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Plant-derived feed ingredients in aquaculture: A comprehensive review of their effects on fish growth performance and nutritional outcomes

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Abstract

The dynamics of the fisheries and aquaculture industry have evolved rapidly in recent decades, with a marked increase in production capacity, trade, business, and consumption, which has led to additional pressure on aquaculture feed resources. Despite fishmeal being a vital source of high-quality protein in farmed fish, its application in fish feed has been challenged on several fronts, including its scarcity, shortage, and environmental degradation. Plant-based protein ingredients are considered potentially useful alternatives to animal-based protein sources because they are readily available, less expensive, and less reliant on aquatic resources. This review critically summarizes the existing literature on the use of plant-based proteins in fish feed and their processing to enhance their suitability. Major sources of plant-based proteins, including soybean meal, pea protein, rapeseed meal, and corn gluten, are discussed in terms of their protein content, amino acid composition, and the presence of anti-nutritional factors (ANFs), which can limit the digestion and absorption of other nutrients. This review also suggests that the application of advanced processing technologies, including fermentation, heat processing, enzyme addition, and extrusion, can be utilized to reduce ANFs and improve the bioavailability of nutrients. The economic and environmental impact of utilizing plant proteins is also explained in the context of reducing feed costs and making fish farming more sustainable. Finally, the research areas for the future were determined, including the development of feeds, the adoption of new processing methods, and the combination of plant proteins with other sustainable foods to meet the increased global demand. This synthesis provides valuable insights for feed manufacturers, aquaculture producers, and researchers interested in adequate sustainability and efficiency of aquaculture by innovative plant-based feeding strategies.

1. Introduction

Approximately 70% of aquaculture (fish and crustaceans) is highly dependent on protein-rich feeds. Over the years, aquaculture has emerged as a significant component of food security, economic development, and nutritional sustainability across the world in response to declining wild fish stocks as a result of overexploitation and destruction of the ecosystems (Basir et al. 2024; Abeysinghe et al. 2025). The accelerated expansion of aquaculture has occurred to meet the increased human protein demand due to the growing human population and increasing urbanization (Akkozova et al. 2025). Globally, the aquaculture industry has increased exponentially to a record 130.9 million tonnes in 2022 and is expected to continue growing through 2032 (Dongyu 2024; Helmizuryani et al. 2024). Therefore, the sustainability of aquaculture has become vital to sustain this expected growth without compromising the integrity of the environment, social equity, and resource efficiency (Costello et al. 2020; Hasan et al. 2025). Traditional aquaculture is highly dependent on fishmeal and fish oil from wild fisheries, which have become scarcer, costly and environmentally unfriendly. This dependency on the finite marine resources has resulted in a major debate to find alternative feed ingredients in order to reduce the environmental pressure and enhance economic viability (Naylor et al. 2021; Oleinikova et al. 2024). The utilization of plant-based feed ingredients has been one of the options considered because of their broad availability, affordability, and the possibility to avoid relying on marine protein sources (Turchini et al. 2019; Paritova et al. 2025; Noor and Alisha 2026). Plant protein sources derived from from legume, cereals, and oilseeds offer adequate nutritional benefits and are usually cheaper and less damaging to the environment (Arshad et al. 2025; Zafar et al. 2025). Nevertheless, challenges in their application in aquafeeds include the availability of anti-nutritional factors, the unbalanced ratio of amino acids, and decreasing palatability that could adversely influence the growth and health of fish (Krogdahl et al. 2010; Khan et al. 2023). Consequently, the effects of the plant-based feed ingredients on the growth and nutritional success of the fish require a precise explanation to achieve sustainable and nutritionally sufficient aquafeeds (Glencross et al. 2020a). Critically, the review evaluates the literature that exists concerning the use of plant-based feed ingredients in aquaculture in terms of their capabilities in improving the growth performance and the nutritional performance of fish. It compares significant sources of plant proteins in aquaculture feed, their nutrition, and technological advances that have justified their use in aquafeeds.

2. Methodology

A comprehensive and systematic review was carried out with a structured literature search strategy, and peer-reviewed articles published between 2010 and 2025 were searched using scientific databases, such as Web of Science, Scopus, PubMed, and Google Scholar. The following keywords and Boolean combinations were used: "plant-based feed ingredients" AND aquaculture", "plant protein sources" AND "fish growth performance", "soyabean meal replacement" AND "fish nutrition", "phytogenic feed additives" AND "fish nutrition", "plant-derived proteins" AND "feed efficiency" AND " fish". Only original research papers and review papers published in English were considered. Inclusion criteria included studies that evaluated plant-derived feed ingredients in aquaculture species and those articles that reported growth performance indicators, including weight gain and feed conversion ratio. It also included studies assessing nutritional composition or digestibility and peer-reviewed publications. In contrast, exclusion criteria include studies not related to aquaculture species, articles without measurable growth, conference abstracts without full data, and non-English publications. After screening titles and different abstracts, relevant full-text articles were evaluated for eligibility.

