Scientia Review, Vol. 02(06), June 2026, pp. 4-10

ISSN: 3107-7919

Scientia Review

Website: www.scientiafoundation.in

POPULAR SCIENCE ARTICLE

Affordable Aquafeed Design through Integration of Agricultural Residue

Kapil Deb Nath[1*], Ranjit Bordoloi[2] and Rupak Taye[3]

[1]Krishi Vigyan Kendra, AAU, Udalguri, Lalpool, Assam, 784514, India

[2]Krishi Vigyan Kendra, AAU, Sonitpur, Napam, Assam, 784028, India

[3]Krishi Vigyan Kendra, AAU, Nagaon, Simaluguri, Assam, 782002, India

*Email: kapil.debnath@aau.ac.in

Received: 03 June 2026
Revised: 04 June 2026
Accepted: 07 June2026
Published online: 13 June 2026

Article ID: SR01127

Citation: Nath, K. D., Bordoloi, R., & Taye, R. (2026). Affordable Aquafeed Design through Integration of Agricultural Residue. *Scientia Review*, 2(6),), 4-10

Abstract

The escalating cost of conventional aquafeed ingredients such as fishmeal and soybean meal has imposed severe economic pressure on smallholder fish farmers across developing nations. Agricultural byproducts including rice bran, wheat bran, mustard oil cake, groundnut oil cake, copra meal and cassava have emerged as viable low-cost alternatives capable of meeting the nutritional demands of commonly cultured freshwater fish species. This article examines the nutritional composition of selected agricultural byproducts and their applicability in feed formulation for Indian major carps and other important aquaculture species. It further discusses anti-nutritional factors and methods to mitigate their adverse effects through fermentation, heat treatment and enzyme supplementation. The economic implications of substituting conventional ingredients with locally sourced agricultural residues are also explored.

Keywords: aquafeed, byproducts, fermentation, fishmeal, sustainability, aquaculture

Introduction

Aquaculture is among the fastest growing food production sectors globally and is projected to contribute more than half of all fish consumed by humans within the coming decade. The Food and Agriculture Organization of the United Nations has documented that fisheries and aquaculture together provided about 178 million tonnes of aquatic organisms in 2020, with aquaculture accounting for a rapidly expanding share of that total (FAO, 2022). This remarkable growth trajectory has been accompanied by an equally significant expansion in demand for aquafeed, which constitutes the single largest operational cost in intensive and semi-intensive fish production systems. Fishmeal and soybean meal have historically served as the cornerstone protein sources in commercial aquafeed formulations owing to their high digestibility and well-balanced amino acid profiles. However, global fishmeal production has stagnated due to overexploitation of forage fish stocks and tightening fisheries regulations, driving prices to levels that are economically prohibitive for smallholder aquaculture operations (Tacon and Metian, 2008).

In this context, the identification and utilization of alternative feed ingredients derived from agricultural byproducts has attracted considerable scientific and policy attention. Agricultural byproducts refer to the residues and co-products generated during the processing of food crops and oilseeds. These materials are typically available in large quantities at low cost and often go underutilized or are discarded as waste. When properly processed and incorporated into feed formulations at appropriate inclusion levels, such byproducts can provide adequate quantities of protein, energy, fiber and micronutrients necessary for fish growth and health. A review by Hasan *et al.* (1997) demonstrated that several oilseed cakes including mustard, sesame, linseed, copra and groundnut can substitute fishmeal protein in common carp diets at inclusion levels up to 75 percent without severe depression of growth, provided anti-nutritional factors are managed appropriately.

Research conducted over the past four decades has generated a substantial body of evidence supporting the feasibility of replacing conventional ingredients with agricultural byproducts in diets for Indian major carps, tilapia and catfish. The challenge lies not merely in identifying these materials but in formulating diets that balance nutritional adequacy with economic efficiency while accounting for anti-nutritional factors that can impair digestibility and animal health. Francis *et al.* (2001) identified protease inhibitors, phytates, glucosinolates, saponins, tannins, lectins and non-starch polysaccharides as the most critical anti-nutritional factors in plant-derived feed ingredients and their work remains the foundational reference in this area. More recently, Akter *et al.* (2024) demonstrated in cage culture trials that a combination of mustard oil cake, soybean meal and rice bran replacing up to 50 percent of fishmeal protein in diets for Labeo rohita produced growth performance statistically comparable to a control diet based on higher fishmeal inclusion, confirming the practical viability of byproduct-based formulations.

