

Review Article

Exploring rice protein concentrate as a sustainable protein replacement for fishmeal in aquafeeds

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Abstract - The rapid expansion of aquaculture requires cost-effective and sustainable alternatives to conventional protein sources such as fishmeal, whose rising cost and environmental concerns limit its use. Rice protein concentrate (RPC), derived from processed rice grains, is a promising substitute due to its high protein content, balanced amino acid profile, hypoallergenic nature, and wide availability. This review highlights the importance of RPC as a protein replacement in aquafeed, either by partially or totally replacing fishmeal (FM), owing to its nutritional, functional, and environmental merits compared to other plant-based protein sources. The deficiency of certain amino acids, such as lysine and methionine, along with the presence of anti-nutritional compounds, limits their utilization in aquafeeds. Efforts to mitigate these constraints include amino acid supplementation and enzymatic treatments. Additionally, incorporating RPC production into circular bioeconomy frameworks optimizes resource use efficiency and supports environmental sustainability. Continuous multidisciplinary research and innovation will be the determining factors in achieving the full potential of RPC in turning aquaculture systems into resilient, affordable, and sustainable systems worldwide, to avoid repetition of 'systems'.

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1. Introduction

Global food demand is projected to rise substantially as the population approaches 9.7 billion by 2050, requiring at least a 50% increase in food production to meet nutritional needs and reduce the pressure on existing food systems (Bahar et al., 2020). In this context, aquaculture has emerged as a key contributor, providing high-quality animal protein in an efficient and environmentally sustainable manner. Consequently, the continued expansion of aquaculture production depends largely on the development of nutritionally balanced and economically viable aquafeeds, in which protein is the most essential and expensive component.

Currently, the aquaculture sector relies heavily on fishmeal (FM), one of the most valuable feed ingredients, because of its high protein content, balanced amino acid profile, and strong palatability (Macusi et al., 2023; Abasubong et al., 2019). However, because FM is derived from wild fish, the annual use of approximately 16 million tonnes of wild catch for its production raises serious sustainability and economic concerns (Kok et al., 2020). Continued dependence on fishmeal threatens long-term environmental sustainability by intensifying pressure on marine resources and contributing to economic instability through fluctuating supply and rising prices (Tidwell & Allan, 2001). These challenges highlight the strategic need to reduce or replace fishmeal in aquafeeds to ensure sustainable aquaculture development.

In response, several plant-based protein sources, particularly soybean and cottonseed meals, have been explored as potential alternatives owing to their relative affordability and availability. Soybean meal possesses a high protein content and a favorable amino acid

profile; however, its inclusion in aquafeeds is often limited by the presence of anti-nutritional factors that can impair digestion and performance in certain aquatic species (Stein et al., 2008). Similarly, cottonseed meal has potential as a feed ingredient, but its application at higher inclusion levels is restricted by the presence of gossypol, a toxic compound (Gadelha et al., 2014). Moreover, the long-term sustainability of these conventional plant proteins is increasingly questioned because their production is associated with intensive agriculture and potential land-use challenges, including deforestation and the loss of biodiversity.

Given these limitations, the diversification of aquafeed protein sources has become increasingly important, prompting the search for novel and sustainable alternatives. Among these, rice protein concentrate (RPC) has gained attention as a promising plant-derived ingredient for meat analogs. RPC is a plant-derived protein ingredient produced from rice grains or rice processing streams, such as broken rice and rice bran (Cai et al., 2018). It is considered a co-product of rice milling rather than a waste by-product and is not typically generated during ethanol production (Jayaprakash et al., 2022). RPC is valued for its high protein content, good digestibility, and hypoallergenic properties, and its production from milling fractions supports circular economy principles and contributes to sustainable feed development (Abasubong et al., 2018). Its supply is linked to rice production and milling, providing a relatively stable but currently limited commercial availability compared with that of major plant proteins.

Despite these advantages, RPC is naturally deficient in certain essential amino acids, particularly methionine and lysine, and may contain anti-nutritional

compounds, such as phytic acid (Abasubong et al., 2018; Abasubong et al., 2019). Nevertheless, these limitations can be mitigated through amino acid supplementation and appropriate feed formulations. Through targeted feed development and ongoing research and innovation, RPC has the potential to play a crucial role in integrated strategies designed to reduce fishmeal dependence while maintaining feed efficiency, fish health, and environmental sustainability in aquaculture.

2. Fishmeal in aquaculture: Role, benefits, and challenges

Fishmeal, produced from whole fish, fish waste, or fish offal, is one of the most widely used protein sources in aquafeed (Vasilaki et al., 2023). Its primary role in aquaculture nutrition is to supply the high-quality dietary protein required for optimal growth and physiological functions in fish and other aquatic species.