3. Aquaculture feed types and production: Incorporation of plant-based ingredients

Aquaculture feeds play a crucial role in supporting the growth, productivity, and health of cultured aquatic species, and are highly diverse in their composition and physical form, depending on the species, culture system, and production purposes (Mehta 2025) and different ingredients used in aqua-nutrition are summarized in Table 1. Aquafeeds have traditionally been based on fishmeal and fish oil from wild marine fisheries, which currently contribute approximately 60% of fishmeal and 80% of fish oil consumed in aquaculture (Hodar et al. 2020). However, marine ingredient sustainability and cost concerns have impelled the development and use of alternative feed ingredients, particularly plant-based protein sources (Hossain et al. 2024). Aquaculture feeds can be broadly divided into natural feeds, supplementary feeds, and complete formulated feeds (Tacon et al. 2022). Natural feeds contain live plankton and detritus naturally found in the environment that may not always be able to sustain intensive culture systems (FAO 2018). Supplementary feeds are cheap agricultural by-products or carbohydrate-rich substances that partially satisfy the nutritional requirements (Ataguba et al. 2017). Complete formulated feeds are well-balanced to contain all the necessary nutrients required for optimal fish growth. The feed is usually provided in dry form, typically in pellets or crumbles, which enable controlled feeding and nutrition to be more readily available (Tacon and Metian 2015). The physical characteristics of feeds, i.e., whether they are dry, moist, or wet, also affect the stability of the feed, its palatability, and nutrient availability (Tacon et al. 2011). Soybean meal, pea protein, rapeseed meal, corn gluten meal, and other oilseed cakes are the plant-based ingredients that are widely used in aquafeeds and are mainly used to decrease the use of fishmeal (Glencross et al. 2020a). These ingredients are processed by grinding, mixing, conditioning, and pelletizing/extrusion to enhance their nutritional content and physical characteristics (Siddik et al. 2024; Fitrianggi et al. 2025; Kusuma et al. 2025). In particular, the extrusion process employs pressure and heat to reduce ANFs like phytates and protease inhibitors, which reduces digestibility and feed stability. A further method of ANFs denaturation

Table 1. Plant-derived feed ingredients used in aquaculture, their nutritional characteristics, advantages, and limitations

Plant feed	Crude protein (%)	Nutritional characteristics	Advantages	Limitations	References
Soybean Meal	44-48	High-quality protein with balanced amino acids, contains fiber, and ANFs	Widely available, cost-effective, good protein digestibility	The presence of ANFs can reduce digestibility and growth, and requires heat treatment to reduce ANFs	(Zhang et al. 2023)
Pea Protein	22-25	Moderate protein with good digestibility, low in methionine, contains tannins and ANFs	Sustainable, low-cost, less allergic, and improves palatability	Less essential amino acid content, ANFs affect nutrient absorption, and high fiber content	(Prakash et al. 2025)
Rapeseed Meal	35-40	Moderate protein, contains glucosinolates and fiber, good amino acid profile, low lysine and methionine	Regionally available, cost-effective, and a good source of protein and energy	Glucosinolates can reduce palatability and thyroid function, high fiber reduces digestibility, and requires processing	(Kaiser et al. 2022)
Corn Gluten Meal	60-70	Very high protein concentration, rich in leucine and glutamic acid, low lysine content	High protein density, good energy source, widely used in combination with other proteins	Poor lysine content, low palatability, limited amino acids, and high fiber content	(Gyan et al. 2024)
Lupin Meal	30-40	High protein, rich in arginine, bitter varieties contain alkaloids, and require detoxification	Good protein quality, sustainable legume source. Potential for high inclusion after processing	Contains alkaloids and ANFs, requires soaking or fermentation, variable palatability	(Malarvizhi et al. 2024)
Mustard oil cake	35-38	Moderate protein, contains essential fatty acids, presence of ANFs such as glucosinolates	Locally available in some regions, cost-effective, good energy source	Toxic compounds, if not processed, ANFs reduce nutrient availability, limit use in some species	(Sultana et al. 2012)
Rice Bran	12-15	Low protein, high fiber and liquid content, rich in vitamins and minerals	Widely available, good energy source, inexpensive	Prone to rancidity, Low protein, high fiber reduces digestibility, limits amino acid balance	(Ranjan et al. 2022)
Cottonseed Meal	40-45	High protein, contains free gossypol and cyclopropenoid fatty acids, low lysine content	Abundant in cotton-producing regions. Less expensive than soybean meal	Toxicity risks due to gossypol, high fiber, and low lysine require detoxification and careful inclusion	(Kumar et al. 2014)
Alfalfa Meal/ Protein	15-20 (Meal) 60-70 (Protein)	Moderate protein, rich in vitamins, minerals, and some bioactive compounds, low ANFs	Safe for inclusion, supports gut health, sustainable, and local sourcing potential	Lower protein content in meal form, protein concentration requires advanced processing, and limited large-scale use	(Coburn 2019)

is a dual-mode fermentation and enzyme supplementation procedure that enhances the bioavailability of nutrients, as well as the synthesis of bioactive compounds, which may reinforce the immune system and gastrointestinal health in fish (Fei et al. 2023).