Nutritional Profile of Common Agricultural Byproducts

Rice bran is one of the most abundantly available and widely used byproducts in aquafeed formulation across Asia. It is obtained during the milling of rough rice and typically contains 12 to 16 percent crude protein, 15 to 20 percent crude fat in its undefatted form and significant quantities of B vitamins and phosphorus. Priyadarsani *et al.* (2025) demonstrated through linear programming optimization that rice byproducts including rice bran, rice polish, broken rice and de-oiled rice bran can be combined to formulate 100 kg of feed for Indian major carps at a cost below Rs 20 per kg while meeting species-specific protein requirements of 20 to 22 percent crude protein. De-oiled rice bran in particular has been highlighted as a nutritionally valuable and shelf-stable ingredient, containing approximately 15.30 percent crude protein, 0.33 percent crude lipid and 14.45 percent crude fiber on a dry matter basis (Kumar *et al.*, 2012). Its reduced fat content compared to full-fat rice bran substantially improves storage stability and is therefore preferred in formulations where feed is prepared in advance of use.

Wheat bran derived from the outer layers of the wheat kernel contains approximately 14 to 17 percent crude protein, moderate levels of metabolizable energy and considerable quantities of niacin and phosphorus. It has been successfully incorporated into diets for common carp and rohu at inclusion levels ranging from 20 to 40 percent of the diet without significant depression in growth performance (Hossain and Jauncey, 1989). A survey of fish feed ingredients conducted in Bangladesh found that wheat bran crude protein ranged from 14.84 to 15.40 percent and crude lipid from 4.09 to 9.71 percent across different sampling locations, confirming that its nutritional value is relatively consistent and predictable compared to some other plant-derived materials (Hoque *et al.*, 2016).

Mustard oil cake is the residue remaining after oil extraction from mustard seeds (Brassica spp.) and is protein-rich with crude protein values typically ranging from 35 to 37 percent. The same survey by Hoque *et al.* (2016) confirmed mustard oil cake crude protein at 35.17 to 37.25 percent and crude lipid at 10.73 to 15.52 percent, representing nutritional characteristics well suited to partial fishmeal replacement. Akter *et al.* (2024) demonstrated that mustard oil cake combined with soybean meal and rice bran in diets containing 45, 68 and 79 percent plant protein ingredients achieved isonitrogenous formulations with crude protein ranging from 32.20 to 32.29 percent, successfully supporting rohu growth in cage culture over 90 days. The primary limitation of mustard cake is the presence of glucosinolates and erucic acid, which are goitrogenic compounds that can suppress thyroid function at high dietary inclusion levels.

Groundnut oil cake contains 40 to 48 percent crude protein and is highly palatable to most cultured fish species. Hasan *et al.* (1997) evaluated groundnut oil cake at 25 and 75 percent fishmeal protein replacement in common carp fry and reported satisfactory growth at the 25 percent level, with performance declining at higher inclusion due to the presence of trypsin inhibitors and aflatoxin risk. Aflatoxin contamination produced by Aspergillus flavus during improper storage represents the most critical safety concern associated with groundnut cake use in aquafeed. Francis *et al.* (2001) identified mycotoxins including aflatoxins as among the most dangerous contaminants in oilseed-based feed ingredients, with hepatotoxic effects in fish and serious food safety implications for human consumers of farmed fish.

Copra meal obtained from the residue of coconut oil extraction contains 18 to 22 percent crude protein with a high fiber fraction and is deficient in lysine and threonine. Mukhopadhyay and Ray (1999) formulated six isonitrogenous diets (35 percent crude protein) with raw and soaked de-oiled copra meal substituted for fishmeal in the diet of rohu fingerlings at 20, 30 and 40 percent levels by weight. Soaking copra meal in water for 16 hours reduced tannin content from 2.4 to 0.9 percent and the 20 and 30 percent inclusion diets produced acceptable growth performance. Cassava or tapioca residue is primarily an energy source containing 60 to 70 percent starch on a dry matter basis with negligible crude protein. Its primary concern is the hydrocyanic acid content in raw material which requires drying or fermentation before safe inclusion in fish diets.

Anti-Nutritional Factors and Processing Approaches

A major constraint on the wider adoption of agricultural byproducts in aquafeed is the presence of various anti-nutritional factors that can depress feed intake, impair nutrient digestibility, damage intestinal tissue and suppress immune function in fish. Francis *et al.* (2001) provided the most comprehensive cataloguing of anti-nutritional factors present in plant-derived feed ingredients, identifying protease inhibitors, phytates, glucosinolates, saponins, tannins, lectins, oligosaccharides, non-starch polysaccharides, phytoestrogens, alkaloids, gossypols, cyanogens, mimosine and cyclopropenoid fatty acids as compounds of concern. Their review, which has accumulated over 2,250 citations in the scientific literature, remains the definitive reference on this topic and underscores the importance of processing in enabling safe and effective use of plant-derived ingredients.