Fishmeal offers several nutritional benefits that make it superior to many alternative protein sources. It contains highly digestible proteins, a well-balanced profile of essential amino acids, and significant amounts of essential fatty acids, such as EPA and DHA (Figure 1). In addition, fishmeal provides important vitamins and minerals and is highly palatable, which enhances feed intake and improves overall feed utilization (Cho & Kim, 2011).

Despite these advantages, the use of fishmeal in aquaculture presents several challenges. The supply and quality of fishmeal are often inconsistent because of fluctuations in wild fish harvests. In addition, the increasing demand from aquaculture and other livestock industries has led to rising prices, whereas seasonal availability and reliance on capture fisheries further limit its sustainability (Hua et al., 2019). These constraints have stimulated growing interest in identifying alternative protein sources for aquafeed.

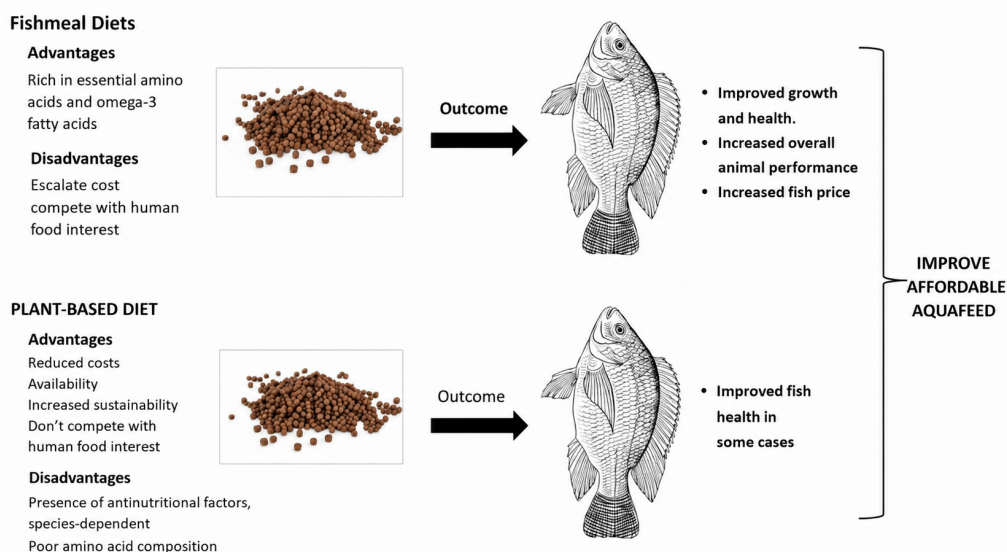


Figure 1. Schematic presentation of the effects of feeding fish pellets with fishmeal-based protein (top pathway) and plant-based protein (bottom pathway). Fish fed fishmeal diet pellets exhibited improved growth performance, higher total weight, and improved fish condition. Fish fed plant protein-based pellets exhibited improved fish condition but relatively lower weight gain and growth rate, and in some cases, relative to fish

provided with fishmeal-based diets.

3. Global rice production and rice protein concentrate (RPC)

3.1 Global rice production

Global rice production has steadily increased in recent years. Worldwide paddy rice production reached approximately 787.3 million tonnes in 2022, an increase from 776.5 million tonnes in 2021 ([Abasubong et al., 2024](#)). Asia accounts for approximately 90% of the global output, producing roughly 795–800 million tonnes of paddy rice annually, thereby dominating the global supply. After milling, this corresponds to approximately 535.8 million tonnes of milled rice in the 2024/25 cropping year, representing nearly a 3% increase over the previous year. This suggests that rice has been in higher demand in Asia as a staple food and an essential part of the diet. China ranks first among rice-producing countries, with an estimated 144–208 million tons of paddy rice produced annually, accounting for 28–30% of global production, followed by India, with 137–205 million tons (~26–28%) ([Abasubong et al., 2024](#)). The third is Bangladesh, with approximately 7–8%, followed by Indonesia, Vietnam, Thailand, Myanmar, the Philippines, and Pakistan. Global production has leveled off at 795–800 million tonnes, as the harvested areas are quite stable (~168 million hectares), and the yields are stable (~4.7 t/ha) ([Abasubong et al., 2024](#)).

Sustainability is becoming increasingly important, with initiatives to limit water consumption and postharvest loss. Rice cultivation is responsible for approximately 7% of the world's methane emissions, which contribute to environmental problems. India remains the world's top rice exporter, with a share of almost 40% of the world's rice exports, even as trade policies and

regulatory controls impact market forces.

