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FUNCTIONAL FEED ADDITIVES IN FINFISH AQUACULTURE: GUT HEALTH, IMMUNITY, AND DISEASE RESISTANCE

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ABSTRACT

The intensification of finfish aquaculture has increased the demand for functional nutritional strategies that support growth, gut health, immune competence, and disease resilience while reducing dependence on antibiotics. This narrative review synthesizes peer-reviewed evidence published between 2020 and 2026 on probiotics, prebiotics, synbiotics, phytogenic compounds, essential oils, yeast derivatives, beta-glucans, nucleotides, organic acids, enzymes, seaweed metabolites, and multi-component blends. Current evidence indicates that these additives can improve feed utilization, digestive function, gut microbial balance, mucosal immunity, antioxidant defense, and resistance to pathogen challenge. Their effects, however, depend on additive type, dose, formulation stability, feeding duration, fish species, life stage, rearing conditions, and basal diet composition. Rather than treating functional additives as generic supplements, this review emphasizes their selection according to specific biological targets and production constraints. A precision aquafeed approach that integrates mechanistic understanding with dose-response evaluation, formulation stability, economic feasibility, and farm-scale validation is needed to develop safe, reproducible, and practical functional feeds for sustainable aquaculture.

Keywords: functional feed additives, precision aquafeed, finfish aquaculture, gut microbiota, disease resistance.

INTRODUCTION

Finfish aquaculture is increasingly expected to supply high-quality animal protein under conditions of intensifying production, increasing disease pressure, rising feed costs, environmental variability, and stricter expectations for responsible antimicrobial use. In intensive farming systems, fish are frequently exposed to high stocking densities, fluctuating water quality, altered microbial communities, pathogen pressure, and nutritionally complex formulated feeds. Under these conditions, nutrition is no longer viewed solely as a means of supporting growth, but also as a central component of preventive health management. Functional nutrition in aquaculture refers to the strategic use of nutrients and feed additives that provide physiological benefits beyond basal nutrient supply, particularly in relation to immunity, gut health, antioxidant defense, stress tolerance, disease resistance, and growth performance (Onomu & Okuthe, 2024; Hoseinifar *et al.*, 2024; Marimuthu *et al.*, 2022). The shift toward functional feed additives has been accelerated by concerns over antibiotic residues, antimicrobial resistance, recurrent disease outbreaks, and regulatory restrictions on antimicrobial growth promotion. Recent reviews and experimental studies have positioned probiotics, prebiotics, synbiotics, phytogenic compounds, organic acids, beta-glucans, nucleotides, yeast products, seaweed metabolites, enzymes, and immunostimulant blends as promising alternatives or complements to therapeutic disease control (Cain, 2022; Hoseinifar *et al.*, 2024; Onomu & Okuthe, 2024).

These additives differ in origin, composition, stability, and biological targets. Probiotics can modulate the intestinal microbiota and produce bioactive metabolites; prebiotics selectively support beneficial microbial functions; synbiotics combine microbial and substrate-based effects; phytogenic compounds may act through antioxidant, antimicrobial, anti-inflammatory, and appetite-modulating pathways; beta-glucans and yeast cell wall components can activate innate immune receptors; organic acids can alter gut pH and suppress acid-sensitive pathogens; and seaweed-derived metabolites can provide polysaccharides, polyphenols, minerals, and antioxidant molecules (Firmino *et al.*, 2021a; Khanjani *et al.*, 2022; Siddik *et al.*, 2023; Vijayaram *et al.*, 2023). Gut health has become a central concept in modern aquaculture nutrition because the fish intestine functions simultaneously as a digestive, absorptive, immune, endocrine, and microbial interface. When the intestinal barrier is stable, villus architecture is preserved, digestive enzymes are active, mucus and goblet cell functions are intact, and microbial communities remain balanced, fish can allocate more metabolic energy to growth rather than inflammation or stress recovery. Conversely, dysbiosis, enteritis, oxidative stress, epithelial damage, and pathogen adhesion can reduce feed efficiency, impair nutrient absorption, and weaken systemic and mucosal immunity (Firmino *et al.*, 2021b; Martínez-Porchas *et al.*, 2023; Guerreiro *et al.*, 2024). Therefore, functional feed additives should be evaluated not only by growth response, but also by their ability to maintain intestinal integrity, immune readiness, microbial balance, and resilience under production stress.

For tropical aquaculture systems, including those relevant to Indonesia, this issue is particularly important. Major cultured finfish such as tilapia, catfish, carp, gourami, milkfish, and marine groupers are commonly produced in systems where feed cost, bacterial disease, water-quality fluctuation, and inconsistent use of health-promoting additives can influence profitability. Although global studies provide a strong evidence base, the application of functional additives in tropical aquaculture requires careful attention to species, local feed ingredients, farmer adoption, additive cost, environmental conditions, and field-level reproducibility. This practical context highlights the need for a synthesis that connects biological mechanisms with formulation decisions and farm-scale applicability.

Despite the rapid expansion of literature on functional aquafeeds, the evidence remains fragmented across additive categories, fish species, biological endpoints, and production contexts. Several recent reviews have discussed probiotics, prebiotics, phytogenics, gut microbiota, immune modulation, and antibiotic-reduction strategies in aquaculture (Hasan & Banerjee, 2020; Puri *et al.*, 2022; Hoseinifar *et al.*, 2024; Onomu & Okuthe, 2024). However, many reviews still emphasize additive categories or general mechanisms, whereas fewer syntheses connect additive selection with biological targets, formulation constraints, methodological reliability, and farm-level feasibility. This review addresses that gap by integrating recent evidence across functional additive categories within a precision aquafeed framework and by evaluating probiotics, phytogenics, yeast derivatives, organic acids, enzymes, seaweed metabolites, and immunostimulant blends as context-dependent nutritional tools rather than interchangeable supplements. The novelty of this review therefore lies not in introducing a new additive class, but in organizing recent evidence into an integrated and application-oriented framework for precision functional nutrition in finfish aquaculture. By connecting biological mechanisms with dose, species, feed matrix, rearing system, methodological limitations, and practical implementation, this review provides a clearer basis for selecting functional additives according to defined production objectives. Accordingly, this review aims to synthesize recent evidence on functional feed additives in finfish aquaculture, with emphasis on their roles in modulating gut health, immunity, disease resistance, and growth performance, while identifying practical implications and research priorities for sustainable aquafeed development.

