06.011
75. Douxfils J, Fierro-Castro C, Mandiki S, Emile W, Tort L, Kestemont P. Dietary β-glucans differentially modulate immune and stress-related gene expression in lymphoid organs from healthy and *Aeromonas hydrophila*-infected rainbow trout (*Oncorhynchus mykiss*). *Fish Shellfish Immunol*. 2017;63:285-296.
76. Petit J, Wiegertjes GF. Long-lived effects of administering β-glucans: indications for trained immunity in fish. *Dev Comp Immunol*. 2016;64:93-102. doi:10.1016/j.dci.2016.03.003
77. Elmowalid GA, Ghonimi WAM, Abd Allah HM, Abdallah H, El-Murr A, Abdelwahab AM. β-1,3-Glucan improved the health and immunity of juvenile African catfish (*Clarias gariepinus*) and neutralized the histological changes caused by lead and fipronil pollutants. *BMC Vet Res*. 2023;19(1):45. doi:10.1186/s12917-023-03585-5
78. Fierro-Castro C, Tort L, Mingatto FE, Biller JD. Assessing the effect of β-glucan diets on innate immune response of tilapia macrophages against trichlorfon exposure: an in vitro study. *Fish Physiol Biochem*. 2024;50(2):527-541. doi:10.1007/s10695-023-01283-5
79. Reverter M, Tapissier-Bontemps N, Sarter S, Sasal P, Caruso D. Moving towards more sustainable aquaculture practices: a meta-analysis on the potential of plant-enriched diets to improve fish growth, immunity and disease resistance. *Rev Aquac*. 2021;13(1):537-555. doi:10.1111/raq.12485
80. Birkbeck T, Ringø E. Pathogenesis and the gastrointestinal tract of growing fish. In: Holzapfel W, Naughton P, eds. *Microbial Ecology in Growing Animals*. Elsevier; 2005:208-234.

SUPPORTING INFORMATION

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