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Plant-based Feed Additives for Sustainable Nile Tilapia Aquaculture: A Review of Applications, Mechanisms, and Future Opportunities

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Abstracts

The use of plant-based feed additives (PBFAs) in Nile tilapia aquaculture is gaining attention as a sustainable alternative to synthetic inputs, with reported benefits for growth, immunity, and disease resistance. This review synthesizes evidence on PBFAs, including crude powders, extracts, essential oils, and purified bioactives, from plants such as garlic, ginger, aloe vera, and moringa. Their effects involve interconnected pathways, including immunomodulation, antioxidant defense, antimicrobial activity, host–microbiome modulation, molecular signaling, and reproductive or endocrine regulation, thereby supporting growth performance, feed efficiency, physiological resilience, reproductive indices, and survival after pathogen challenge. However, commercial adoption is constrained by phytochemical variability, limited standardization, incomplete understanding of species- and context-dependent responses, and regulatory gaps. Future work should prioritize mechanistic validation, optimized formulation, and practical delivery strategies for sustainable Nile tilapia production.

Keywords

Phytogenics, immunomodulation, antioxidant defense, gut microbiota, disease resistance

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Introduction

Nile tilapia (*Oreochromis niloticus*) is a globally important freshwater aquaculture species, valued for affordable animal protein production and its adaptability to diverse farming systems. Its rapid growth, efficient feed utilization, omnivorous feeding habit, and environmental tolerance have supported widespread culture (Hussain, 2025). The species is farmed in more than 100 countries,

with global consumption projected to reach approximately 7 million tons by 2025 (Fitzsimmons *et al*., 2025). However, further development of the tilapia sector increasingly depends on improving production efficiency, resilience, product quality, and sustainability. Intensification has increased exposure to high stocking densities, fluctuating water quality, nutritional stress, and disease outbreaks. Bacterial pathogens, including *Streptococcus* spp., *Aeromonas hydrophila*, *Edwardsiella* spp., and other opportunistic bacteria, remain major causes of morbidity, mortality, and economic losses (Haenen *et al*., 2023). Although antibiotics, chemotherapeutants, disinfectants, and synthetic hormones may provide short-term control, their repeated or inappropriate use raises concerns regarding antimicrobial resistance, chemical residues, disruption of aquatic microbial communities, food safety, and consumer acceptance (Ntakirutimana *et al*., 2025).

These concerns have stimulated the development of antibiotic-free and sustainable health-management strategies aligned with certification requirements and bio-circular-green economy approaches. Probiotics, vaccines, biofloc technology, improved husbandry, and functional feeds have received increasing attention, although their application may be limited by pathogen specificity, system dependency, cost, or management complexity (Hoseinifar & Van Doan, 2023; Ojewole *et al*., 2026). Among these approaches, plant-based feed additives (PBFAs) are promising because they can be incorporated directly into aquafeeds and provide diverse biological activities through polyphenols, flavonoids, alkaloids, terpenoids, saponins, tannins, and essential oil constituents (Hossain *et al*., 2024; Gruber *et al*., 2025; Okon *et al*., 2025).

In this review, PBFAs encompass plant materials and by-products, crude powders, extracts, essential oils, and purified plant-derived bioactives incorporated into aquafeeds to improve growth, physiological resilience, immunity, antioxidant capacity, disease resistance, or reproductive performance in Nile tilapia. However, available evidence remains heterogeneous because of differences in botanical species, preparation methods, inclusion levels, feeding duration, fish life stage, culture conditions, and evaluated endpoints. Therefore, this review critically synthesizes current evidence on the applications and mechanisms of PBFAs in Nile tilapia aquaculture, while identifying practical constraints and future priorities for their reliable and sustainable use.

Plant-based Feed Additives in Nile Tilapia Culture

Definition and classification

In Nile tilapia aquaculture, PBFAs are dietary botanical materials and preparations used to support growth, feed utilization, physiological resilience, immunity, antioxidant capacity, disease resistance, and reproductive performance (Gabriel, 2019). Compared with conventional chemotherapeutants, they are generally more compatible with residue-free and sustainable aquaculture, although their efficacy depends strongly on composition, dose, and processing method. PBFAs are commonly used as crude powders, extracts, essential oils, or purified bioactive compounds (Van Hai, 2015). Each form has distinct advantages and limitations: crude powders provide a broad spectrum of phytochemicals but may vary in composition and digestibility, while extracts and essential oils deliver more concentrated active compounds and therefore require precise dosing. Purified bioactives may support more targeted applications, although their higher cost and stricter formulation requirements may limit practical use (Reverter *et al*., 2014). These differences highlight the importance of standardization, dose optimization, and safety evaluation for reliable aquafeed application.