REVIEW METHODOLOGY

This article was designed as a narrative literature review with a structured and transparent selection logic. The review aimed to synthesize recent evidence on functional feed additives in finfish aquaculture, particularly their effects on gut health, immune response, disease resistance, antioxidant defense, digestive physiology, and growth performance. Although this study did not follow a full systematic review or meta-analysis protocol, the literature identification and screening process was organized to improve reproducibility and reduce selection bias. Relevant literature was searched using major scientific databases, including Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink, Wiley Online Library, MDPI, Frontiers, Taylor & Francis Online, and Google Scholar. The search focused on peer-reviewed publications published between 2020 and 2026. Older references were used only when they provided essential conceptual background or were directly relevant to defining key additive classes. The search strategy combined terms related to aquaculture species, functional nutrition, feed additives, and physiological outcomes. Examples of search strings included “functional feed additives” AND fish OR aquaculture, “probiotic” AND fish AND gut microbiota, “prebiotic OR synbiotic” AND finfish AND immunity, “phytogenic OR essential oil” AND aquaculture AND disease resistance, “beta-glucan OR yeast” AND fish AND immune response, “organic acid OR enzyme” AND aquafeed AND digestibility, and “seaweed metabolite” AND fish AND antioxidant response.

The initial search identified publications across experimental studies, review articles, meta-analyses, and mechanistic papers related to functional nutrition in aquaculture. Titles and abstracts were first screened to exclude articles that were unrelated to finfish aquaculture, did not address feed-based interventions, focused exclusively on terrestrial livestock, or lacked relevance to gut health, immunity, disease resistance, digestive physiology, antioxidant defense, or growth. Full texts were then examined to determine whether the articles provided sufficient information on additive type, fish species, inclusion level or dose, feeding duration, biological endpoints, and practical implications for aquafeed formulation. Studies were considered eligible when they met at least one of the following criteria: (1) evaluated dietary probiotics, prebiotics, synbiotics, yeast-derived products, beta-glucans, nucleotides, phytogenic compounds, essential oils, organic acids, enzymes, seaweed-derived metabolites, or other functional additives in finfish aquaculture; (2) reported outcomes related to growth performance, feed utilization, digestive enzyme activity, intestinal morphology, gut microbiota, immune response, antioxidant status, stress tolerance, or pathogen resistance; or (3) provided recent review-based, mechanistic, or meta-analytical evidence relevant to functional nutrition and aquafeed formulation. Priority was given to studies that clearly described the additive type, fish species, feeding duration, inclusion level, biological endpoints, and practical implications for aquaculture nutrition.

Articles were excluded when they did not address aquaculture nutrition, were not directly related to finfish or aquatic feed additives, focused exclusively on terrestrial animals without clear mechanistic relevance to aquafeeds, lacked sufficient bibliographic information, or did not report outcomes relevant to gut health, immunity, disease resistance, digestive physiology, antioxidant defense, or growth. Studies dealing with broader aquaculture health management were retained only when they provided conceptual support for functional nutrition, antimicrobial reduction, preventive disease-control strategies, or sustainable aquafeed development. To strengthen the reliability of the synthesis, the methodological quality and relevance of each study were assessed narratively.

Particular attention was given to whether the study reported additive characterization, dose or inclusion level, fish species and life stage, feeding duration, replication, control treatment, growth and health-related endpoints, microbiological or immunological methods, and disease- or stress-challenge validation. Studies with clearer additive descriptions, appropriate controls, multiple biological endpoints, and practical implications were given greater interpretive weight. Operationally, this qualitative weighting was based on the completeness of additive identification, dose design, replication and control structure, endpoint integration, and the presence of challenge-test or farm-relevant validation. In contrast, studies with single-dose designs, limited replication, incomplete additive characterization, or outcomes restricted to short-term growth response were interpreted more cautiously. The final synthesis retained the reference set available in the draft manuscript and organized the evidence by additive class and biological target. The main additive groups included probiotics, prebiotics, synbiotics, phytogenic compounds, essential oils, yeast derivatives, beta-glucans, nucleotides, organic acids, enzymes, seaweed metabolites, and multi-component immunostimulant blends. The biological targets used for integration were gut microbiota modulation, mucosal immunity, antioxidant defense, digestive efficiency, stress resilience, disease resistance, and growth performance. Because the reviewed studies differed substantially in fish species, life stage, additive formulation, inclusion level, feeding duration, rearing conditions, basal diet composition, and challenge model, a quantitative meta-analysis was not conducted. Instead, this review provides a critical narrative synthesis aimed at identifying consistent findings, context-dependent responses, methodological limitations, practical implications, and research priorities for precision functional aquafeed development.

FUNCTIONAL FEED ADDITIVES AS PREVENTIVE HEALTH TOOLS

Functional nutrition should be interpreted as a preventive, system-level intervention rather than a narrow supplementation practice. Conventional feed formulation prioritizes protein, lipid, carbohydrate, energy, vitamin, and mineral requirements. Functional feed formulation adds another layer by asking whether the diet can improve physiological resilience under biological challenge. In this context, feed additives are not expected simply to increase weight gain under ideal laboratory conditions; they should help maintain performance under stress, low-fishmeal diets, pathogen exposure, thermal challenge, salinity fluctuation, or gut inflammatory pressure (Cain, 2022; Hoseini *et al.*, 2025; Yousefi *et al.*, 2025). The most defensible framework is not “one additive equals one outcome,” but additive-host-microbiome-environment interaction. Fish species differ in trophic level, digestive anatomy, gut transit time, endogenous enzyme profile, microbial community, mucosal immune organization, and tolerance to plant-based feed ingredients. Carp, tilapia, catfish, trout, seabream, seabass, flounder, grouper, eel, and largemouth bass may respond differently to the same additive. Likewise, the same additive can have different effects depending on dose, strain viability, feed processing, inclusion period, basal diet composition, and environmental conditions (Du *et al.*, 2021; Guerreiro *et al.*, 2024; Puri *et al.*, 2022).

A precision approach is therefore required. Researchers and feed formulators should identify which additive works for which species, at which dose, in which feed matrix, under which stressor, and through which biological pathway. This is important because several studies report beneficial effects, whereas others show neutral or inconsistent outcomes, especially for growth performance when fish are not challenged or when inclusion levels are suboptimal (Ke *et al.*, 2021; Özel *et al.*, 2023; Guerreiro *et al.*, 2024). Functional additives should be interpreted as preventive nutritional tools whose value depends on how well their dominant biological function matches a production problem. For example, microbial additives are most relevant when microbiota stabilization and mucosal signaling are targeted; phytogenic compounds are often more suitable for antioxidant, antimicrobial, anti-inflammatory, and palatability-related functions; yeast derivatives, beta-glucans, and nucleotides are commonly associated with immune priming and epithelial support; whereas organic acids and enzymes are more directly linked to digestibility and microbial control (Khanjani *et al.*, 2022; Mohan *et al.*, 2022; Siddik *et al.*, 2023; Sultana *et al.*, 2024). This functional classification avoids treating diverse additives as interchangeable supplements. This classification also provides the basis for organizing the following sections by additive category and dominant biological target.