Fermentation is one of the most effective and economically accessible methods for reducing anti-nutritional factor content in agricultural byproducts. A landmark study by Bairagi *et al.* (2002) demonstrated that solid-state fermentation of duckweed leaf meal using a Bacillus sp. isolated from carp intestine for 15 days at 37 degrees Celsius reduced tannin from 1.0 to 0.02 percent and phytic acid from 1.23 to 0.09 percent while simultaneously improving crude protein content and digestibility. Diets containing 30 and 40 percent fermented leaf meal produced significantly better growth in rohu fingerlings than those containing raw leaf meal, establishing the efficacy of microbial fermentation as a processing tool for plant-based aquafeed ingredients. Mukhopadhyay and Ray (1999) similarly demonstrated that fermentation of sesame seed meal using lactic acid bacteria reduced phytic acid below detectable limits and tannin from 20 to 10 g per kg, enabling 40 percent inclusion of fermented sesame seed meal in rohu diets with superior growth and feed conversion ratio compared to unfermented meal.

Phytate represents a particularly widespread and economically significant anti-nutritional factor in grain and oilseed-based ingredients because it chelates essential minerals including zinc, calcium, iron and phosphorus, rendering them largely unavailable for fish metabolism. Kumar *et al.* (2012) conducted a comprehensive review of phytate and phytase in fish nutrition, documenting that phytate-bound phosphorus in plant ingredients is largely unavailable to gastric or agastric fish species and that dietary phytase supplementation effectively converts bound phosphate to available phosphate. Their review found that phytase supplementation at optimal dosages improved growth performance, mineral bioavailability and feed conversion in multiple fish species while simultaneously reducing phosphorus excretion into aquaculture pond environments, addressing both economic and environmental dimensions of the anti-nutritional problem.

Heat treatment through autoclaving, toasting or extrusion cooking is highly effective against heat-labile protease inhibitors and lectins. Non-starch polysaccharides constitute another major class of anti-nutritional compounds in cereal and legume-based feed ingredients that impair digestion by increasing intestinal viscosity and reducing enzyme-substrate interaction. Sinha *et al.* (2011) provided a thorough review of non-starch polysaccharides in fish nutrition, documenting their negative effects on digestive enzyme activity, nutrient absorption and gut morphology across multiple freshwater and marine species. They highlighted that extrusion cooking, enzyme supplementation and microbial fermentation are the most effective mitigation strategies and that combining these approaches can synergistically reduce non-starch polysaccharide-related digestibility losses. Extrusion cooking in particular simultaneously gelatinizes starch, destroys heat-labile anti-nutrients and improves pellet water stability, making it a preferred processing approach in commercial aquafeed manufacture.

Feed Formulation Principles and Practical Approaches

Effective low-cost feed formulation requires a systematic approach that balances the protein, energy, mineral and vitamin requirements of the target species against the nutritional composition and limitations of available byproduct ingredients. The Pearson square method is widely used by smallholder farmers for simple two-ingredient formulations, while linear programming enables least-cost optimization when multiple ingredients are available at variable prices. Priyadarsani *et al.* (2025) applied linear programming modelling to formulate rice byproduct-based diets for

Indian major carps and demonstrated that protein contents of 20.45 to 22.17 percent could be achieved from combinations of rice bran, rice polish, broken rice and de-oiled rice bran at a formulation cost below Rs 20 per kg, well below the typical cost of commercially manufactured carp feed in India. Their study is particularly relevant for Assam and other rice-producing states of northeast India where these byproducts are available at minimal cost from rice mills.

A practical low-cost grow-out diet for rohu can be assembled from regionally available ingredients. Mathew and Chadha (1998) demonstrated that a cost-effective supplemental feed formulated from rice bran, wheat bran, black gram bran, mustard oil cake, sesame oil cake and fishmeal in various combinations with molasses as a binder produced carp polyculture yields superior to a conventional control diet consisting solely of rice bran and mustard oil cake at a 3 to 1 ratio. Their feeding trial conducted in 0.1 hectare ponds over 330 days showed that the lowest cost formulation excluding fishmeal still produced acceptable growth, supporting the economic viability of wholly plant-based feed for polyculture systems where natural productivity supplements dietary intake. In similar polyculture systems, Akter *et al.* (2024) found that replacing up to 50 percent of fishmeal protein with plant protein ingredients combining mustard oil cake, soybean meal and rice bran produced equivalent or superior weight gain and specific growth rate compared to diets with higher fishmeal content.