Administration routes

Oral dietary delivery is the principal route for PBFAs in grow-out Nile tilapia because it enables non-invasive, population-scale administration of powders, extracts, essential oils, or encapsulated products through feed. This approach is commonly associated with improved growth, feed efficiency, antioxidant status, and immune responses (Gabriel, 2019). Immersion and parenteral administration have also been used experimentally, particularly in hatchery,

broodstock, and mechanistic studies, but their practical application is limited by the need for tighter dose control, handling requirements, stress, and poor scalability.

Effects of Plant-based Additives on Tilapia Performance

Growth performance and feed utilization efficiency

As summarized in **Table 1**, PBFAs have frequently been associated with increased weight gain (WG), specific growth rate (SGR), and final body weight (FBW), together with lower feed conversion ratio (FCR) in Nile tilapia. However, growth responses are less consistent than immune and antioxidant outcomes and vary with botanical source, preparation form, inclusion level, feeding duration, basal diet, fish size or strain, and culture conditions. The available studies cover a wide range of preparations, from low-dose extracts and essential oils to higher-inclusion crude powders and plant by-products. Excessive inclusion of crude materials may reduce efficacy because of fiber, anti-nutritional compounds, or palatability constraints. Thus, dose–response validation and standardized preparation remain important before routine commercial use.

Immune responses and disease resistance

Immune enhancement is among the most consistently reported responses to PBFAs in Nile tilapia. As summarized in **Table 2**, dietary botanicals have been associated with increased lysozyme activity, IgM, leukocyte-related indices, phagocytic activity, respiratory burst, and immune-related gene expression. Pathogen-challenge studies further show that these changes can coincide with improved disease resilience and, in some cases, higher post-challenge survival (Abd El-Gawad *et al*., 2020; Naliato *et al*., 2021; Van Doan *et al*., 2021a,b; Diab *et al*., 2023). Nevertheless, responses vary among additives and experimental conditions, and PBFAs should be considered prophylactic feed-based tools rather than direct therapeutics.

Antioxidant and hepatoprotective effects

Antioxidant modulation is another consistently reported effect of PBFAs. **Table 2** shows increases in superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPx), glutathione (GSH), and total antioxidant capacity, together with reduced lipid peroxidation, reflected by lower malondialdehyde (MDA). Hepatoprotective responses have also been reported, including reductions in alanine aminotransferase (ALT), aspartate aminotransferase (AST), and MDA, as well as improvements in liver histology or detoxification-related indicators (Aanyu, 2016; Firmino *et al.*, 2021; Negm *et al.*, 2022). However, hepatoprotective outcomes remain less consistently evaluated than antioxidant enzyme activities.

Reproductive modulation and broodstock performance

Phytogenic compounds have been investigated for reproductive modulation and partial sex-ratio control in tilapia. Studies on fenugreek and *Tribulus terrestris*, together with related evidence from red tilapia, indicate potential effects on sex ratio, gonadal development, sperm quality, sex steroids, and reproductive gene expression (Ghosal *et al.*, 2015; Sadiq, 2021). However, these responses remain variable and less predictable than synthetic hormone treatments, suggesting greater potential for supporting broodstock performance than for consistent sex reversal.

Mechanisms of Action of Plant-based Additives in Nile Tilapia

The biological effects of plant-based additives in Nile tilapia are mediated through multiple, interconnected pathways involving digestion, gut microbiota, immune regulation, antioxidant defense, pathogen control, and endocrine modulation. These integrated mechanisms provide the physiological basis for their reported effects on growth, health, disease resistance, and reproductive performance.