MICROBIAL STRATEGIES: PROBIOTICS, PREBIOTICS, AND SYNBIOTICS

Probiotics

Probiotics are among the most extensively investigated functional additives in fish nutrition. They are live microorganisms administered in adequate amounts to confer host benefit, typically through modulation of gut microbiota, digestive enzyme production, pathogen exclusion, immune stimulation, short-chain fatty acid production, and improvement of epithelial barrier integrity (Hasan & Banerjee, 2020; Puri *et al.*, 2022; Vijayaram *et al.*, 2024). In aquaculture, probiotic candidates include Bacillus, Lactobacillus, Lactococcus, Leuconostoc, Enterococcus, Saccharomyces, fungi, and actinobacteria (Ghosh *et al.*, 2023). A major advantage of Bacillus species is spore formation, which improves survival during feed processing, storage, gastric passage, and variable water conditions. Studies on largemouth bass, yellow catfish, red sea bream, tilapia, and other species show that dietary Bacillus supplementation may improve growth performance, feed conversion, digestive enzyme activity, intestinal morphology, innate immune markers, and resistance to pathogens (Du *et al.*, 2021; Jang *et al.*, 2022; Xue *et al.*, 2022; Vijayaram *et al.*, 2024). Jang *et al.* (2022), for instance, linked *Bacillus* sp. PM8313 combined with beta-glucan to modulation of intestinal microbiota, growth, immunity, and disease resistance in red sea bream. Xue *et al.* (2022) reported that dietary *Bacillus amyloliquefaciens* affected growth, immune responses, intestinal microbiota composition, and disease resistance in yellow catfish. Lactic acid bacteria remain another important probiotic category. LAB can produce organic acids, bacteriocins, and metabolites that suppress pathogens, reinforce mucosal immunity, and modulate gut microbial balance. Paritova *et al.* (2024) evaluated two-strain probiotics, Leuconostoc mesenteroides and Lactococcus lactis, in Nile tilapia and reported effects on growth performance, immune response, and gut microbiota. Paritova *et al.* (2025) extended this direction in African catfish by focusing on multistrain probiotics and their effects on gut microbiota, immunological response, and growth performance. Yasmin *et al.* (2024) examined *Lactobacillus plantarum* GCLP4 derived from grass carp gut and reported modulation of growth, digestive enzymes, and immune-biochemical parameters in rohu fingerlings.

Autochthonous probiotics are theoretically attractive because they may be better adapted to fish intestinal conditions than allochthonous strains. Liu *et al.* (2021) showed that autochthonous probiotics could alleviate adverse effects of dietary histamine in juvenile grouper, suggesting that probiotic utility may extend beyond general growth promotion into mitigation of diet-induced gut stress. Ghori *et al.* (2022) also emphasized gut microbiome modulation as a pathway through which probiotics improve growth and health in rohu. Despite promising results, probiotic efficacy remains strain-specific and context-dependent. The term probiotic is not a mechanistic guarantee. A Bacillus strain that improves digestive enzyme activity in one fish may not colonize or persist in another. LAB strains may reduce microbial diversity in some contexts while increasing beneficial taxa in others. Probiotic responses also depend on basal diet composition, inclusion level, rearing water microbiota, and challenge conditions (Hasan *et al.*, 2023; Martínez-Porchas *et al.*, 2023). Publication-quality probiotic studies should therefore report strain identity, origin, viability, inclusion dose, feed-processing survival, feeding duration, gut colonization evidence, microbiome sequencing methods, and immune and growth endpoints. Probiotic efficacy should therefore be interpreted at the strain level rather than at the genus or species level. A defensible probiotic study should report strain identity, origin, viability, delivery method, feeding period, and evidence of biological activity in the host intestine. Without these details, positive growth or immune responses are difficult to reproduce or translate into commercial feed formulation.

Prebiotics and synbiotics

Prebiotics are non-digestible dietary substrates that selectively support beneficial microorganisms or beneficial microbial functions in the host gut. In fish, common prebiotic candidates include fructooligosaccharides, mannan oligosaccharides, inulin, beta-glucans, galactomannan oligosaccharides, honey-derived saccharides, mushroom polysaccharides, seaweed polysaccharides, and yeast cell wall fractions (Mohan *et al.*, 2022; Puri *et al.*, 2022; Vijayaram *et al.*, 2023). Their primary value is not direct nutrient provision but microbial and immunological modulation. Prebiotics can improve gut health through several routes. Fermentation of non-digestible carbohydrates may generate short-chain fatty acids or other metabolites that support epithelial cells and gut barrier function. Prebiotics can also increase beneficial bacteria such as lactic acid bacteria, while some polysaccharides act as immunostimulants through pattern-recognition receptor pathways. Mannan-rich compounds may additionally reduce pathogen adhesion by acting as decoy binding substrates (Puri *et al.*, 2022; Vijayaram *et al.*, 2023; Aryati *et al.*, 2025).

Synbiotics combine probiotics and prebiotics with the goal of improving survival, colonization, or metabolic activity of beneficial microbes. Synbiotic research is expanding because probiotic survival in aquatic animals can be transient. A prebiotic substrate may increase probiotic persistence or function, thereby improving feed efficiency, gut morphology, immune markers, and disease resistance (Magouz *et al.*, 2023; Olowe *et al.*, 2023; Sukul *et al.*, 2023; Vijayaram *et al.*, 2023). Sukul *et al.* (2023) evaluated autochthonous bacilli and fructooligosaccharide in rohu and reported improvements in growth, feed utilization, hemato-immunological parameters, and disease resistance. Magouz *et al.* (2023) studied a synbiotic product in Nile tilapia reared in inland brackish groundwater and reported improvements in growth performance, growth-related genes, intestinal health, and immunity. Olowe *et al.* (2023) assessed two dietary synbiotics in Japanese eel and focused on growth, hematological parameters, and nonspecific immune responses. Sîrbu *et al.* (2022) also reported that probiotic and prebiotic supplementation can affect growth, physiological condition, and resistance to pathogen challenge in Nile tilapia. The synbiotic concept is mechanistically attractive, but it increases formulation complexity. A synbiotic combination should not be assumed to be superior unless the probiotic strain can utilize or respond to the selected substrate and the combined product produces effects beyond those of the individual components. Future studies should therefore compare probiotic-alone, prebiotic-alone, synbiotic, and control treatments to distinguish additive, synergistic, and redundant responses.