Binding agents are important in low-cost pellet manufacture where mechanical pellet mills rather than extruders are used. Molasses is an effective and inexpensive binder used in pelleted farm-made feed across South Asia, as documented in the formulations developed by Mathew and Chadha (1998) for carp polyculture in India. Cassava starch is an alternative binder that also contributes energy to the diet. A minimum pellet water stability of 30 minutes is generally recommended for pond aquaculture to ensure that nutrients remain available for fish consumption rather than dissolving into the water column. The use of vitamin and mineral premixes at 0.5 percent inclusion is standard practice in supplementary feed formulation to compensate for the variable micronutrient content of plant-derived ingredients and to ensure that fish requirements for fat-soluble vitamins, trace minerals and vitamin C are met.

For carnivorous species such as catfish or snakehead, higher protein targets of 35 to 40 percent crude protein require higher inclusion of protein-dense byproducts and may necessitate supplemental synthetic amino acids. Kumar *et al.* (2012) documented that the limiting amino acids in most plant-based aquafeed formulations are methionine and lysine and that supplementation with these amino acids at levels of 0.3 to 0.5 percent of the diet can substantially recover growth performance in diets where plant proteins dominate. This supplementation strategy enables higher inclusion of cost-effective byproducts without sacrificing the amino acid balance required by fast-growing fish species.

Growth Performance and Feed Conversion in Experimental Trials

Numerous feeding trials have evaluated the growth response of commercially important freshwater fish species to diets in which agricultural byproducts replace varying proportions of conventional ingredients. Hossain and Jauncey (1989) conducted one of the earliest systematic evaluations of Bangladeshi oilseed meals as partial fishmeal substitutes in common carp diets, testing mustard, linseed and sesame oilseed meals at 25, 50 and 75 percent protein replacement levels over a period sufficient to assess growth, feed conversion and protein utilization. Their findings established that these oilseed meals could partially substitute fishmeal in carp diets and that growth performance depended strongly on the anti-nutritional factor content and the degree to which inclusion levels were managed. This foundational work has been cited extensively in subsequent studies on Indian major carp nutrition and continues to inform practical feed formulation recommendations in South Asian aquaculture.

Mukhopadhyay and Ray (1999) contributed critical evidence on fermentation as a processing strategy by demonstrating that fermented sesame seed meal could be included at 40 percent in rohu diets with significantly better growth and feed conversion than raw sesame seed meal diets. The ability of lactic acid bacteria fermentation to reduce phytic acid below detectable limits in sesame seed meal was particularly significant because phytate had been identified as the primary factor limiting the nutritional value of this ingredient in unprocessed form. Their research, conducted at Visva-Bharati University in West Bengal, is particularly relevant to Northeast India where sesame is grown in several districts of Assam and the seed meal is available as a low-cost processing byproduct.

Bairagi *et al.* (2002) extended this line of inquiry to duckweed leaf meal, demonstrating that fermentation with a fish gut bacterium not only reduced tannin and phytic acid dramatically but also increased free amino acids and fatty acid content, improving overall nutritional value. In 80-day feeding trials with rohu fingerlings, diets containing 30 percent fermented duckweed leaf meal produced growth statistically comparable to the fishmeal-based reference diet, while raw leaf meal diets at equivalent inclusion caused significant growth depression. Bairagi *et al.* (2004) subsequently confirmed similar results with Leucaena leucocephala leaf meal fermented with Bacillus subtilis and Bacillus circulans, reporting significant reductions in crude fiber, tannin, phytic acid and mimosine alongside improved growth and feed utilization in rohu fingerlings. These studies collectively established the broad applicability of microbial bioprocessing in enhancing the nutritional value of diverse plant-derived feed ingredients.

The most recent and directly applicable evidence comes from Akter *et al.* (2024), who conducted a 90-day cage culture feeding trial with Labeo rohita comparing three isonitrogenous diets containing plant protein ingredients at 45, 68 and 79 percent of total dietary protein against a high-fishmeal control. Their results demonstrated that a diet providing 50 percent fishmeal replacement with mustard oil cake, soybean meal and rice bran maintained growth performance equivalent to the control while offering substantially lower feed ingredient cost, confirming that the three-decade body of laboratory evidence on plant protein substitution translates effectively to commercial-scale cage culture systems.