3.2 Rice protein concentrate (RPC)

RPC is obtained from brown rice grains through a series of mechanical and biochemical processes aimed at isolating and concentrating the protein fraction, thus compromising starch, fiber, and other non-protein constituents ([Miedzianka et al., 2023](#)). Its application in animal nutrition is increasing owing to its digestibility and renewable status as a plant-based protein source of plant origin. In addition, it is a hypoallergenic substitute for animal-derived feed proteins, such as fish meal or soy, which makes it more beneficial for pet foods and animals with sensitivities or dietary intolerances ([Abasubong et al., 2018](#)). The flavor and quality consistency of RPC support the healthy development and growth of animals, and its clean-label status appeals to the increasing consumer demand for natural and non-GMO feed ingredients. RPC is particularly suitable for specialized diets for companion animals, aquaculture, and farm animals in the juvenile stages.

3.3 RPC production in aquaculture production

The process starts with choosing superior white or brown rice, which is then purified to eliminate contaminants, such as husks, stones, and dust. The treated grains are milled to yield a refined rice flour with a large surface area for enzyme hydrolysis ([Miedzianka et al., 2023](#)). α -amylase and glucoamylase enzymes hydrolyze complex carbohydrates into simple sugars; thus, this process is critical for starch hydrolysis.

Enzymatic hydrolysis lowers slurry viscosity to enable protein separation and enhance overall product purity ([Perrechil et al., 2023](#)). Following hydrolysis, the blend undergoes mechanical separation processes, such as centrifugation, membrane filtration (microfiltration or

ultrafiltration), or decantation, to separate the protein-rich liquid from insoluble components, such as fiber, starch remnants, and cell wall components (Cabeza et al., 2025). The protein component undergoes purification and separation processes to eliminate lipids, cell wall components, and antinutritional compounds that inhibit nutrient metabolism (Cabeza et al., 2025).

The solution is concentrated and dehydrated, and is frequently spray-dried during production or freeze-dried in products that require the conservation of heat-sensitive ingredients (Tang et al., 2024). These drying methods yield concentrated and homogeneous protein powders that are suitable for various applications. The resulting rice protein concentrate typically contains 60–80%

protein, depending on the rice strain and processing method used (Amagliani et al., 2017). Although low in lysine, a key essential amino acid, RPC is recognized for its favorable amino acid profile, high digestibility, and hypoallergenic properties. It is gluten- and soy-free, making it a superior alternative for animal and human health (Anyiam et al., 2025). In aquaculture, RPC is considered an environmentally friendly fishmeal alternative, offering a vegetable protein source that reduces ocean-dependent resource exploitation. Its use in functional food products, dietary supplements, and animal feed indicates its versatility and growing contribution to sustainable food and animal feed systems. The systematic illustration of the production of RPC is