PHYTOGENIC ADDITIVES AND ESSENTIAL OILS

Phytogenic feed additives are plant-derived products, including essential oils, extracts, powders, juices, polyphenols, flavonoids, saponins, tannins, terpenoids, alkaloids, and organosulfur compounds. Phytogenic additives may contribute to antibiotic-reduction strategies through antimicrobial, antioxidant, anti-inflammatory, and palatability-related mechanisms, but their effectiveness depends strongly on botanical source, extraction method, chemical standardization, inclusion level, and fish species (Firmino *et al.*, 2021a; Rimoldi *et al.*, 2020; Gruber *et al.*, 2025). Unlike probiotics, phytogenics are not living organisms; their effectiveness depends on botanical species, plant part, extraction method, chemical profile, stability, bioavailability, and interaction with the basal diet. Firmino *et al.* (2021a) argued that phytogenic bioactive compounds can shape fish mucosal immunity. This is particularly relevant because mucosal surfaces, including intestine, skin, and gills, are first-line defense interfaces in aquatic animals. Essential oils may modulate cytokine expression, antioxidant enzymes, antimicrobial activity, and epithelial defense. Firmino *et al.* (2021b) further demonstrated the value of integrating diet, immunity, and microbiota by examining gilthead seabream fed an essential-oils-based functional diet. Their work represents an important shift from simple growth measurement toward integrated immunological and microbiome interpretation.

Rimoldi *et al.* (2020) evaluated galactomannan oligosaccharides and phytogenics in European sea bass fed low fishmeal and fish oil diets, highlighting the relevance of functional additives in modern aquafeeds that increasingly replace marine ingredients. This point is crucial: feed additives may become more necessary as aquafeeds shift toward alternative proteins and lipids that can modify gut microbiota, bile metabolism, inflammatory tone, and palatability. Recent phytogenic studies continue to diversify. Gruber *et al.* (2025) examined phytogenic feed additives as sustainable alternatives to antibiotics in Nile tilapia, focusing on growth and disease resistance. Trejo-Ramos *et al.* (2025) evaluated oregano essential oil in striped bass, with attention to growth and gut prokaryote microbiota. Khalafalla *et al.* (2025) investigated herbal essential oils in Nile tilapia fingerlings and reported effects on growth, antioxidant response, and gene expression. Yousefi *et al.* (2025) examined *Abies sibirica* essential oil in rainbow trout and linked dietary supplementation to growth, digestive enzymes, skin mucus immunological parameters, and heat-stress response. Sharif *et al.* (2024) investigated monoterpenoids in a *Moringa oleifera*-based diet for Nile tilapia, focusing on growth performance, feed efficiency, digestibility, and body composition.

Other plant-derived studies indicate that not all phytogenic effects are mediated by essential oils. Wheat grass juice and barley grass juice have been evaluated in common carp as plant-based feed supplements affecting growth, body composition, biochemical profile, and flesh quality (Barbacariu *et al.*, 2021; Burducea *et al.*, 2022). These studies broaden the phytogenic category from concentrated volatile compounds toward aqueous plant juices and plant-derived bioactive ingredients. Phytogenic research requires particular caution because plant-derived additives are chemically heterogeneous. Botanical species, plant part, extraction method, active-compound profile, and inclusion level can substantially alter biological activity. Neutral findings, such as the lack of significant growth response to fennel essential oil in Black Sea salmon at tested levels, are therefore important because they prevent overgeneralization of phytogenic efficacy (Özel *et al.*, 2023). Future phytogenic studies should prioritize chemical standardization, dose-response evaluation, and linkage between mechanistic endpoints and production outcomes.

YEAST PRODUCTS, BETA-GLUCANS, NUCLEOTIDES, AND IMMUNOSTIMULANT BLENDS

Yeast-derived products occupy a distinctive position between nutritional ingredients and functional immunostimulants. *Saccharomyces cerevisiae*, yeast hydrolysates, yeast culture, yeast cell wall products, beta-glucans, mannan oligosaccharides, peptides, nucleotides, vitamins, and minerals can contribute to growth, palatability, gut microbial modulation, and immune activation (Choi *et al.*, 2022; Huang *et al.*, 2025; Kovács & Pál, 2025; Sultana *et al.*, 2024). Yeast products may function partly as protein sources, partly as prebiotics, and partly as immunostimulants.

Beta-glucans are among the most recognized immunostimulants in aquaculture. They are glucose polymers, commonly derived from yeast, fungi, cereals, or algae, and may stimulate innate immune responses through recognition by immune cells. Khanjani *et al.* (2022) reviewed beta-glucan as a promising feed additive and immunostimulant in aquaculture. The value of beta-glucan is often associated with increased lysozyme activity, phagocytic activity, complement activity, respiratory burst, cytokine modulation, and disease resistance. However, beta-glucan effects depend on source, molecular structure, solubility, dose, feeding duration, and fish species.

Nucleotides are conditionally important nutrients during periods of rapid growth, stress, tissue repair, or immune activation. Medagoda *et al.* (2023) showed that a mixture of nucleotides, beta-glucan, and vitamins C and E improved growth and health performance in olive flounder. This type of multi-component formulation reflects the direction of commercial functional feeds, where single mechanisms are combined to support several physiological systems simultaneously. Choi *et al.* (2023) evaluated four functional feed additives in juvenile olive flounder, focusing on growth, serum biochemistry, antioxidant capacity, gene expression, histomorphology, digestive enzyme activity, and disease resistance. Choi *et al.* (2022) also examined probiotic bacteria and processed yeast as alternatives to antibiotics in juvenile olive flounder.

Yeast culture in largemouth bass has recently attracted attention. Huang *et al.* (2025) reported that dietary yeast culture supplementation affected growth performance, digestive function, and intestinal health. Sultana *et al.* (2024) reviewed factors affecting yeast digestibility and immunostimulation in aquatic animals, emphasizing that yeast efficacy is shaped by cell wall accessibility, processing, digestibility, beta-glucan exposure, and host species. Kovács and Pál (2025) provided a bibliometric and narrative review of *Saccharomyces cerevisiae* in aquaculture, reinforcing its role as a multifunctional additive associated with growth, immunity, disease resistance, and gut integrity.

A major challenge in this additive group is product definition. Live yeast, inactive yeast, hydrolyzed yeast, yeast extract, yeast culture, yeast cell wall fractions, beta-glucan isolates, and nucleotide-rich extracts are biologically different products. Future research should therefore report processing method, active-component concentration, molecular characteristics, and inclusion level rather than using “yeast” as a generic descriptor. Such reporting is essential for comparing studies and identifying which yeast-derived components are responsible for observed effects.