Growth promotion and feed utilization

Growth improvement in Nile tilapia is likely mediated through coordinated effects on appetite regulation, digestive capacity, intestinal

Table 1. Representative studies on the effects of plant-based feed additives on growth performance in Nile tilapia

No.	Plant/Additive	Form	Dose/Duration	Growth effects	References
1	Moringa (*Moringa oleifera*)	Leaf powder	Up to 10% in diet	WG, SGR, FBW ↑; FCR ↓	Abd El-Gawad *et al.*, 2020
2	Ginger (*Zingiber officinale*)	Powder	10 g kg^{-1} in feed for 30 days	WG, SGR, FBW ↑; FCR ↓	Naliato *et al.*, 2021
3	Garlic (*Allium sativum*)	Aqueous extract	2-4% in feed	SGR ↑	Naqi *et al.*, 2019
4	Neem (*Azadirachta indica*)	Leaf powder	2.0 g kg^{-1} in feed for 60 days	WG, SGR, FBW ↑; FCR ↓	Radwan *et al.*, 2024
5	Turmeric (*Curcuma longa*)	Powder/extract	1-4 g kg^{-1} in feed for 6 weeks	WG, SGR, FBW ↑; FCR ↓	Yusuf *et al.*, 2017
6	Anise (*Pimpinella anisum*)	Essential oil	0.20% in feed for 8 weeks	WG, SGR, FBW ↑	Tok *et al.*, 2025
7	Fennel (*Foeniculum vulgare*)	Powder and extract	1% powder + 1% extract for 40 days	WG, SGR, FBW ↑; FCR ↓	Ahmed *et al.*, 2025
8	Peppermint (*Mentha piperita*)	Powder	0.6% in feed for 90 days	WG, SGR, FBW ↑; FCR ↓	Abou Zaid *et al.*, 2025a
9	Tamarind (*Tamarindus indica*)	Leaf extract	1% in feed for 12 weeks	WG, SGR, FBW ↑; FCR ↓	Adeniyi *et al.*, 2021
10	Onion (*Allium cepa*)	Powder	0.5% in feed for 30 days	WG, SGR, FBW ↑; FCR ↓	Elgendy *et al.*, 2023
11	Stonebreaker (*Phyllanthus niruri*)	Aqueous extract	5% in feed for 60 days	WG, SGR, FBW ↑; FCR ↓	Ibrahim *et al.*, 2024
12	Heart-leaved moonseed (*Tinospora cordifolia*)	Powder	5.17-5.49 g kg^{-1} in feed for 56 days	WG, SGR, FBW ↑; FCR ↓	El Basuini *et al.*, 2022
13	Lotus (*Nelumbo nucifera*)	Leaf powder	0.6% in feed for 60 days	WG, SGR, FBW ↑; FCR ↓	Abdel Rahman *et al.*, 2019a
14	Rosemary (*Rosmarinus officinalis*)	Crude powder	1% in feed for 60 days	WG, SGR, FBW ↑	Abdel-Tawwab *et al.*, 2024
15	Bahera (*Terminalia bellirica*)	Extract	1% in feed for 60 days	WG, SGR, FBW ↑; FCR ↓	Prisingkorn *et al.*, 2022
16	Coriander (*Coriandrum sativum*)	Oil	0.5-2% in feed for 8 weeks	WG, SGR, FBW ↑	Das *et al.*, 2023
17	Longan (*Dimocarpus longan*)	Peel powder	46-49 g kg^{-1} in feed for 60 days	WG, SGR, FBW ↑	Wannavijit *et al.*, 2025
18	Coconut (*Cocos nucifera*)	Oil	2-3% in feed for 60 days	WG, SGR, FBW ↑	Dawood *et al.*, 2021
19	Sugarcane (*Saccharum officinarum*)	Bagasse powder	20 g kg^{-1} in feed for 8 weeks	WG, SGR, FBW ↑	Lumsangkul *et al.*, 2021
20	Mango (*Mangifera indica*)	Seed powder	36.43-45 g g kg^{-1} for 8 weeks	WG, SGR, FBW ↑; FCR ↓	Fontana *et al.*, 2024
21	Passionfruit (*Passiflora edulis*)	Peel powder	20 g kg^{-1} in feed for 8 weeks	WG, SGR, FBW ↑; FCR ↓	Outama *et al.*, 2022
22	Makiang (*Syzygium nervosum*)	Seed powder	5 g kg^{-1} in feed for 8 weeks	WG, SGR, FBW, FI ↑; FCR ↓	Le Xuan *et al.*, 2024a
23	Dragon fruit (*Hylocereus undatus*)	Peel powder	80 g kg^{-1} in feed for 8 weeks	WG, SGR, FBW ↑	Xuan *et al.*, 2024