Although technology has improved, there are some obstacles to the use of plant proteins in aquafeed, such as a high fiber content, inconsistent amino acid composition, and low palatability (Glencross et al. 2020b; Ullah 2024; Rakhmonov et al. 2025). To address these challenges, amino acid supplementation and the use of a combination of different protein sources in feed formulation have been commonly employed to match the specific nutritional requirements of carnivorous and omnivorous fish species. The nutritional needs depend on the species and the life stage of a fish; for example, starter feeds require high levels of digestible ingredients with minimal fiber quantities. Optimization of feeding rate and schedule is necessary to maximize feed efficiency and minimize wastage, while guaranteeing water quality (Boyd and Tucker 2012). The amount of essential amino acids, including methionine and lysine, in plant proteins is usually not as much as in fishmeal, so their application as sole protein in the diet of carnivorous fish is limited. Conversely, they are economical, readily available, and less harmful to the environment, which takes the strain off the wild fish stocks and ensures more sustainable aquaculture systems (Hussain et al. 2024). In addition, the production of plant-derived proteins is locally possible, which also decreases emissions associated with transportation (Jouan et al. 2020). However, there are still issues like the lack of consistency in the quality of the ingredients, reduced protein levels as compared to fishmeal, and the need to use additional additives like essential amino acids and micronutrients to meet the nutritional requirements of high-performance fish (Warwas 2023). Also, the feed formulation should overcome the problem of water quality and palatability due to high suspended solids concentration caused by plant-based feeding (Hossain et al. 2024).

4. Amino acid composition of alternative plant proteins

Fishmeal has long been the gold standard of protein source in aquaculture, as it is high in protein content, and balanced in amino acids (Gasco et al. 2018). However, increasingly sustainable variants are available, Table 2 provides a comparative analysis of the content of essential amino acids (EAA) in the various plant-based protein ingredients compared to fishmeal. Even though processed soybean protein isolate (PI) and pea protein concentrate (PC) contain relatively high amounts of crude protein, they have a deficiency in EAAs, including methionine and lysine (Van den Berg et al. 2022). Generally, most vegetable sources contain lysine at 20-70% of the level in fishmeal and the deficiency in methionine is even more severe, especially with faba bean and lupin species. These shortages underscore the need to scientifically supplement or combine plant blends of proteins to meet the nutritional needs of cultivated fish species. The nutrition of different plant-based raw materials of feed was evaluated in comparison to fishmeal in terms of total protein content and essential

Table 2. Plant-derived feed ingredients used in aquaculture, their nutritional characteristics, advantages, and limitations