ORGANIC ACIDS, ENZYMES, SEAWEED METABOLITES, AND EMERGING ADDITIVES

Organic acids, enzymes, seaweed metabolites, and emerging botanical or fungal compounds expand the functional aquafeed toolbox by targeting digestibility, microbial balance, antioxidant defense, and nutrient availability through different mechanisms. Organic acids are most relevant for gut acidification, mineral solubilization, and microbial suppression; enzymes are central to improving the use of plant-based ingredients; seaweed metabolites provide polysaccharides, minerals, pigments, and antioxidant compounds; and medicinal mushrooms offer prebiotic and immunostimulant potential (Hoseini *et al.*, 2025; Mohan *et al.*, 2022; Siddik *et al.*, 2023). Their practical value should be judged by measurable improvements in feed efficiency, gut integrity, stress tolerance, or disease resilience rather than by mechanistic plausibility alone. Organic acids and acidifiers can improve nutrient digestibility, mineral availability, microbial balance, and gut health. Their mechanisms include reduction of gut pH, inhibition of acid-sensitive pathogens, improved protein digestion, enhanced mineral solubilization, and modulation of intestinal microbiota. Organic acids may be especially useful in plant-based diets, where mineral binding and anti-nutritional factors can compromise nutrient availability (Hoseini *et al.*, 2025).

Hoseini *et al.* (2025) examined dietary citric acid, lactic acid, and potassium sorbate mixture in common carp juveniles and connected acidifier use to growth performance and intestinal immunological parameters. This study reflects a broader shift toward additive blends that target both digestion and health. Organic acids are often commercially attractive because they are relatively stable, compatible with pelleted feeds, and mechanistically plausible in reducing pathogen loads.

Enzymes, including phytase, xylanase, protease, amylase, and multi-enzyme blends, are widely discussed in functional feed contexts, especially in diets with plant ingredients. Their main function is to improve nutrient availability and reduce anti-nutritional effects. Enzyme strategies are particularly important for phosphorus release from phytate, fiber breakdown, and improved digestibility of alternative feed ingredients. Although enzyme-focused finfish literature from 2020 to 2026 was less dominant in this synthesis than probiotic and phytogenic literature, enzymes remain central to functional aquafeed design and are often included in commercial additive packages (Marimuthu *et al.*, 2022; Onomu & Okuthe, 2024).

Marine-derived and fungal-derived compounds are expanding the aquafeed toolbox. Seaweeds contain polysaccharides, pigments, minerals, vitamins, polyphenols, and bioactive metabolites that may improve antioxidant capacity, gut microbiota, immunity, and growth when included at appropriate levels (Siddik *et al.*, 2023). Brown seaweed metabolites such as alginates, fucoidans, and laminarins are particularly relevant as prebiotic-like and immunomodulatory compounds. However, seaweed use requires attention to species, harvest conditions, heavy metals, iodine levels, palatability, digestibility, and inclusion dose. Mushroom-derived compounds are another emerging prebiotic and immunostimulant category. Mohan *et al.* (2022) reviewed medicinal mushrooms as potential prebiotics in aquaculture. Mushrooms contain beta-glucans and other polysaccharides that may support beneficial microbes and immune activation. Yet the field remains less mature than probiotic and phytogenic research, and more fish-specific trials are needed. Green tea has entered the recent literature as a functional botanical additive with genomic and immunological relevance. Akter *et al.* (2026) reviewed genomic insights into *Camellia sinensis* as a functional feed additive in sustainable aquaculture, emphasizing immune and stress-related pathways. This points toward a new research direction: botanical additives are no longer evaluated only by crude growth outcomes but increasingly through transcriptomic and genomic endpoints.

INTEGRATED MECHANISMS: FROM GUT MICROBIOTA TO SYSTEMIC RESILIENCE

Across additive classes, several convergent mechanisms explain the functional benefits observed in recent studies. First, microbiota modulation is central. Probiotics, prebiotics, synbiotics, yeast products, phytogenics, organic acids, and seaweed metabolites can all alter gut bacterial composition or function. This can influence nutrient metabolism, pathogen exclusion, fermentation products, epithelial signaling, and immune development (Martínez-Porchas *et al.*, 2023; Rimoldi *et al.*, 2020; Ghori *et al.*, 2022). These pathways should be interpreted as interacting biological processes rather than isolated effects. Figure 1 integrates the mechanistic logic discussed in the preceding sections by positioning the intestine as the main interface through which functional additives influence microbiota balance, mucosal immunity, antioxidant regulation, digestive efficiency, and disease resistance. The figure is therefore used as a conceptual synthesis of the reviewed evidence, not as a representation of one experimental trial or a quantitative effect-size model.

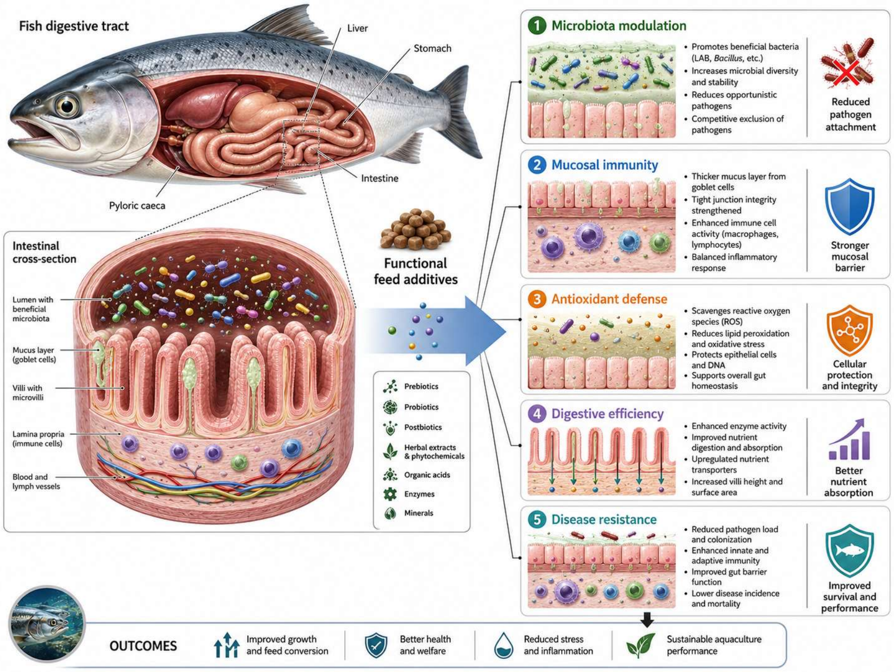

Figure 1. Mechanistic integration of functional feed additives in fish gut health and systemic resilience. The illustration summarizes how microbial, phytogenic, yeast-derived, organic-acid, enzyme, mineral, and other functional additives may converge at the digestive tract to support microbiota modulation, mucosal immunity, antioxidant defense, digestive efficiency, and disease resistance. Source: authors' conceptual synthesis based on the reviewed literature.