presented in Figure 2

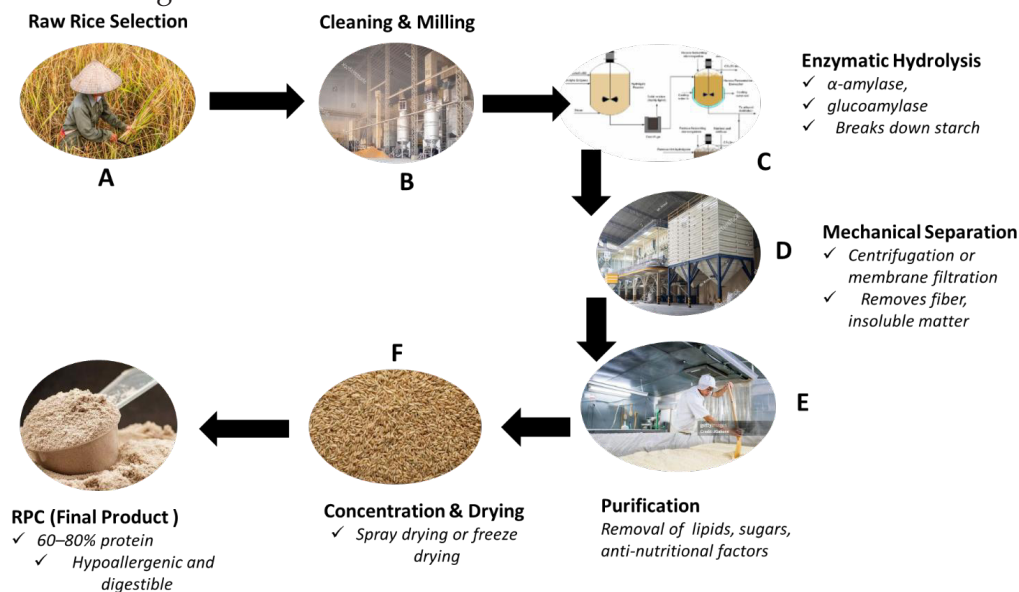


Figure 2. Production process of rice protein concentrate (RPC) from rice grain. The process begins with (A) rice cultivation and harvesting, followed by (B) rice milling to separate the rice fractions. (C) Protein extraction and concentration determination were performed using enzymatic or chemical methods. The extracted protein was then (D) dried and processed into RPC. The final product can include (E) rice protein powder or (F) residual rice bran, which may be used in other applications in the food industry. This process exemplifies a circular economy approach by valorizing rice milling byproducts for sustainable feed ingredient production.

4. Nutritional value and applications in aquatic species

4.1 The importance and nutritional contents of RPC in aquaculture productions

The total removal of fishmeal as the sole source of protein in aquafeed production has been a major focus for aquaculture nutritionists to reduce feed costs. Consequently, there has been an increased interest in evaluating rice protein concentrate (RPC) in comparison with other plant-based protein sources. RPC is an essential ingredient in aquaculture feed because of its unique combination of nutritional content, sustainability, and cost-effectiveness (Table 1). RPC varies depending on its processing technology and concentration ratio, which affect its composition, thereby contributing to the circular economy by reusing agricultural residues from feed production (Abasubong et al., 2024; Abasubong et al., 2018; Abasubong et al., 2019; Jayaprakash et al., 2022).

The starch and fiber content of RPC is usually eradicated during processing, making it more digestible for aquatic animals than other feed types. RPC contains approximately 60–80% protein with minimal fat and carbohydrate content compared to other plant protein

sources (Manzoor et al., 2023). Despite its high protein content, RPC is rich in amino acids such as leucine, valine, isoleucine (branched-chain amino acids or BCAAs), threonine, and methionine; however, the opposite is observed for lysine content. This has limited its application as a noble feed ingredient compared to fishmeal; however, supplementation with lysine-containing ingredients (such as legumes or synthetic lysine) could be significant in improving the health of animals (Jayaprakash et al., 2022). Compared to prevalent allergens such as soy, gluten, and milk proteins, RPC has limited allergenicity potential because of its high digestibility (typically >85%) (Jayaprakash et al., 2022). This makes RPC a valuable product for consumers with food allergies and intolerances.

Despite its nutritional value, it contains anti-nutritional factors, such as phytates, which reduce the bioavailability of minerals if not properly removed during processing. Other desirable functional properties of RPC include water solubility, emulsification, and gelation, making it an ideal candidate for various food and feed applications, such as beverages, protein bars, meat analogs, and aquafeeds (Singh et al., 2021).

Table 1. Proximate composition and amino acid profile (g/100 g protein) of rice protein concentrate (RPC) compared with fishmeal (FM) and other plant protein sources (approximate average values).

Nutrient (g/kg)	RPC	FM	CSM	SBM	RSM
Crude Protein	665	645	449	441	378
Crude fat	85.6	78	5	15	38
Ash	39	213	66	63	68
Moisture	< 10	< 10	< 10	< 10	< 10
Essential amino acid composition (g/kg, dry matter)					
Lysine	18.9	49.9	17.1	28.2	22
Methionine	20.2	20.6	5.7	5.3	7
Threonine	24.7	30.3	13.1	17.9	16.6
Valine	35.0	33.5	17.6	21	19.1
Isoleucine	25.7	27.9	12.5	20.3	14.9
Leucine	52.9	52.2	24	35	27.2
Arginine	49.7	43.6	46.5	32.1	22.7
Histidine	15.4	14.4	11.1	11.6	10.1
Phenylalanine	36.2	29.1	23	23.9	16.4
Non-essential amino acids composition (g/kg, dry matter)					
Alanine	38.5	39.7	15.7	19.6	16.7
Asparagine	59	62	36.6	50.3	26
Cystine	13.7	10.1	6.4	6.2	7.6
Glycine	28	45	16.3	19.3	18.8
Glutamine	21.9	94.8	85.3	85.9	69.5
Proline	21.9	28.3	14.1	21.6	22.4
Serine	32.5	32.9	17.7	23.1	16.4
Tyrosine	32.4	25.1	11.3	16	11.1

Note: RPC, rice protein concentrate; FM, fishmeal; CSM, cottonseed meal; SBM, soybean meal; RSM, rapeseed meal. Source: [Cai et al. \(2018\)](#) and [Abasubong et al. \(2019\)](#)

4.2 Experimental findings of RPC in aquatic species.

Based on its nutritional value compared to other plant protein sources, RPC is becoming relevant in aquafeed as an eco-friendly substitute for fishmeal-based diets. This is because RPC has proven to have high digestibility, essential amino acids, and minimal anti-nutritional factors, improving fish growth and health

while minimizing the environmental footprint. However, its major drawback is the deficiency in lysine content. To reduce this effect, supplementation with additional amino acids and other supplements is essential to improve the nutritional value and support maximum fish growth and health. The experimental findings of RPC in aquatic species are presented in Table 2.