Source	Protein (%)	Lys (CS)	Met (CS)	Cs	Arg (CS)	Trp	Leu (CS)	Ile (CS)	Phe	His	Thr (CS)	Tyr	Val	Agr/Lys (CS)	References
Fishmeal	70	7.7	2.7	0.8	6.2	-	6.9 (4.2↓)	4.2 (=)	4.0	2.7	3.4 (17.1↓)	3.6	3.9	2.34 (182↑)	(Cho and Kim 2011)
Faba bean	29	6.3 (16↓)	0.8 (70.4↓)	1.2	9.0 (45.2↑)	-	7.3 (1.4↑)	4.2 (=)	3.9	2.3	3.8 (7.3↓)	4.8	4	2.26 (172.3↑)	(Dhull et al. 2022)
Faba bean PC	63	6.63 (11.6↓)	0.71 (73.7↓)	1.1	8.68 (40↑)	-	5.25 (27.1↓)	2.46 (41.4↓)	2.95	1.97	2.62 (36.1↓)	3.11	2.29	2.62 (215.7↑)	(Badjona et al. 2023)
Lupin (*L. angustifolius*)	33.8	4.7 (37.3↓)	0.7 (74.1↓)	1.5	11.0 (77.4↑)	0.83	7.3 (1.4↑)	4.6 (9.5↑)	4.25	3.3	4.1 (=)	4.25	4.75	1.75 (110.8↑)	(Lemus-Conejo et al. 2023)
Dehulled lupin (*L. albus*)	42	5 (33.3↓)	0.8 (70.4↓)	1.6	11.3 (82.3↑)	-	7.1 (1.4↓)	4.2 (=)	4.7	2.5	3.8 (7.3↓)	3.1	4.8	1.17 (41↑)	(Pereira et al. 2022)
Lupin PI	61	3.44 (54.1↓)	0.6 (77.8↓)	0.33	9.02 (45.5↑)	0.99	7.31 (1.5↓)	4.26 (1.4↑)	4.95	2.39	3.51 (14.4↓)	3.31	4.73	1.1 (32.5↑)	(Lo et al. 2021)
Fermented Lupin	40	5.57 (25.7↓)	0.82 (69.6↓)	1.4	9.75 (57.3↑)	-	7.13 (1↓)	3 (28.6↓)	4.75	2	3.13 (23.7↓)	3.25	3.5	1.23 (48↑)	(Ritter et al. 2022)
Pea seed	23.9	7.2 (4↓)	1.0 (63↓)	1.4	8.4 (35.5↑)	0.6	10.2 (41.7↑)	5.45 (29.6↑)	7.69	3.86	4.43 (8↑)	3.13	6.24	0.94 (13↑)	(Daba and Morris 2022)
Field pea PC	46.5	7.61 (1.5↑)	0.9 (66.7↓)	1.25	8.32 (34.2↑)	1.44	7.08 (1.7↓)	5.31 (26.4↑)	5.2	2.58	4.18 (2↑)		4.97	1.18 (42↑)	(Rasskazova and Kirse-Ozolina 2020)
Pea PI	80	6 (20↓)	0.78 (71.1↓)	0.25	7.4 (19.4↑)	1.2	7.7 (6.9↑)	4.6 (9.5↑)	5.1	2.7	3.7 (9.8↓)	3.5	4.5	1.19 (43.4↑)	(Lam et al. 2018)
Bambara nut	None	8 (6.7↑)	0.64 (76.3↓)	2.41	7.48 (20.6↑)	1.4	7.7 (6.9↑)	4.6 (9.5↑)	5.1	2.7	3.8 (7.3↓)	3.5	4.8	1.16 (39.8↑)	(Tan et al. 2020)
Full fat soybean meal	36	6.3 (16↓)	1.29 (52.2↓)	nan	7.44 (20↑)	1.5	7.9 (9.7↑)	4.6 (9.5↑)	5.1	2.6	4.3 (4.9↑)	3.5	4.8	1.16 (39.8↑)	(Aderibigbe et al. 2020)
Soybean (expeller)	43.5–49.3	6.3 (16↓)	1.4 (48.2↓)	1.6	7.5 (21↑)	1.4	7.7 (6.9↑)	4.6 (9.5↑)	5.1	2.7	3.8 (7.3↓)	3.5	4.8	1.16 (39.8↑)	(Villegas et al. 2024)
Soybean (dehulled)	53.5	6.3 (16↓)	1.4 (48.2↓)	1.6	7.3 (17.7↑)	1.5	7.9 (9.7↑)	4.6 (9.5↑)	5.1	2.6	4.3 (4.9↑)	3.5	4.8	1.16 (39.8↑)	(Joshi and Varma 2016)
Soy PC	67–72	6.3 (16↓)	1.3 (51.9↓)	1.25	7.3 (17.7↑)	1.2	7.8 (8.3↑)	4.5 (7.1↑)	5.2	2.5	3.5 (14.6↓)		4.6	1.2 (44.6↑)	(Li et al. 2020)
Soy PI	90–92	6 (20↓)	1.0 (63↓)	nan	7.2 (16.1↑)	7.2 (16.1↑)	1.2	7.8 (8.3↑)	4.5 (7.1↑)	5.2	2.5	3.5 (14.6↓)	-	4.6	(Zheng et al. 2022)
Fermented soybean	48.9	6.2 (17.3↓)	1.6 (40.74↓)	nan	7.8 (25.8↑)	1.23	8.2 (13.9↑)	4.91 (16.9↑)	5.5	2.66	4.1 (=)	-	4.1	1.3 (56.6↑)	(Jang et al. 2021)
Peanut meal (corticated-decorticated)	32–46.5	2.29 (69.5↓)	0.53 (80.4↓)	nan	5.28 (14.8↓)	0.48	3.18 (55.8↓)	1.80 (57↓)	2.37	1.26	1.40 (65.9↓)	-	2.08	2.3 (177↑)	(Asen et al. 2021)
Peanut meal expeller	34.1-46.5	2.46 (67.2↓)	0.43 (84.1↓)	nan	5.01 (19.2↓)	0.37	3.03 (57.9↓)	1.58 (62.4↓)	2.32	1.05	1.27 (69↓)	-	2.06	3.43 (313↑)	(Karr-Lilienthal et al. 2006)
Alfalfa leaf PC (chloroplastic)	53.22	4.57 (39.1↓)	0.3 (88.9↓)	nan	5 (19.3↓)	4	8 (11.1↑)	4.57 (8.8↑)	5.2	2.4	4.5 (9.8↑)	-	5.2	1.1 (32.5↑)	(Sahni et al. 2020)
Carob seed germ meal	34.8	6.49 (13.5↓)	1.41 (47.8↓)	nan	14.1 (127↑)	-	7.1	3.88 (7.6↓)	3.64	3.5	4.14 (1↑)	-	4.31	2.17 (161.4↑)	(Mamone et al. 2019)

CS: Codon set; Lys: Lysine; Met: Methionine; Cs: Cysteine; Arg: Arginine; Trp: Tryptophan; Leu: Leucine; Ile: Isoleucine; Phe: Phenylalanine; His: Histidine; Thr: Threonine; Tyr: Tyrosine; Val: Valine; PC: Protein concentrate; PI: Protein isolate amino acids (EAA) mixture. Fish meal typically contains 70% crude protein, with optimal amino acid levels, especially lysine (7.7%) and methionine (2.7%), critical for fish growth and development (Ebeneezar et al. 2022). In this Table 2, the absolute values of amino acids present in each of the ingredients, as well as the change in the percentage values relative to fishmeal, have been presented using arrows. A downward arrow identifies a decrease in the content of a particular amino acid compared to that of fishmeal, and vice versa. As an example, lysine 6.3 (16 ↓) in faba bean indicates that lysine is 6.3% in the content, which is 16% lower than in fishmeal (Peng et al. 2022). In contrast, the higher arginine content as inscribed in the label of the product called Arginine 9.0 (45.2↑). The arginine level was 45.2% more than fishmeal (Mao et al. 2024). On the other hand, plant protein sources differ widely in their protein content and EAA composition. The processed ingredients such as soy protein isolate (90-92%), pea protein isolate (80%), and faba bean protein concentrate (63%) are high in crude protein content compared to their unprocessed or sparsely processed forms, such as faba bean (29%) and pea seed (23.9%), restricting their use in high-performance fish diets (de Paiva Gouvêa et al. 2023). Though lysine and methionine are limiting in almost all plant ingredients, there are many plant-origin protein sources, such as carob seed germ meal, lupins, and faba beans, which show arginine excess by 35-100% compared to fishmeal (Ahmad et al. 2023). The resultant high arginine-to-lysine (Arg/Lys) ratio could potentially interfere with the balance of amino acids and nitrogen metabolism of the fish. For example, peanut meal expeller presents a ratio of Arg/Lys equal to 3.43, which is far greater in comparison with fishmeal (2.34). Similar but moderate variations are also noted in other essential amino acids like leucine, isoleucine, phenylalanine, and valine as well compared to fishmeal.