Second, intestinal morphology and barrier function mediate performance. Improvements in villus height, microvilli structure, goblet cells, mucus secretion, epithelial integrity, and reduced inflammatory lesions can improve nutrient absorption and reduce the energetic costs of immune activation (Du *et al.*, 2021; Firmino *et al.*, 2021b; Aryati *et al.*, 2025). These outcomes are especially important in low-fishmeal or alternative-protein diets that may increase gut sensitivity. Third, innate immune activation is a major pathway. Fish rely strongly on innate immune defenses, including lysozyme, complement, phagocytosis, respiratory burst, mucus antimicrobial factors, and cytokine signaling. Beta-glucans, yeast derivatives, probiotics, and phytogenics are especially relevant in this domain (Khanjani *et al.*, 2022; Medagoda *et al.*, 2023; Choi *et al.*, 2023). Wang *et al.* (2022) also emphasized that tilapia health can be improved through strategies that enhance immune competence.

Fourth, antioxidant regulation is repeatedly reported. Intensive aquaculture stress can generate oxidative imbalance. Essential oils, plant polyphenols, seaweed metabolites, vitamins C and E, and yeast-derived compounds can increase antioxidant enzyme activity or reduce oxidative markers (Firmino *et al.*, 2021a; Siddik *et al.*, 2023; Khalafalla *et al.*, 2025). Antioxidant improvement, however, should not be interpreted as a production benefit unless linked to survival, growth, disease resistance, or stress tolerance. Fifth, digestive enzyme modulation improves nutrient utilization. Probiotics may produce enzymes or stimulate host enzyme activities; organic acids may improve digestive conditions; phytogenics may stimulate bile and enzyme secretion; yeast products may improve gut function; and enzyme additives directly target digestibility (Huang *et al.*, 2025; Hoseini *et al.*, 2025; Xue *et al.*, 2022). Finally, disease resistance emerges as a compound outcome of microbiota stability, immune readiness, antioxidant balance, and epithelial integrity. Challenge tests against Aeromonas, Vibrio, Streptococcus, and other pathogens often reveal functional benefits more clearly than growth trials alone (Gruber *et al.*, 2025; Jang *et al.*, 2022; Zhang *et al.*, 2025).

Table 1. Representative Recent Evidence On Functional Feed Additives In Finfish Aquaculture

Additive group	**Representative component**	**Fish species/model**	**Main outcomes**	**Practical interpretation**	**Ref.**
Probiotic	*Bacillus subtilis* DSM 32315	Largemouth bass	Growth, immunity, intestinal morphology, microbiota, inflammation	Spore-forming probiotic supports gut and immune parameters	Du *et al.* (2021)
Probiotic	*Bacillus amyloliquefaciens*	Yellow catfish	Growth, digestive enzymes, immune response, disease resistance	Bacillus supplementation supports digestive and immune modulation	Xue *et al.* (2022)
Probiotic + beta-glucan	*Bacillus* sp. PM8313 + beta-glucan	Red sea bream	Growth, immunity, gut microbiota, disease resistance	Combined microbial and polysaccharide immune support	Jang *et al.* (2022)
LAB probiotic	*Leuconostoc mesenteroides* + *Lactococcus lactis*	Nile tilapia; African catfish	Growth, gut microbiota, immune response	Multistrain LAB may improve microbial balance and innate immunity	Paritova *et al.* (2024, 2025)
Autochthonous probiotic	*Bacillus pumilus*, *Psychrobacter* sp., *Bacillus clausii*	Juvenile grouper	Mitigation of histamine-related adverse effects	Host-associated strains may reduce diet-induced gut stress	Liu *et al.* (2021)
Synbiotic	Bacilli + fructooligosaccharide	Rohu	Growth, feed utilization, hemato-immunology, disease resistance	Potential synergy between strains and fermentable substrate	Sukul *et al.* (2023)
Phytogenic	Galactomannan oligosaccharides + plant bioactives	European sea bass	Gut microbiota modulation under low-fishmeal diet	Functional additives may offset alternative-feed challenges	Rimoldi *et al.* (2020)
Essential oil	Essential-oils-based diet	Gilthead seabream	Intestinal transcription, immunity, microbiota	Links diet, microbiota, and mucosal immune response	Firmino *et al.* (2021b)
Phytogenic	Plant essential-oil blend	Nile tilapia	Growth and disease resistance	Supports antibiotic-reduction strategies	Gruber *et al.* (2025)
Yeast / immunostimulant	Yeast products, beta-glucan, nucleotides, vitamins	Olive flounder; largemouth bass	Growth, digestive function, gut health, immunity	Yeast-derived compounds support gut and immune functions	Choi *et al.* (2022, 2023); Huang *et al.* (2025); Medagoda

					et al. (2023)
Organic acid	Citric acid, lactic acid, potassium sorbate	Common carp	Growth and intestinal immune parameters	Acidification may improve digestion and microbial control	Hoseini *et al.* (2025)
Seaweed metabolite	Seaweed polysaccharides and bioactives	Multiple finfish	Growth, antioxidant response, immunity, gut microbiota	Marine bioactives are promising but require dose control	Siddik *et al.* (2023)

PRACTICAL IMPLICATIONS FOR AQUAFEED FORMULATION AND INDONESIAN AQUACULTURE

Functional aquafeed design should begin with production objectives. If the goal is improved growth under normal conditions, additives targeting digestibility, palatability, enzyme activity, and nutrient utilization may be prioritized. If the goal is disease resilience, probiotics, beta-glucans, yeast derivatives, phytogenics, and immunostimulant blends may be more relevant. If the goal is gut stabilization under alternative-protein diets, prebiotics, organic acids, synbiotics, enzymes, and phytogenics may be appropriate. If the goal is heat-stress mitigation, antioxidant-rich botanicals, vitamins, and essential oils deserve attention (Firmino *et al.*, 2021b; Hoseini *et al.*, 2025; Yousefi *et al.*, 2025). For Indonesia, the practical relevance of functional feed additives is closely linked to the structure of national aquaculture production. Freshwater commodities such as Nile tilapia, catfish, pangasius, common carp, and giant gourami are produced across diverse pond, cage, reservoir, and intensive culture systems, whereas milkfish and grouper remain important in brackishwater and marine aquaculture.

Official Indonesian statistics indicate that major cultured commodities include Nile tilapia, catfish, milkfish, carp, gourami, pangasius, grouper, shrimp, and seaweed, with Nile tilapia, catfish, and milkfish representing particularly large finfish production groups in 2024. KKP data reported 2024 aquaculture production of approximately 1.56 million tons for Nile tilapia, 1.16 million tons for catfish, and 0.79 million tons for milkfish, illustrating the commercial importance of species for which functional feed strategies could have broad practical impact (BPS-Statistics Indonesia, 2026). In freshwater aquaculture, functional additives should be evaluated against disease problems that are already relevant to Indonesian production systems. Motile Aeromonas septicemia caused by Aeromonas hydrophila is repeatedly reported as an important disease problem in freshwater fish, including tilapia, carp, and catfish. Indonesian studies also identify A. hydrophila and Streptococcus agalactiae as important bacterial pathogens in Nile tilapia, with implications for vaccine development and preventive health management (Nafiqoh *et al.*, 2022).