No.	Plant/Additive	Form	Dose/Duration	Growth effects	References
24	Avocado (*Persea americana*)	Seed powder	10 g kg^{-1} in feed for 8 weeks	WG, SGR, FBW ↑; FCR ↓	Le Xuan *et al.*, 2024b
25	Fishwort (*Houttuynia cordata*)	Powder	10 g kg^{-1} in feed for 72 days.	Growth, FCR, and SR unchanged	Srichaiyo *et al.*, 2020
26	Coffee (*Coffea arabica*)	Silverskin powder	20 g kg^{-1} in feed for 8 weeks	WG, SGR, FBW ↑; FCR ↓	Van Doan *et al.*, 2021b
27	Pineapple (*Ananas comosus*)	Peel powder	10 g kg^{-1} in feed for 8 weeks	WG, SGR, FBW ↑; FCR ↓	Van Doan *et al.*, 2021a
28	Banana (*Musa paradisica*)	Peel waste powder	15 g kg^{-1} in feed for 28 days	WG, SGR, FBW ↑; FCR ↓	Munir *et al.*, 2026
29	Banana (*Musa* sp.)	Flower powder	20 g kg^{-1} in feed for 10 weeks	WG, SGR, FBW ↑; FCR ↓	Phinyo *et al.*, 2024
30	Orange (*Citrus sinensis*)	Pulp powder	10% and 20% OP, with or without enzyme supplementation, for 12 weeks	10% OP + enzymes: no adverse effect; 20% OP ± enzymes: FBW ↓; FCR ↑	Tawfik *et al.*, 2022
31	Lemon (*Citrus limon* L.)	Peel powder	1 % and 2 % in feed for 45 days	Growth performance not improved	Abdel Rahman *et al.*, 2019b

Note: WG, weight gain; SGR, specific growth rate; FBW, final body weight; FI, feed intake; FCR, feed conversion ratio; SR, survival rate , ↑, increased or improved; ↓, decreased or reduced.

Table 2. Representative studies on the effects of plant-based feed additives on hematological, physiological, immune, antioxidant, disease-resistance, and gene-expression responses in Nile tilapia

No.	Plant	Preparation form	Dose	Duration	Main improved or modulated parameters	Author – Year
1	Aloe vera (*Aloe vera*)	Leaf extract powder	1-3%	105 days	Hematological parameters improved ↑	Syed *et al.*, 2022
2	Ashwagandha (*Withania somnifera*)	Ethanol extract	2.5-5%	60 days	Intestinal histomorphology improved; IL-1β, TNF-α, and IL-6 ↓ after *S. iniae* challenge	Zahran *et al.*, 2020
3	Green tea (*Camellia sinensis*)	Leaf powder	0.125-2.0 g kg^{-1}	12 weeks	Hematological and biochemical parameters improved; post-challenge survival ↑	Abdel-Tawwab *et al.*, 2010
4	Garlic (*Allium sativum*)	Garlic meal	2 %	60 days	TP, glucose, and LYZ ↑	Yones *et al.*, 2019
5	Turmeric (*Curcuma longa*)	Powder	2-8 g kg^{-1}	8 weeks	WBC, NO, and LYZ ↑; LPI and IL-4 expression ↑	Abdelrazek *et al.*, 2017
6	Moringa (*Moringa oleifera*)	Leaf powder	5%	60 days	WBC ↑; LYZ, IgM ↑; challenge with *A. hydrophila:* PCS ↑	Abd El-Gawad *et al.*, 2020
7	Anise (*Pimpinella anisum*)	Essential oil	0.30%	8 weeks	RBC, Hb, WBC ↑; biochemistry modulated; SOD, CAT, GPx ↑	Tok *et al.*, 2025
8	Blackberry syrup (*Blackberry syrup*)	Syrup	15 g kg^{-1}	90 days	RB, KA, PA, PI, LYZ, MPO, Ig ↑; SOD, CAT ↑; against to *P. shigelloides*: PCS ↑	Yilmaz, 2019
9	Ginger (*Zingiber officinale*)	Powder	10 g kg^{-1} feed	30 days	Hemato-immune and antioxidant responses modulated; post-challenge survival ↑	Naliato *et al.*, 2021
10	Black cumin (*Nigella sativa*)	Powder	30 g kg^{-1} feed	45 days + 14-day challenge	IgM ↑; gene expression of *IL-8*, *IL-10*, *IL-1β*, and immune-related markers ↑; challenge with *B. cepacia*: PCS ↑	Mahboub *et al.*, 2022a
11	Coriander (*Coriandrum sativum*)	Essential oil	0.5-2%	60 days	LYZ and antiprotease ↑; inflammatory/immune-related gene expression modulated; post-challenge survival ↑	Das *et al.*, 2023
12	Pomegranate (*Punica granatum*)	Peel extract	0.3-0.5%	45 days	Biochemical and immune parameters improved; post-challenge survival ↑	Monir *et al.*, 2020
13	Rosemary (*Rosmarinus officinalis*)	Leaf powder	1%	60 days	LYZ ↑; MDA ↓	Abdel-Tawwab *et al.*, 2024
14	Guava leaf (*Psidium guajava*)	Leaf extract	2% in feed	60 days	WBC ↑; LYZ, PA ↑	Abdel-Tawwab & Hamed, 2020
15	Licorice (*Glycyrrhiza glabra*)	Extract	2-4% in feed	8 weeks	LYZ, RB, Ig ↑; against to *A. hydrophila*: PCS ↑	Abdel-Tawwab & El-Araby, 2021
16	Fenugreek (*Trigonella foenum-graecum*)	Methanolic extract	0.09% in feed	90 days	LYZ, PA ↑; SOD ↑; gene expression of *IL-1β*, *TNF-α*, and *TGF-β* ↑; challenge with *A. hydrophila*: PCS ↑	Diab *et al.*, 2023