5. Effects on fish growth performance

The incorporation of plant-based proteins in aquaculture has been widely studied regarding its effects on fish growth and performance (Table 3; Fig. 1), yielding both encouraging results and significant limitations (Napier and Betancor 2023). Partial replacing of fishmeal with plant proteins up to 50%, has successfully maintained or even enhanced growth performance in many fish species when inclusion levels and ingredient quality were well controlled (Wang MengLe et al. 2018). For example, *Labeo rohita* showed that a 50% replacement of fishmeal with plant protein ingredients produced markedly higher final body weights (153.62 g) than diets containing 75% fishmeal replacement due to increased ANF levels and imbalance of nutrients (Khan et al. 2003). Similarly, Indian major carps receiving plant-based protein diets at 2% of their body weight exhibited optimum growth and nutrient utilization, whereas feeding at higher levels reduced growth efficiency (Kumar et al. 2022). Carnivorous fish such as rainbow trout have been shown to increase in size and grow faster when plant-based diets are appropriately formulated. Increase in growth rate increased (42%) and feed intake (30%) has been reported after successive feeding trials (Geurden et al. 2013). Meta-analytical studies revealed that inclusion of fermented plant proteins in fish diets significantly improved weight gain, specific growth rate, and feed conversion ratio in both fresh and marine water species of fish, with faster growing carnivorous fish such as European seabass exhibiting 15-fold growth improvement (Akter et al. 2024).

Success of plant-based protein replacements in fish feed relies on a number of factors such as amino acid supplementation, palatability and processing technology (Akter et al. 2024). Carnivorous fish species require a precise balance of essential amino acids, particularly methionine and lysine, which are frequently supplemented in plant proteins to approximate the nutritive value of fishmeal (Xing et al. 2024). Palatability issues of the plant-based ingredients can be addressed either through the addition of feed attractants, such as krill meal or the use of fermentation processes, which will enhance feed flavor and digestibility (Kuebutornye et al. 2024). Generally, inclusion levels of 30-50% of fishmeal are considered feasible under standard conditions and higher replacement levels need further processing or supplementation in order to prevent growth suppression (Hussain et al. 2024).

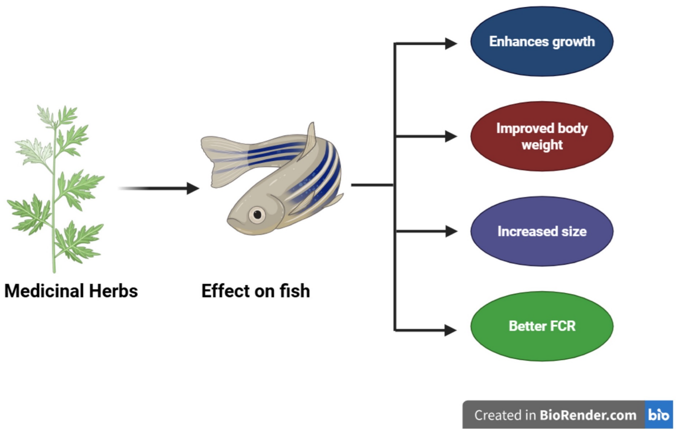

Fig. 1. *Effect on fish growth performance*

Table 3. Effects of plant-derived feed ingredients on fish growth performance

Fish species	Plant ingredient	Fishmeal replacement level (%)	Growth performance	References
Labeo rohita	Soybean meal, Pea Protein	50	Increases final weight and improves FCR at 50% replacement	(Akter et al. 2024)
Rainbow trout	Fermented plant protein blends	30-40	42% higher growth rate and 30% increased feed intake	(Engin and Koyuncu 2023)
European seabass	Fermented soybean meal	40	12-15% higher growth rates	(Yang et al. 2022)
Nile Tilapia	Corn gluten, soybean meal	40	Comparable growth to fishmeal diets	(Awad et al. 2024)
African catfish	Moringa leaf meal	10-20	Improved growth and FCR, rich in micronutrients, suitable as a partial replacement	(Zhang et al. 2020)
Cirrhinus mrigala	Moringa leaf meal	Up to 20	Enhanced growth, digestibility and mineral content	(Faisal et al. 2024)
Catla catla	Rice bran	Up to 20	Supported moderate growth, lower protein content	(Priyadarshini et al. 2011)
Puntius sophore	Groundnut cake	15-25	Positive growth if supplemented with lysine/ methionine, risks of aflatoxins	(Hasan and Chakrabarti 2009)