In catfish, *Aeromonas* spp. have been isolated from diseased Clarias cultured in Java, supporting the relevance of gut-health, immune-priming, and antimicrobial-reduction strategies for this commodity (Mulia *et al.*, 2023). Therefore, for tilapia and catfish systems, probiotics, synbiotics, organic acids, yeast derivatives, beta-glucans, and phytogenic additives should be tested not only for growth and feed conversion, but also for their capacity to reduce susceptibility to bacterial challenge, stabilize gut microbiota, and maintain mucosal immunity under high-density culture. For brackishwater and marine species, the priority differs. Milkfish culture is often associated with pond-based systems where water-quality fluctuation, organic loading, and pathogen exposure can vary substantially. Recent Indonesian evidence from

South Sulawesi indicates that intensification of milkfish culture increases the risk of bacterial and parasitic infections, which may contribute to production losses (Rachmat *et al.*, 2025). In grouper culture, bacterial and viral diseases are major constraints. Vibriosis has long been reported as a major bacterial disease in Indonesian marine fish farming and is particularly relevant to grouper, whereas iridovirus and viral nervous necrosis are important concerns in grouper seed production and hatchery systems (Istiqomah *et al.*, 2020).

These disease profiles suggest that marine functional feeds should prioritize additives that support epithelial barrier integrity, antioxidant defense, larval or juvenile robustness, and mucosal immunity, while recognizing that feed additives cannot replace vaccination, biosecurity, seed-quality control, or water-quality management. Feed cost and ingredient availability are also central to Indonesian aquafeed formulation. Smallholder aquaculture farmers in Indonesia face constraints related to feed cost and efficiency, water quality, and seed quality; feed may account for a major share of production costs, making additive adoption highly sensitive to price and measurable return. Indonesia has also promoted the use of locally available ingredients to reduce dependence on imported raw materials, especially fishmeal, through self-sufficient fish-feed initiatives (Wasik *et al.*, 2025). This context is important because alternative plant-based or locally sourced ingredients may change palatability, digestibility, mineral availability, gut microbiota, and intestinal inflammatory responses. Functional additives such as enzymes, organic acids, probiotics, yeast derivatives, and phytogenic compounds may therefore be most useful when they are evaluated within realistic local feed matrices rather than purified experimental diets. Mechanistic plausibility must ultimately be translated into practical feed formulation and farm-level decision-making. Figure 2 provides an applied framework linking additive selection, formulation control, feeding management, and measurable aquaculture outcomes. This framework emphasizes that functional additives should be selected according to defined production objectives, such as improved feed conversion, stronger immune competence, lower disease pressure, better survival, gut stabilization, or sustainable production performance.

This figure is intended as a conceptual framework and should not be interpreted as a quantitative causal model. Dose is a central formulation issue. Low doses may be ineffective, whereas excessive doses may reduce palatability, disturb microbiota, trigger unnecessary immune activation, or reduce growth. This is especially relevant for essential oils, polyphenols, beta-glucans, seaweed metabolites, organic acids, and some prebiotics. Studies should therefore avoid single-dose designs unless strong prior evidence is available. Feed-processing stability is another key issue. Probiotics must survive pelleting, extrusion, storage, and gut transit. Essential oils may volatilize or oxidize. Enzymes can be heat-sensitive. Beta-glucans and yeast products may vary in bioavailability depending on source and processing method. Microencapsulation, post-pellet coating, cold extrusion, and protected delivery systems may improve functional performance, but they also increase production costs and require validation under local manufacturing conditions. Although global evidence provides useful mechanistic guidance, direct extrapolation to Indonesian aquaculture should be made cautiously because species composition, farming systems, feed ingredients, water quality, farmer capacity, and production economics differ across regions. For tilapia and catfish, priority trials should combine growth, FCR, gut histology, microbiota profiling, and challenge tests against *A. hydrophila* and *S. agalactiae*. For milkfish, additive studies should address pond-based stressors, fluctuating salinity, parasitic and bacterial exposure, and feed efficiency under semi-intensive systems. For grouper, functional feeds should be evaluated alongside hatchery health management, *Vibrio* control, and viral disease surveillance, particularly during seed and juvenile stages.

Figure 2. Practical framework for applying functional feed additives in finfish aquaculture from feed formulation to farm-level outcomes. The figure links major additive groups with smart feed formulation, feeding practice, and expected production benefits, including improved FCR, stronger immunity, lower disease pressure, better survival, gut health, and sustainable production. Source: authors' conceptual synthesis based on the reviewed literature.

Economic feasibility must be integrated into efficacy assessment. A feed additive that improves immune markers but does not improve survival, growth, feed conversion, or disease-related losses under farm conditions may have limited commercial value. Conversely, modest improvements in FCR or survival can be economically meaningful in large-scale production. Therefore, future Indonesian studies should include cost per kilogram of gain, additive cost per ton of feed, survival benefit, reduction in treatment cost, farmer usability, compatibility with local feed mills, and return on investment. This approach would make functional aquafeed research more relevant to commercial adoption and prevent overgeneralization from laboratory-scale trials.

Table 2. Mechanistic Pathways and Research Priorities for Modern Functional Aquafeeds

Target pathway	**Additive groups**	**Key indicators**	**Interpretation challenge**	**Priority research direction**	**Ref.**
Gut microbiota modulation	Probiotics, prebiotics, synbiotics, phytogenics, organic acids, seaweed metabolites	16S rRNA, diversity indices, beneficial/pathogenic taxa, inferred metabolites	Taxonomic shifts do not automatically prove functional benefit	Link microbiome data with metabolomics, histology, and performance	Martínez-Porchas *et al.* (2023); Rimoldi *et al.* (2020)
Mucosal immunity	Probiotics, phytogenics, yeast products, beta-glucans	Mucus lysozyme, IgM/IgT, goblet cells, cytokine genes, antimicrobial peptides	Immune activation may be beneficial or energetically costly	Define optimal immune priming without chronic inflammation	Firmino *et al.* (2021a); Khanjani *et al.* (2022)
Antioxidant defense	Essential oils, plant extracts, seaweed metabolites, vitamins C and E	SOD, CAT, GPx, MDA, oxidative damage, antioxidant genes	Improved markers may not translate into production benefit	Combine stress challenge with antioxidant and production endpoints	Siddik *et al.* (2023); Medagoda *et al.* (2023)
Digestive efficiency	Probiotics, enzymes, organic acids, phytogenics, yeast culture	Protease, amylase, lipase, FCR, apparent digestibility	Growth may reflect intake rather than improved digestion	Separate feed intake, digestibility, and metabolic efficiency	Huang *et al.* (2025); Hoseini *et al.* (2025)
Disease resistance	Probiotics, synbiotics, beta-glucans, yeast products, phytogenics	Survival after challenge, pathogen load, lesion score, immune genes	Challenge models vary and may not mimic farms	Standardize pathogen dose, route, and post-challenge duration	Jang *et al.* (2022); Gruber *et al.* (2025)
Stress resilience	Phytogenics, vitamins, yeast products, synbiotics, green tea metabolites	Cortisol, glucose, heat-stress survival, oxidative markers, stress genes	Stressor type determines additive response	Evaluate thermal, salinity, crowding, and transport stress separately	Yousefi *et al.* (2025); Akter *et al.* (2026)
Low-fishmeal diet adaptation	Phytogenics, enzymes, organic acids, probiotics, yeast products	Enteritis score, bile metabolism, microbiota, growth, FCR	Effects are confounded by protein-source quality	Test additives under defined ingredient-replacement gradients	Rimoldi *et al.* (2020); Choi *et al.* (2023)
Precision formulation	Multi-component blends	Integrated growth, immunity, microbiome, metabolome, and economics	Blends obscure individual mechanisms	Use factorial designs and systems-biology interpretation	Onomu & Okuthe (2024); Hoseinifar *et al.* (2024)