Table 2. Summary of experimental studies evaluating rice protein concentrate (RPC) as a dietary replacement for fishmeal across diverse aquaculture species.

Common name	Duration of feeding	Experimental Design	Parameters Measured	Key experimental outcome	Recommended RPC Inclusion (%)	References
Rainbow Trout (<i>Oncorhynchus mykiss</i>)	94 days	RPC 0–53% FM in isoproteic (47% CP), isoenergetic diets; 30 fish/tank, 3 replicates	ADC of DM, CP, EE, ADF; WG, SGR, FCR; somatic indices; fillet proximate & FA composition	WG and SGR equivalent to control $\leq 20\%$ RPC; digestibility declines above 20%; lysine limiting	$\leq 20\%$	Palmegiano et al. (2006)
Rainbow Trout (<i>Oncorhynchus mykiss</i>)	84 days (12 weeks)	Enzyme-treated RPC 5–15% in 20% FM diets; 240 juveniles, 3 replicates	WG, SGR, feed intake, survival; whole-body composition; lipid retention; protein digestibility	Growth unaffected $\leq 15\%$; lipid retention decreased $\geq 10\%$; enzyme treatment mitigates AA limitation	$\leq 10\%$ (enzyme-treated)	Gai et al. (2012)
Blackspot Sea Bream (<i>Pagellus bogaraveo</i>)	Short-term	RPC 0–64% FM; practical diets; controlled feeding	Growth, flesh quality (proximate & FA composition), and digestive enzyme activity	Growth maintained $\leq 64\%$; flesh protein quality and enzyme activity unaffected	$\leq 64\%$	Palmegiano et al. (2006) and Daprà et al. (2009)
Gilthead Sea Bream (<i>Sparus aurata</i>)	80 days	PPC + RPC blend 0–90% FM; Lys & Met supplemented; 12 tanks $\times$ 20 fish	WG, SGR, FCR, PER, PRE; ADC CP/GE; fillet sensory, proximate & AA profile	Growth & FCR similar to control at 30–60% FM; declined at 90%; survival $\geq 90\%$	30–60%	Sánchez-Lozano et al. (2009)
Pacific White Shrimp (<i>Litopenaeus vannamei</i>)	60 days	RPC 0–100% FM; triplicate tanks; 36.6% protein diets	WG, SGR, FCR, PER, survival; tail-muscle proximate & AA composition; ADC	Growth and survival maintained $\leq 50\%$ RPC; digestibility declined above 50%; EAA was highest at 25–50%	$\leq 50\%$	Oujifard et al. (2012)
European Sea Bass (<i>Dicentrarchus labrax</i>)	90 days (winter)	RPC 0–25% FM; winter indoor tank conditions	WG, SGR, FCR, PER; nutrient digestibility; hematology	Growth and digestibility unaffected $\leq 25\%$; higher RPC reduced growth	$\leq 25\%$	Güroy et al. (2013)
Siberian Sturgeon (<i>Acipenser baerii</i>)	Multi-week	RPC in practical diets; multiple inclusion levels	Growth, body composition, feed utilization, and ADC.	Acceptable growth & nutrient digestibility at moderate inclusion	Moderate ($\leq 50\%$)	Sicuro et al. (2015)
Blunt Snout Bream (<i>Megalobrama amblycephala</i>)	56 days	100% FM replaced by RPC $\pm$ Lys (0–1.5%) indoor recirculating tanks	WG, SGR, FCR, muscle fiber, flesh quality, proximate composition, serum biochemistry	RPC alone reduced growth & FCR; 1.5% Lys restored growth,	100% with Lys	Cai et al. (2018)