6. Nutritional outcomes and health implications

To counter the nutritional limitations of plant-based feed ingredients, the use of innovative processing methodologies, specifically the microbial fermentation method, has gained much attention because of their potential to enhance the nutrient availability as well as reducing the ANFs in plant-based aquafeeds (Table 4). Fermentation results in the increase of bioavailability of proteins, lipids as well as carbohydrates by breaking down the complex molecules and disintegration of ANFs, thereby facilitating the nutrient digestion and absorption in fish. Several studies have demonstrated improvements in the palatability and digestibility of fermented plant proteins, which translated into improved growth performances and feed conversion efficiency across a wide range of species including carnivorous species of fish, which are most sensitive to plant-based diets (Manikandan et al. 2020). In addition to nutritional improvements, fermentation can lead to the production of bioactive constituents, such as antioxidants, anti-inflammatory compounds, prebiotics, and probiotics, which aid the immune system and GI tract (Wei et al. 2021). Fermented plant-based ingredients are not only nutritious but also exert health-promoting effects. For example, the *Bacillus* species fermentation positively impacts the nutritional value of plant proteins and exerts probiotic effects by suppressing intestinal pathogens and improving intestinal morphology (Chen et al. 2024; Rashid et al. 2024a). This dual functionality of nutritional improvement and probiotic action enhances nutrient uptake, fish health, and overall fish quality, which are critical factors for sustainable fish farming. Additionally, non-starch polysaccharides and other ANFs decrease by solid-state fermentation of plant feed mixtures, including rapeseed, soybean, rice bran, sunflower seed meals, which further enhances the digestibility and growth performance of fish species such as the European sea bass (Vieira et al. 2023).

The usage of plant-derived ingredients in aquafeeds as alternative to fishmeal has prompted immense interest because of environmental sustainability, though the fishmeal is recognized as nutritionally superior protein source (Hussain et al. 2024). Given the adverse effects ANFs on fish health and production, different strategies have been developed and implemented in the production of aquafeeds to mitigate these problems and complement the nutritional quality of plant-based feed ingredients (Tachie et al. 2023; Rashid et al. 2024b). A comparative summary of major processing techniques, their application, purpose, advantages, and limitations, is given in Table 5 to illustrate how they enhance the quality and effectiveness of the plant-derived feed ingredients used in the aquaculture sector.

7. Therapeutic roles of medicinal plants and herbs in aquaculture

The growing interest in the use of medicinal plants and herbs in aquaculture is not only because of their nutritional properties but also their therapeutic properties in enhancing fish health. These herbs and medicinal plants are endowed with a wide variety of bioactive

Table 4. Key anti-nutritional compounds of plant-based elements in aquafeed

Anti-nutritional factors	Source	Harmful effects on fish	Tolerable dietary levels	Amelioration techniques	References
Protease inhibitors	Soybean meal, groundnut oil cake	Pancreatic hypertrophy, hyperplasia, reduced protein digestion and amino acid utilization, growth retardation	Salmonids:<5mg/g Nile tilapia:<1.6 mg/g; carp:>8.3 mg/g problematic	Moist heat treatment, extrusion, fermentation, germination, amino acid supplementation	(Francis et al. 2001)
Phytates	Legumes, cereals, oilseed meals	Reduced protein, carbohydrate and mineral utilization, skeletal deformities, reduced thyroid function, cataracts, increased mortality	<0.5%(5g/kg) in diet for carps, tilapia, trout and shrimp	Dietary phytase supplementation, fermentation, milling, moist heating, mineral premix supplementation	(Kumar et al. 2012)
Glucosinolates	Rapeseed, mustard oil cake	Goitrogenic effects, reduced palatability, thyroid dysfunction	Not well defined, generally low inclusion recommended	Heat treatment, solvent extraction, fermentation	(Dossou et al. 2018)
Saponins	Legumes, oilseed cakes	Reduced feed intake, intestinal irritation, impaired absorption	Variable, species dependent	Fermentation, heat treatment, solvent extraction,	(Penn 2005)
Tannins	Various legumes, oilseed meals	Reduced protein digestibility, enzyme inhibition, reduced palatability, growth suppression	Low levels tolerated, high levels detrimental	Heat treatment, fermentation, enzyme supplementation	(Omnes et al. 2017)
Lectins	legumes	Intestinal damage, reduced nutrient absorption, immunogenic effects	Low levels tolerated	Heat treatment, fermentation	(Wassef et al. 2019)
Gossypols	Cottonseed meal	Toxicity, reduced growth, and organ damage	<100mg/kg diet	Heat treatment, solvent extraction, and fermentation	(Wang et al. 2019)
Non-starch polysaccharides (NSPs)	Various plant meals	Increased gut viscosity, reduced nutrient digestibility, impaired growth	Species-dependent, low inclusion preferred	Enzyme supplementation, fermentation	(Morales et al. 2022)
Phytoestrogens	Soybean, clover	Endocrine disruption, reproductive effects	Not well defined	Processing, fermentation	(Novriadi 2018)
Alkaloids	Lupin, some legumes	Toxicity, reduced feed intake, and growth suppression	Low levels tolerated	Detoxification by soaking, fermentation	(Serrano et al. 2011)
Mycotoxins	Contaminated grains and plant meals	Immunosuppression, reduced growth, and organ damage	Varies by toxin type	Proper storage, screening, and detoxification methods	(Pietsch 2025)