METHODOLOGICAL LIMITATIONS IN CURRENT EVIDENCE

The current literature is promising but uneven. Study outcomes are difficult to compare because trials differ in additive characterization, inclusion level, fish species, life stage, basal diet, feeding duration, rearing condition, endpoint selection, and disease- or stress-challenge model. These differences are not merely technical details; they determine whether an observed response can be reproduced or translated into farm-level application. Therefore, future studies should provide clearer additive descriptions, dose-response designs, appropriate controls, sufficient replication, and integrated measurements of growth, digestibility, gut histology, immune response, microbiota, and challenge performance.

Additive identity is sometimes inadequately described. Probiotic strain identity, botanical chemical profile, yeast processing method, beta-glucan structure, organic acid form, and active compound concentration should be reported in detail. Many trials also lack dose-response curves, even though single-dose designs are insufficient for determining optimal inclusion levels and safety margins. Publication bias toward positive findings remains another concern. Neutral results, such as those reported for fennel essential oil in Black Sea salmon, are important because they prevent overgeneralization (Özel *et al.*, 2023). The literature also often separates growth, immunity, and gut health even though these outcomes are biologically linked. A fish may grow faster because of increased intake, improved digestibility, reduced inflammation, altered microbiota, or water-quality effects. Without integrated measurements, mechanisms remain speculative. High-quality future studies should therefore combine growth performance, digestibility, gut histology, immune assays, microbiome sequencing, metabolomics, and disease or stress challenge. Finally, review studies themselves must be transparent about scope and selection. Narrative reviews are useful for conceptual synthesis, but they should not imply quantitative certainty where study designs are heterogeneous. The present review therefore interprets evidence by mechanism and practical relevance rather than by pooled effect size.

FUTURE DIRECTIONS: TOWARD PRECISION FUNCTIONAL AQUAFEEDS

The future of functional aquafeeds lies in precision nutrition. This means designing additive programs according to clearly defined production objectives, such as improving feed conversion, stabilizing gut health under alternative-protein diets, enhancing disease resilience, or mitigating environmental stress. Integrated approaches combining growth performance, gut histology, immune assays, microbiome analysis, metabolomics, transcriptomics, formulation stability, and economic evaluation will be needed to distinguish biologically meaningful responses from short-term or context-limited effects. Juvenile fish under high disease pressure may benefit from probiotic-beta-glucan or yeast-derived immunostimulant programs, whereas fish fed high plant-protein diets may require enzymes, organic acids, phytogenics, or synbiotics to maintain gut function. Coldwater fish under thermal stress may require antioxidant and stress-modulating additives such as selected essential oils or polyphenol-rich botanicals (Yousefi *et al.*, 2025; Akter *et al.*, 2026). Omics methods will be increasingly important. Transcriptomics can reveal immune and metabolic pathways affected by additives. Metabolomics can identify microbial and host metabolites linked to performance. Metagenomics can move beyond taxonomy toward functional potential. Proteomics can identify epithelial and immune proteins. Integrated omics can distinguish whether an additive merely shifts microbiota composition or actually improves host function.

Another priority is additive interaction. Many commercial products combine probiotics, prebiotics, enzymes, organic acids, yeast fractions, vitamins, and phytogenics. These mixtures may be effective, but they make mechanism attribution difficult. Factorial experimental designs are needed to determine whether effects are additive, synergistic, antagonistic, or redundant. Without such designs, the industry may continue to use expensive blends without knowing which components are essential. Safety and regulatory assessment must also advance. Natural does not automatically mean safe. Essential oils, concentrated extracts, seaweed minerals, and immune stimulants can have adverse effects at inappropriate doses. Long-term feeding studies should evaluate growth, organ health, histopathology, reproductive performance, fillet quality, residue concerns, and environmental discharge. Finally, functional feed studies should include economic analysis. A functional additive should be evaluated not only by statistical significance but also by cost per kilogram of gain, survival benefit, reduction in treatment cost, feed conversion improvement, farmer adoption potential, and return on investment under commercial conditions.

CONCLUSION

Functional nutrition and modern feed additives are important tools for sustainable finfish aquaculture. Recent evidence supports the potential of probiotics, prebiotics, synbiotics, phytogenic compounds, essential oils, yeast products, beta-glucans, nucleotides, organic acids, enzymes, seaweed metabolites, and multi-component blends to support gut health, immune competence, disease resistance, stress resilience, and growth performance. However, the current evidence should be interpreted with caution because the strength of support differs among additive groups: probiotics and beta-glucans have comparatively stronger mechanistic and experimental support, phytogenic and seaweed-derived additives remain more chemically heterogeneous, and emerging botanical or fungal products require further validation before broad farm-level recommendation. Therefore, these additives should not be applied as generic supplements. Their value depends on whether their dominant biological function matches a clearly defined production problem. The strongest applications are likely to arise from precision functional nutrition, in which additive selection is linked to gut microbiota modulation, mucosal immunity, antioxidant regulation, digestive efficiency, and farm-level feasibility. Future research should move beyond descriptive additive trials toward mechanism-driven, dose-responsive, economically evaluated, and farm-validated studies. For tropical and Indonesian aquaculture, this approach is particularly important to ensure that functional feeds are not only biologically promising, but also practical, affordable, and reproducible under real production conditions. Before broad farm-level adoption, recommendations should be validated according to target species, farming system, local feed matrix, disease-risk profile, additive cost, and economic feasibility.

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