Common name	Duration of feeding	Experimental Design	Parameters Measured	Key experimental outcome	Recommended RPC Inclusion (%)	References
Blunt Snout Bream (<i>Megalobrama amblycephala</i>)	56 days	control diet (10% FM), RPC diet (100% FM replaced), and RPC + 0.5–3% XOS	Growth, feed efficiency, hepatic and intestinal enzymes. plasma AAs, <i>tor/s6k1</i> , <i>4e-bp2</i> , <i>mtor</i> expression, antioxidant (SOD, CAT, GPx), and immune responses against <i>A. hydrophila</i>	RPC alone reduced growth, feed efficiency, hepatic and intestinal enzyme activities, plasma amino acids, <i>tor/s6k1</i> and <i>4e-bp2</i> , <i>mtor</i> signaling, and antioxidant and immune responses to <i>A. hydrophila</i> . However, XOS supplementation improved these parameters.	1.5% with XOS	Abasubong et al. (2018, 2019)
Chinese Soft-shelled Turtle (<i>Pelodiscus sinensis</i>)	84 days	100% FM replaced by RPC ± microencapsulated Lys	digestibility, hepatic enzymes	Lys supplementation restored growth & CP digestibility	100% with Lys	Sun et al. (2018)
Nile Tilapia (<i>Oreochromis niloticus</i>)	84–90 days	RPC 0–100% FM	Growth, FCR, digestibility, body composition, intestinal histology, immunity, economics	Growth maintained ≤25–50%; high RPC increased FCR & reduced protein retention; immunity optimal ≤25%	≤25–50%	Abdel Rahman et al. (2021) , Assi et al. (2020)
Rohu (<i>Labeo rohita</i>)	60 days	RPC 75–100% FM + XOS 0–2%	Growth, digestive enzymes, and intestinal morphology	1% XOS improved growth, digestion, and gut morphology	75–100% with 1% XOS	Khizar et al. (2024)

Note: RPC = Rice Protein Concentrate; FM = Fishmeal; WG = Weight Gain; SGR = Specific Growth Rate; FCR = Feed Conversion Ratio; PER = Protein Efficiency Ratio; CP = Crude Protein; ADC = Apparent Digestibility Coefficient; XOS = Xylooligosaccharides; SOD = Superoxide Dismutase; CAT = Catalase; GPx = Glutathione Peroxidase; mTOR = Mammalian Target of Rapamycin.

5. Formulation strategies and dietary supplementation

The inclusion of RPC in aquafeeds to achieve its optimum benefits requires prudent formulation strategies to overcome its intrinsic nutritional limitations and supply optimum gains. Although RPC is valued for its high protein content and hypoallergenic nature, its application in aquatic feeds is challenging due to amino acid imbalance, anti-nutritional factor content, and palatability and digestibility issues in the feed. Therefore, targeted dietary supplementation and precise feed formulations are required to ensure optimal growth, health, and feed conversion in a broad spectrum of aquatic species.

5.1 Balancing and fortification of amino acids

The main obstacle to the use of RPC in aquafeeds is its limited lysine content (Lys). Lysine is responsible for protein synthesis, immune stimulation, improved growth performance, and cellular repair in aquatic animals. Lysine deficiency reduces feed efficiency, causes weight loss, and impairs health (Mousa et al., 2023). To solve this problem, supplementation of feed with synthetic amino acids, including L-lysine hydrochloride (L-lysine HCl) and DL-methionine, is typically necessary to optimize the amino acid composition to be consistent with the metabolic and physiological needs of the target fish and crustacean species (Assi et al., 2020; Cai et al., 2018). Such supplementation is necessitated by the fact that the requirement for amino acids differs among animal species based on their trophic levels, digestive capacities, and growth rates. The practical application of the model protein is formulated to have amino acids suitable for satisfying the animals' endogenous demands, which

optimizes the utilization efficiency and retention of nitrogen. Thus, by optimizing these ratios, the excretion of nitrogenous wastes (i.e., ammonia and urea) is kept to a minimum, enhancing growth performance and reducing the environmental footprint of aquaculture. Thus, proper amino acid balancing ensures that there is no possibility of amino acid antagonism and toxicity due to excesses or imbalances.

5.2 Supplementation with functional additives and digestive enzymes

Complex protein matrices, such as phytic acid, which chelate divalent cations such as zinc, calcium, and phosphorus, reducing their absorption and anti-nutritional factors, may affect the digestibility and bioavailability of nutrients in RPC (Gupta & Lapsley, 2015). Exogenous enzymes have been demonstrated to significantly improve feed efficiency and nutrient availability. Examples of these enzymes include carbohydrases, which break down non-starch polysaccharides, phytases, which break down phytic acid, and proteases, which aid in protein degradation (Maas et al., 2025). To improve sustainable aquaculture, phytase is especially useful for releasing phytate-bound phosphorus, decreasing the dependence on inorganic phosphorus additives, and minimizing the release of phosphorus into aquatic environments (Maas et al., 2025). Additionally, the thoughtful application of functional feed additives, such as organic acids, which lower gut pH and inhibit pathogenic bacteria, prebiotics and probiotics, which positively modulate gut microbiota, and nucleotides, which enhance immune function and cell division, all contribute to gut health, improve nutrient digestion efficiency, and increase disease resistance (Abasubong et al., 2022; Latif et al., 2023). By adopting a comprehensive approach, the overall physiological robustness of the

animals was improved, and the integrity of the digestive tract was preserved.