Table 5. Processing techniques for plant-derived feed ingredients in aquafeeds

Processing method	Purpose	Effects	Advantages	Limitations	References
Heat treatment	Reduce heat-labile ANFs	Denatures protease inhibitors and lectins	Widely used, improves digestibility	May reduce heat-sensitive nutrients	(Oliva-Teles 1994)
Fermentation	Degrade ANFs, enhance nutrient bioavailability	Breaks down Phytates, tannins, and produces bioactive compounds	Improves palatability, immunity and growth	Requires controlled conditions, may increase cost	(Yang et al. 2022)
Enzyme supplementation	Enhance digestion of complex carbohydrates	Increases nutrient availability and digestibility	Targeted improvement, flexible application	Cost and stability of enzymes can be limiting	(Haghbayan and Shamsaie 2015)
Extrusion	Improve physical properties and digestibility	Denatures ANFs, improves pellet durability	Enhances feed intake and reduces waste	High energy input, equipment cost	(Allan and Booth 2004)

compounds like alkaloids, flavonoids, essential oils, saponins, and phenols that have a diverse range of pharmacological activities that include immunostimulatory, antimicrobial, antioxidant, antiparasitic, anti-inflammatory, and hepatoprotective (Fig. 2) (Tadese et al. 2022; Bagheri et al. 2024; Ouedraogo et al. 2024). Herbal additives dietary supplementation has been shown to result in increased disease resistance, reduce oxidative stress, enhance gut health, and extend the survival of a broad array of cultured fish species. In contrast, synthetic antibiotics or chemotherapeutics, plant-based therapeutics can be biodegraded, are less harmful to the environment, and carry the lesser risk of developing resistance. These qualities render them suitable to use in functional feeds especially in the sustainable and organic aquaculture systems (Elumalai et al. 2020). Table 6 includes an overview of the chosen medicines plants that have been commonly used in fish health care, their bioactive compounds, protein content, therapeutic effects and the recommended levels of dietary inclusion.

8. Economic and environmental considerations

Economic and environmental factors are key factors that have driven the aquaculture industry to adopt the use of plant-based feed ingredients (Mitra 2021). Economically, plant proteins are cheaper than fishmeal, which is prone to fluctuations in the market, expensive and has sustainability issues. Nevertheless, the comparatively lower protein level and the inclusion of ANFs in the majority of plant feedstuffs require further processing and improvement of their protein quality and digestibility, which may lead to higher production costs (Daniel 2018). Such innovations as water-based protein concentration technologies like those of 50/50 Botaneco and canola protein concentrates with up to 75% protein content also focus on producing better-quality and more affordable plant proteins at large scale and highly efficient processing. The above processing techniques, including alkaline secretion, enzyme-assisted hydrolysis and fermentation, not only improve the nutritional quality of plant proteins but also decrease ANFs, which, in turn, increases the feed efficiency and growth performance. Fermentation has been one of such methods and has potentially proven to be an ideal method in increasing nutrient bioavailability, reducing unpleasant bioactive compounds, and improving palatability. Such advantages provide better feed-conversion and growth, especially in carnivorous fish that have been relying on fishmeal. These improvements translate into economic benefits by lowering the cost of feed per unit of fish produced and reducing dependence on expensive marine derived ingredients. From an environmental perspective, the switch of fishmeal to plant proteins reduces the pressure on wild fish populations and supports the development of more sustainable aquaculture practices (Hua et al. 2019). Additionally, there will be the stimulation of local economies and decrease in greenhouse emissions associated with long-distance transportation of feed ingredients by developing regionally adapted plant-based protein sources such as alfalfa protein concentrates, which are particularly rich in vitamins and minerals (Hadidi et al. 2023).

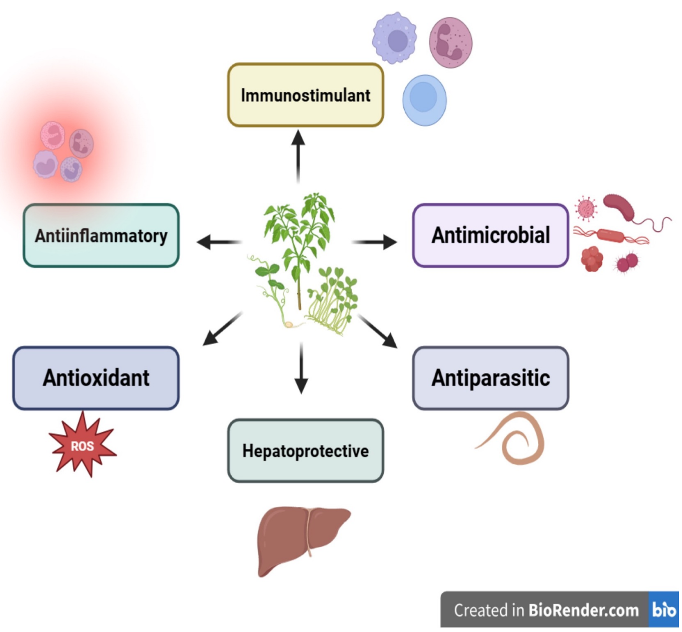

Fig. 2. Therapeutic roles of medicinal herbs in fish

9. Challenges and future directions

Despite the considerable potential of plant-derived ingredients as sustainable alternatives to fishmeal, several challenges must be addressed to enable their effective and widespread use in aquaculture feeds (Hossain et al. 2024). The existence of ANFs is one of the key challenges since it potentially causes nutrient digestibility problems, decreases feed efficiency, and in turn affects fish health (Kumar et al. 2012), particularly in the carnivorous species that have high nutritional requirements. Furthermore, plant-based ingredients tend to have imbalanced amino acid profiles and are generally deficient in necessary fatty acids, making it necessary to supplement them with other protein sources to meet the nutritional requirements of fish (Naylor et al. 2021). Feed intake and palatability are significant challenges in feed formulation because certain plant proteins possess undesirable flavours or textures that lower voluntary feed intake, especially in sensitive fish species. Another challenge in the feed formulation is the risk of mycotoxin contamination and inconsistency in ingredient quality