No.	Plant	Preparation form	Dose	Duration	Main improved or modulated parameters	Author – Year
17	Soursop leaf (*Annona muricata*)	Leaf extract	1% in feed	60 days	TP ↑; LYZ, PA ↑	Maryani *et al.*, 2025
18	Sugar apple (*Annona squamosa*)	Leaf extract	20 g kg^{-1} in feed	60 days	LYZ, NO, C3, PA ↑; SOD, CAT, GSH, TAC ↑; against to *A. sobria*: PCS ↑	Almarri *et al.*, 2023
19	Peppermint (*Mentha piperita*)	Essential oil	0.2-1.0 g kg^{-1}	8 weeks	CAT and SOD ↑; MDA and NO ↓; plasma biochemistry modulated	Aguiar *et al.*, 2023
20	Sugarcane (*Saccharum officinarum*)	Bagasse powder	20 g kg^{-1} in feed	8 weeks	SMLA, SMPA ↑; SL, RB ↑; SP unchanged; immune-related gene expression: IL1, IL8, LBP ↑; antioxidant-related gene expression: GSTα, GPX, GSR ↑	Lumsangkul *et al.*, 2021
21	Mango (*Mangifera indica*)	Seed powder	36.43-45 g kg^{-1}	8 weeks	SMLA, SL ↑; SP unchanged; intestinal morphology improved; immune-related gene expression: IL-1, IL-8, LBP ↑; antioxidant-related gene expression: GSTα, GPX, GSR ↑	Fontana *et al.*, 2024
22	Passionfruit (*Passiflora edulis*)	Peel powder	20 g kg^{-1} in feed	8 weeks	Immune responses ↑; immune-related gene expression: IL-1, IL-8, LBP ↑; antioxidant-related gene expression: GST-α, GPX, GSR ↑;	Outama *et al.*, 2022
23	Makiang (*Syzygium nervosum*)	Seed powder	5 g kg^{-1} in feed	8 weeks	Immune responses ↑; immune-related gene expression: IL-1, IL-8, LBP ↑; antioxidant-related gene expression: GST-α, GPX, GSR ↑;	Le Xuan *et al.*, 2024a
24	Dragon fruit (*Hylocereus undatus*)	Peel powder	80 g kg^{-1} in feed	8 weeks	Immune responses ↑; immune-related gene expression: IL-1, IL-8, LBP ↑; antioxidant-related gene expression: GST-α, GPX, GSR ↑;	Xuan *et al.*, 2024
25	Avocado (*Persea americana*)	Seed powder	10 g kg^{-1} in feed	8 weeks	Immune responses ↑; immune-related gene expression: IL-1, IL-8, LBP ↑; antioxidant-related gene expression: GST-α, GPX, GSR ↑;	Le Xuan *et al.*, 2024b
26	Fishwort (*Houttuynia cordata*)	Powder	10 g kg^{-1} in feed	72 days	SMLA, SMPA ↑; SL, SP, ACH50, PA ↑; RB unchanged;	Srichaiyo *et al.*, 2020
27	Coffee (*Coffea arabica*)	Silverskin powder	20 g kg^{-1} in feed	8 weeks	SMLA, SMPA ↑; SL, SP, ACH50, PI, RB ↑; challenge with *S. agalactiae*: PCS ↑	Van Doan *et al.*, 2021b
28	Pineapple (*Ananas comosus*)	Peel powder	10 g kg^{-1} in feed	8 weeks	SMLA, SMPA ↑; SL, SP, ACH50, PA, RB ↑; immune-related gene expression: IL1, IL8, LBP ↑; challenge with *S. agalactiae*: RPS ↑	Van Doan *et al.*, 2021a
29	Banana (*Musa acuminata*)	Peel waste powder	15 g kg^{-1} in feed	28 days	WBC, NEU ↑; non-specific immune responses and antioxidant enzymes ↑; IL-10, TNF-α, HSP70 expression ↑	Munir *et al.*, 2026
30	Banana (*Musa* sp.)	Flower powder	20 g kg^{-1} in feed	10 weeks	WBC, NEU ↑; NSI ↑; antioxidant enzymes ↑; immune-related gene expression: IL-10, TNF-α, HSP70 ↑; liver histology slightly modulated	Phinyo *et al.*, 2024
31	Orange (*Citrus sinensis*)	Pulp powder	10-20% OP, with or without enzymes	12 weeks	Serum biochemistry, carcass composition, and GHR, IGF-1, FAS, LPL expression modulated	Tawfik *et al.*, 2022