5.3 Blending proteins and improving their palatability

By combining RPC with other protein sources, such as wheat gluten, soy protein concentrate, corn gluten meal, or emerging alternatives such as insect meal, aquafeeds containing RPC can achieve enhanced nutritional value and sensory appeal. The goal of these blending techniques is to provide a more comprehensive and balanced diet for optimal growth and metabolic processes by enhancing the amino acid profiles of the individual ingredients (Palmegiano et al., 2006). Additionally, blending improves pellet texture and water stability, which are essential for maintaining feed intake and preventing nutrient leaching. For animals with extremely sensitive palatability, such as shrimp, the addition of natural feed attractants, such as betaine, fish hydrolysates, or krill meal, is required (Derby et al., 2016). These attractants improve feed conversion ratios and growth performance by increasing feed intake and stimulating feeding behavior. In addition, palatability enhancers counteract any unfavorable sensory characteristics (e.g., unpleasant taste or bitterness) caused by RPC or other plant proteins (Smith et al., 2005).

5.4 Lipid and energy balance

RPC, a dense source of dietary energy required to meet the high metabolic demands of most aquatic species, is usually lipid-poor (Palmegiano et al., 2006). Therefore, appropriate lipid sources, such as fish and vegetable oils (e.g., fatty acids), should be added to diets rich in RPC. Microalgal oils reportedly contain higher levels of essential fatty acids than oils derived from soybeans, sunflowers, or canola (Nguyen et al.,

2018). Protein catabolism is inhibited and directed toward anabolic functions, such as growth and tissue repair, when the dietary energy level is balanced. Maintaining a proper protein-to-energy ratio during feed formulation is essential to avoid over-oxidizing protein for energy production, which wastes energy and produces an excessive amount of nitrogenous waste (Jiang et al., 2016). This has been well demonstrated in Nile tilapia (*Oreochromis niloticus*) and channel catfish (*Ictalurus punctatus*), where imbalanced protein-to-energy ratios lead to elevated ammonia excretion and reduced feed efficiency (Li et al., 2013). Maintenance processes such as immunity, stress, and reproduction are also made possible by adequate energy provision (Munteanu & Schwartz, 2022). In Pacific white shrimp (*Litopenaeus vannamei*) and common carp (*Cyprinus carpio*), adequate dietary energy has been linked to enhanced immune responses, improved tolerance to environmental stressors, and better reproductive output (Cuzon et al., 2004; Radünz Neto et al., 1996).

5.5 Feed processing and pellet quality considerations

High inclusion levels of rapidly degradable ingredients, such as RPC, can markedly influence the physical quality of aquafeed pellets, particularly the extrusion behavior, pellet hardness, durability, and water stability. These properties are critical for maintaining pellet integrity during immersion in aquatic environments, where uncontrolled disintegration can lead to nutrient leaching and environmental pollution (de Cruz et al., 2015). To maintain adequate pellet quality, formulators must carefully select suitable binders, including carboxymethyl cellulose, gelatinized starch, and lignosulfonates, which enhance particle cohesion and improve

structural stability. In addition, the precise control of extrusion parameters is essential. Key processing variables include barrel temperature profiles, die pressure, feed moisture content, screw speed, and residence time, all of which influence starch gelatinization, protein denaturation, and pellet expansion. Proper optimization of these parameters helps produce pellets with sufficient mechanical strength, reduced nutrient loss, and improved water stability, while preserving nutrient quality (Zambrano et al., 2022). Improved pellet physical quality also enhances feed handling, storage stability, and acceptability by aquatic animals, thereby contributing to higher feed utilization efficiency and improved productivity.

6. Limitations of rice protein concentrate in aquaculture

One of the main setbacks of RPC in aquafeeds is the result of lysine and methionine deficiencies, which significantly affect optimal growth, protein deposition, and immune reactions in aquatic species (He et al., 2013). Without strategic supplementation, this deficiency could restrict the tolerable inclusion rates of RPC in feed mixtures, resulting in impaired growth performance, lower feed conversion efficiency, and impaired health in farmed animals (Adhikari et al., 2025). However, the presence of anti-nutritional factors is a concern. These compounds inhibit metabolism and suppress nutrient uptake, thereby suppressing the activity of digestive enzymes in the gastrointestinal tract (Salim et al., 2023). If not effectively countered by processing methods such as enzymatic hydrolysis or microbial fermentation, ANFs further reduce the digestibility of RPC to a level that adversely affects nutrient utilization and animal well-being.