Table 6. Therapeutic roles of medicinal plants and herbs in aquaculture

Plant	Bioactive compound	Protein/ Amino acid content	Therapeutic effect in fish	Target	Recommended inclusion level	References
Garlic	Allicin, Sulfur	~20% protein, ~1.3% Lysine	Antibacterial, Immunostimulant	*Aeromonas, Vibrio*	1-3	(Nya and Austin 2009)
Turmeric	Curcumin	7-9% Protein, Arginine, Methionine present	Antioxidant, Hepatoprotective	Oxidative stress, gut issues	1-2	(Mahmoud et al. 2017)
Neem	Azadirachtin, Nimbin	~18-20% Protein, Low in sulfur AAs	Antiparasitic, Antibacterial	*Lernaea, Ichthyophthirius*	0.5-2	(Radwan et al. 2024)
Tulsi	Eugenol, Ursolic Acid	~17-20% Protein,	Antimicrobial, anti-stress	Bacterial infection	1-2	(Rao and Kumar 2023)
Ginger	Gingerol, Shogaol	~9% Protein, contains essential amino acids	Antioxidant, Immune boosting	*Aeromonas, Vibrio*	0.5-1.5	(Sukumaran et al. 2016)
Bhumi Amla	Lignans, Phyllanthin	~12% protein, moderate EAA	Hepatoprotective, antiviral	Liver dysfunction, viral infections	≤1	(Ramamurthy and Rajakumar 2016)
Ashwagandha	Withanolides	~14-16% Protein, good arginine and leucine	Anti-stress, immunomodulatory	Stress-related disorder	1-2	(Debnath and Sahoo 2025)
Curry leaf	Carbazole alkaloids	~18-20%Protein, contains Lys, Arg	Antioxidant, antimicrobial	General pathogens	1	(Debnath 2025)
Lemongrass essential oil	Citral, Limonene	~10% Protein, moderate amino acid level	Antifungal, gut health	Fungal and digestive diseases	≤1	(Krasteva 2023)

(Oliva-Teles et al. 2022). Additionally, the widespread use of plant proteins raises emerging environmental concerns related to land and water use, as well as the sustainability of agricultural production systems. These aspects should be considered in conjunction with the environmental benefits achieved by decreasing the use of marine-based feed sources (Napier and Betancor 2023). Further policies are aimed at diversifying protein sources as a way of not relying on plant traditional ingredients. Based on the protein gap, new sources of protein are currently under consideration as supplementary sources of protein in aquafeeds, including insect meals, single-cell proteins (microbial biomass), algal proteins, and fungal proteins. These ingredients have potential good nutritional values and lower environmental footprints, but the improvements are required in terms of scale, cost, and regulatory acceptability (Ahmad and Ashraf 2023). Processing technologies like triboelectrostatic dry separation and enzyme-assisted extraction increase the concentration and functional quality and digestibility of plant proteins to facilitate greater protein levels of feeds in aquafeeds without affecting performance (Kleekayai et al. 2023). Moreover, the proteins of plants grown locally, such as grass protein concentrates, will mitigate the negative impact on the environment and help the local economy (Jørgensen et al. 2022).

10. Conclusions

The trend towards fish meal substitutes can be attributed to the increasing popularity of producing sustainable aquaculture, which encourages the use of plant-based feed ingredients as a possible alternative feed source. The plant-based sources of protein provide a viable alternative because they are available, cheap and cause less pressure on the marine sources. Nonetheless, the anti-nutritional factors, disproportional amino acid balance, reduced nutrient utilization, and palatability are factors that challenge their use and limit growth and health of fishes. To a significant degree, the limitations have been overcome by the present developments in processing technologies, especially fermentation. They have not only minimized the anti-nutritional factors, but also enhanced the bioavailability of nutrients, and have also embarked on the production of high-efficiency bioactive compounds that confer a high level of immunity and resistance to diseases in farmed fish. Consequently, plant proteins can be fed to fish in increased amounts without negatively affecting the growth of carnivorous fish that are adapted to fishmeal-based diets. The use of plant-based ingredients will reduce dependence on marine resources for feed, reduce the price of the feed, and enable an eco-friendlier production. Research is necessary to create plant-based proteins that can be optimally supplemented with essential amino acids and micronutrients, reduce antinutritional factors through modern feed processing techniques, and assess the health effects of long-term consumption on a broad host of aquaculture species. Also, synergistic interactions of plant proteins with new ingredients like insect meals, single-cell proteins and algal biomass will be of significance to improving both nutritional value and sustainability. New frameworks that promote innovation, promote quality consistency of ingredients and measures of the environmental effects will also be necessary to facilitate the commercial adoption of plant-based aquafeeds.

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