No.	Plant	Preparation form	Dose	Duration	Main improved or modulated parameters	Author – Year
32	Orange (*Citrus sinensis*)	Peel powder	10 g kg^{-1} in feed	100 days	TG, CHOL, AST, ALT, urea, CREA, GLU ↓; IgM, LYZ, PA, PI ↑; SOD, CAT ↑; MDA ↓; HM accumulation in liver/gills ↓	Khalil *et al.*, 2026
33	Lemon	Peel powder	1% and 2% in feed	45 days	Glucose ↓; CAT, GSH ↑; LYZ, MPO, PA, NO ↑; challenge with *A. hydrophila*: RPS ↑;	Abdel Rahman *et al.*, 2019b

Note: TP, total protein; LYZ, lysozyme; WBC, white blood cells; RBC, red blood cells; Hb, hemoglobin; NO, nitric oxide; LPI, lymphocyte proliferation index; IgM, immunoglobulin M; Ig, total immunoglobulin; RB, respiratory burst activity; KA, potential killing activity; PA, phagocytic activity; PI, phagocytic index; MPO, myeloperoxidase; PCS, post-challenge survival; C3, complement component 3; SOD, superoxide dismutase; CAT, catalase; GPx, glutathione peroxidase; GSH, glutathione; TAC, total antioxidant capacity; MDA, malondialdehyde; IL-1, interleukin-1; IL-1β, interleukin-1 beta; IL-4, interleukin-4; IL-6, interleukin-6; IL-8, interleukin-8; IL-10, interleukin-10; TNF-α, tumor necrosis factor alpha; TGF-β, transforming growth factor beta; HSP70, heat shock protein 70; SMLA, skin mucus lysozyme activity; SMPA, skin mucus peroxidase activity; SL, serum lysozyme activity; SP, serum peroxidase activity; ACH50, alternative complement hemolytic activity; LBP, lipopolysaccharide-binding protein; GST-α, glutathione S-transferase alpha; GSR, glutathione reductase; RPS, relative percentage survival; NEU, neutrophils; NSI, non-specific immunity; MCHC, mean corpuscular hemoglobin concentration; HCT, hematocrit; GHR, growth hormone receptor; IGF1, insulin-like growth factor 1; FAS, fatty acid synthase; LPL, lipoprotein lipase; TG, triglycerides; CHOL, cholesterol; AST, aspartate aminotransferase; ALT, alanine aminotransferase; CREA, creatinine; GLU, glucose; HM, heavy metals.

integrity, nutrient absorption, and metabolic efficiency. Phytogenic compounds may enhance feed intake by improving palatability and modulating appetite-related signals, while also increasing the activity of digestive enzymes such as proteases, amylases, and lipases (Faheem *et al.*, 2023). In parallel, their effects on gut morphology and mucosal integrity may improve the absorptive surface area and nutrient transport, whereas antioxidant and anti-inflammatory actions can reduce metabolic costs associated with stress and tissue damage. These mechanisms provide a physiological basis for the improved SGR, WG, and FCR reported in several studies (Soengas *et al.*, 2025). However, growth responses remain variable and dose-dependent, indicating that PBFAs should be viewed as modulators of digestive and metabolic efficiency rather than universal growth promoters. Benefits may decline when inclusion levels are excessive, raw materials are poorly standardized, or the additive is incompatible with the basal diet.