Nutritionally, RPC lacks the entire range of beneficial ingredients present in traditionally obtained proteins, such as fish meal, including EPA and DHA (long-chain omega-3 fatty acids), as well as certain vitamins and trace minerals. These nutrients are also involved in cell construction, brain growth, and immunological regulation; therefore, their absence in RPC-based diets requires additional supplementation to meet the nutritional requirements of aquatic animals (Das et al., 2024). Moreover, palatability may also be a constraint to RPC utilization, as certain fish and crustaceans exhibit reduced feed intake when their diets contain high levels of RPCs based on differences in flavor, odor, or texture compared to fishmeal. Aversion deters growth and efficiency of production unless countered by the addition of natural attractants or flavor stimulants.

From an economic perspective, manufacturing high-quality RPC is technologically intricate and more expensive than manufacturing conventional plant protein materials. Manufacturing is intricate and involves many energy- and resource-consuming operations, such as enzymatic hydrolysis, filtration, and drying. Variations in raw rice quality and inconsistencies in processing conditions also lead to variance in RPC nutritional value and functional properties (Kalita et al., 2021; Modupalli et al., 2024; Xi et al., 2025). These challenges hinder feed development and limit the reliability and scalability of RPC as a protein feed ingredient in commercial aquaculture industries.

7. Future prospects of rice protein concentrate in aquaculture

Many plant-based proteins ingredients have been used to partially or completely substitute fishmeal in the practical diets

of aquatic species. However, the major drawback of this ingredient is its antinutritional factors. However, RPC remains more promising because it is a cost-effective, sustainable, affordable, and environmentally friendly feed ingredient compared with other sources of plant protein. To ensure better utilization of RPC, improved processing techniques should be applied to eradicate antinutritional factors and enhance its digestibility. In addition, technologies such as enzymatic hydrolysis, fermentation, and protein fractionation should be employed to enrich the nutritional quality of RPC with bioactive peptide compounds. This compound stimulates fish health, immunity, and disease resistance. This will enhance the functional value of RPC as a protein source beyond the minimum requirement.

Following these technological developments, future formulation approaches are expected to include amino acid enrichment and protein blending to overcome the current nutritional limitations of RPC, namely, its poor profiles of lysine, methionine, and essential fatty acids. By adding synthetic amino acids or blending RPC with complementary protein sources, such as insect meal, soybean meal, or microbial protein, producers can create synergistic feeds that are specifically suited to the physiological needs of different aquaculture species. Simultaneously, the incorporation of functional additives such as probiotics, prebiotics, and digestive enzymes increases nutrient uptake, supports immune system function, and improves feed efficiency.

In the coming years, the sustainability benefits of RPC will be at the forefront of its wider use, particularly in the aquaculture sector's drive to reduce its dependency on fishmeal and other marine-derived

ingredients. RPC production offers opportunities to valorize rice byproducts and agro-industrial waste, promoting a circular economy and reducing environmental impacts. However, to reach its full potential, additional studies are required to optimize the processing methods and ascertain species-specific diet incorporation rates. In this approach, RPC can serve as a precursor to crucial ingredients for the development of high-performance, sustainable aquafeeds.

8. Conclusion

RPC addresses the environmental and financial issues surrounding ocean-sourced protein ingredients by providing a sustainable substitute for traditional fishmeal in aquaculture nutrition. It is an excellent option for partial fishmeal substitution because of its elevated protein level, digestibility, and hypoallergenicity, particularly in the feed of omnivorous and moderately carnivorous fish. Advances in processing technology and intelligent feed formulation can effectively minimize the inherent drawbacks of RPC, including amino acid imbalances and antinutritional factors (ANFs). By adding lysine, methionine, and other essential amino acids as supplements, either alone or in combination with complementary protein sources, nutritional profiles can be customized to match the species requirements and maximize growth performance. It also maximizes resource-use efficiency and supports environmental sustainability when RPC production is incorporated into circular bio-economy frameworks. To fully realize RPC's potential of RPC in transforming aquaculture systems into robust, reasonably priced, and sustainable systems globally, ongoing multidisciplinary research and innovation are crucial.

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Conflict of interest

The author declared no conflict of interest.

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