Immunomodulatory activity

Immunomodulation is one of the most consistently reported effects of phytogenic supplementation in Nile tilapia. Bioactive compounds such as polysaccharides, alkaloids, flavonoids, and phenolic compounds may enhance the responsiveness of macrophages, neutrophils, and lymphocytes, thereby strengthening both cellular and humoral innate defenses (Sumana *et al.*, 2025). These mechanisms provide a biological basis for the commonly observed increases in lysozyme activity, the phagocytic capacity, the respiratory burst, serum IgM, and immune-related gene expression. At the molecular level, phytochemicals may regulate Toll-like receptor signaling, cytokine production, and NF-κB-associated inflammatory pathways, supporting immune readiness while preventing excessive inflammation. However, immunostimulation should not be interpreted as universally beneficial. Excessive or prolonged activation may impose metabolic costs or disturb immune homeostasis. Therefore, the practical value of PBFAs lies in promoting balanced immune competence rather than maximal immune activation.

Antioxidant and hepatoprotective mechanisms

Under intensive culture conditions, oxidative stress can compromise growth, immunity, tissue integrity, and stress tolerance in Nile tilapia. Plant-based antioxidants may counteract these effects through direct reactive oxygen species scavenging and the activation of endogenous antioxidant defenses, including SOD, CAT, and GPx (Adilbekov *et al.*, 2025). A key regulatory route is the Nrf2/Keap1–ARE pathway, through which antioxidant and detoxification genes are upregulated, leading to reduced lipid peroxidation and lower MDA levels. These mechanisms explain why improved antioxidant status often coincides with better immune responses and physiological resilience. Hepatoprotective effects may also arise from reduced oxidative damage and an improved detoxification capacity, but this evidence remains less conclusive because many studies rely mainly on biochemical indicators. Stronger confirmation requires the integration of liver histology, oxidative-stress markers, and hepatic gene-expression data.

Antimicrobial and antiparasitic properties

Phytogenics may also support disease resistance through direct antimicrobial and antiparasitic actions. Phenolics, essential oils, alkaloids, saponins, and tannins can disrupt microbial membranes, inhibit enzyme activity, attenuate virulence, interfere with quorum sensing, and reduce biofilm formation (Khanashyam *et al.*, 2023). These actions may lower pathogen pressure and complement host immune defenses, helping explain the improved post-challenge survival reported in some studies. Saponins and tannins may further affect ectoparasites by damaging surface structures and impairing osmoregulatory function (Doan *et al.*, 2020; Singh *et al.*, 2025). However, antimicrobial activity demonstrated under in vitro conditions does not necessarily translate into effective in vivo protection, because bioavailability, metabolism, pathogen load, feeding duration, and environmental stress can strongly modify outcomes. Therefore, antimicrobial mechanisms should be evaluated

together with immune responses, microbiome changes, and pathogen-challenge results.

Endocrine and reproductive regulation

Reproductive modulation by PBFAs is mainly linked to bioactive compounds capable of interacting with endocrine pathways. Steroidal saponins, flavonoids, and phytoestrogens may influence gametogenesis, gonadal development, and sex differentiation by regulating steroidogenesis, aromatase activity, androgen–estrogen balance, sex steroid receptors, and hypothalamic–pituitary–gonadal axis signaling (Otieno Karanja, 2025). These mechanisms provide a basis for reported effects on male-biased sex ratios, testicular development, reproductive gene expression, and gonadal maturation in tilapia. Nevertheless, endocrine responses are highly dose dependent and less predictable than those induced by synthetic hormones. The current evidence therefore supports PBFAs more strongly as modulators of reproductive physiology or the broodstock condition than as reliable tools for complete sex reversal. Future studies should clarify dose thresholds, endocrine safety, strain-specific responses, and regulatory acceptability before hatchery-scale application.

Challenges and Future Prospects for PBFAs in Nile Tilapia Aquaculture

PBFAs offer considerable potential for improving growth, health, stress tolerance, and sustainability in Nile tilapia aquaculture. However, their transition from experimental use to reliable commercial application remains limited by variability in raw materials, incomplete dose optimization, insufficient mechanistic validation, and unclear regulatory pathways. Therefore, future development should move beyond screening individual botanicals toward standardized, mechanism-informed, and production-oriented feed solutions.

Key Challenges

Inconsistent composition and efficacy: The efficacy of plant-based additives depends strongly on their phytochemical composition. However, these profiles vary with genotype, geographical origin, cultivation conditions, harvest stage, plant part, processing, extraction, and storage. Consequently, the same botanical species may differ markedly in bioactive concentration and biological activity across studies, reducing reproducibility, limiting cross-study comparison, and hindering the development of standardized commercial products with predictable efficacy (Taştan & Salem, 2021).

Insufficient dose and application standardization: Optimal inclusion levels, additive forms, and feeding durations remain poorly defined for Nile tilapia. Current studies often test limited dose ranges and use different preparations, including crude powders, aqueous or organic extracts, essential oils, and purified compounds, which differ in potency, palatability, stability, and bioavailability. Effective doses may also vary with fish size, life stage, health status, basal diet, and culture system. Because some bioactives have narrow effective ranges, low inclusion may be ineffective, whereas excessive doses may reduce feed intake, disturb nutrient balance, introduce anti-nutritional effects, or induce physiological stress (Iheanacho *et al.*, 2025). Dose–response validation and practical feeding windows are therefore essential before commercial application.

Limited mechanistic resolution: Although plant-based additives often improve growth, immunity, antioxidant status, and disease resistance, the mechanisms remain insufficiently defined. In Nile tilapia, key pathways such as Nrf2/ARE, NF-κB, Toll-like receptor signaling, cytokine regulation, digestive enzymes, microbiome modulation, and endocrine responses are rarely assessed together (Mohammadi *et al.*, 2022). This makes it difficult to determine whether observed benefits are directly caused by the additive or indirectly associated with improved gut health and physiological status, thereby limiting mechanism-based formulation and context-specific recommendations.

Diet and microbiome contingencies: The efficacy of plant-based additives is strongly influenced by interactions with the basal diet and

gut microbiome. Phytochemicals may bind to feed components, be degraded during processing, or be transformed by intestinal microbes, altering their bioavailability and activity. These effects are particularly relevant in plant-protein-rich aquafeeds, where fibers, oils, anti-nutritional factors, and other functional ingredients may reshape responses (Piazzon *et al.*, 2017). Although microbiome-mediated effects on digestion, immunity, and disease resistance are increasingly reported, causal links with metabolites, intestinal morphology, and pathogen resistance remain insufficiently demonstrated.

Regulatory and economic constraints: Regulatory pathways for botanical additives remain unclear in many regions, particularly regarding safety evaluation, maximum inclusion limits, residues, contaminants, endocrine activity, and antimicrobial or reproductive claims. Commercial use also requires reliable sourcing, standardization, stabilization, shelf-life assurance, and quality control, which may increase production costs (Speranza *et al.*, 2021). Without clear quality standards and cost–benefit validation, plant-based additives may remain less competitive than conventional feed additives, especially in price-sensitive tilapia systems.

Future Prospects

Future research should move from exploratory trials toward standardized, tilapia-specific, and commercially scalable phytogenic solutions. Priority should be given to authenticated plant materials, defined plant parts, controlled processing, and quantitative profiling of key bioactive compounds. Chemical standardization, metabolomic fingerprinting, and functional bioassays should be combined to improve batch consistency, define dose–response relationships, and establish effective ranges, safety margins, and practical feeding windows.

Mechanistic studies should link performance outcomes with digestive enzyme activity, intestinal morphology, gut microbiota, immune gene expression, antioxidant pathways, and pathogen-challenge responses. Multi-omics approaches may help identify biomarkers of efficacy and risk under farm-relevant stressors such as high stocking densities, poor water quality, heat stress, and bacterial infection. In parallel, formulation strategies such as encapsulation, fermentation, phytogenic blends, and synbiotic combinations should be optimized to improve stability, palatability, bioavailability, and efficacy in practical aquafeeds.

Commercial translation will require long-term farm trials, cost–benefit analysis, sustainability assessment, and regulatory alignment. Locally available medicinal plants and agro-industrial by-products may support cost-effective and bio-circular-green aquafeed development, but their use must be accompanied by clear quality standards, safety evaluation, residue monitoring, and transparent labeling. Overall, a successful application will depend on converting promising experimental findings into standardized, safe, economically viable, and regulation-ready feed additives.

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