Economic Analysis of Byproduct-Based Feed Formulations

The economic case for agricultural byproduct inclusion in aquafeed rests on the differential between ingredient costs and maintained biological performance. Priyadarsani *et al.* (2025) provided some of the most current economic evidence specific to India, demonstrating that rice byproduct-based formulations for Indian major carps could be produced at below Rs 20 per kilogram while achieving protein contents of 20 to 22 percent. Given that commercial pelleted carp feeds in India typically cost Rs 30 to 45 per kilogram, this represents a potential feed cost saving of 35 to 55 percent without compromising the core nutritional specification for grow-out.

Tacon and Metian (2008) provided the macro-economic context for these formulation economics, documenting through a global survey of over 800 feed manufacturers and aquaculture stakeholders in over 50 countries that fishmeal prices and supply constraints were already by 2006 compelling the aquafeed industry to seek alternatives. Their survey found that fishmeal inclusion levels in compound aquafeeds were declining as prices rose and they predicted that this trend would accelerate with fishmeal increasingly reserved for high-value starter and broodstock feeds. This prediction has proven accurate and has intensified the relevance of byproduct-based formulations for mainstream grow-out feeds over the subsequent decade and a half.

Mathew and Chadha (1998) provided farm-level economic evidence from India, demonstrating through a 330-day carp polyculture trial that low-cost supplemental feeds formulated from locally available ingredients including rice bran, wheat bran and oilseed cakes produced net fish production and economic returns superior to a simple rice bran plus mustard oil cake control diet. Their work highlighted that even relatively modest investments in improving feed formulation through ingredient diversification and balanced nutritional composition can produce economically significant improvements in fish yield and producer income, particularly when feed cost constitutes the majority of variable production costs.

Kumar *et al.* (2012) added an environmental economics dimension by documenting that phytase supplementation of plant-based diets reduces phosphorus loading in pond effluents, a benefit that has economic value in the context of environmental compliance and pond sustainability. Excessive phosphorus discharge from aquaculture operations accelerates eutrophication of water bodies and increases the cost of water quality management. The partial offset of phytase supplementation cost by savings in inorganic phosphate supplementation and reduced environmental remediation costs means that the economic analysis of byproduct-based diets must account for these broader efficiency gains.

Environmental Sustainability Considerations

Beyond direct economic benefits, the integration of agricultural byproducts into aquafeed formulations offers meaningful environmental co-benefits. Reducing reliance on fishmeal alleviates pressure on overexploited forage fish populations that form the base of many marine food webs. FAO (2022) reported that approximately 20 percent of global wild fish capture is converted to fishmeal and fish oil, a proportion that exerts considerable pressure on small pelagic species such as anchovies, sardines and herrings whose populations are already stressed by climate change and direct harvest pressure. Every kilogram of fishmeal successfully replaced by agricultural byproducts in aquafeed reduces this extractive demand on wild marine fisheries.

Additionally, the valorization of agricultural processing residues through their incorporation into aquafeed reduces the volume of organic waste entering landfills or waterways where its decomposition generates greenhouse gases and nutrient pollution. Sinha *et al.* (2011) noted that the aquafeed industry's move toward plant-based ingredients is not only economically motivated but reflects growing recognition that the sustainability of aquaculture as a food production system depends on reducing its dependence on marine capture fisheries. The circular economy logic of converting agricultural waste streams into high-value aquafeed ingredients is increasingly recognized in food systems policy as a model for resource efficiency that simultaneously addresses feed cost, waste management and fisheries conservation objectives.

Regional Context for Northeast India and Assam

Northeast India and particularly Assam offers a compelling regional case study for the application of low-cost byproduct-based aquafeed. Rice is the dominant cereal crop throughout the Brahmaputra valley and rice bran is available in large quantities at minimal cost from the region's numerous rice mills. Mustard cultivation in the alluvial plains of Assam generates substantial quantities of mustard oil cake following cold pressing for edible oil. The findings of Akter *et al.* (2024) on the efficacy of mustard oil cake combined with rice bran as fishmeal replacers in rohu diets are directly applicable to Assam given the near-identical set of ingredient availabilities and the cultural and economic importance of rohu in local aquaculture and fish consumption.

The linear programming framework developed by Priyadarsani *et al.* (2025) is particularly actionable for Assam fish farmers and extension officers because it translates published nutritional data on rice byproducts into practical, cost-optimized formulation recipes without requiring sophisticated laboratory infrastructure. Their demonstration that Indian major carp diets meeting 20 to 22 percent crude protein can be assembled entirely from rice byproducts at below Rs 20 per kilogram provides a practical benchmark against which smallholder farmers in rice-growing districts of Assam can evaluate their current feed costs and formulation practices.

Broader support for the development of low-cost aquafeed from agricultural byproducts in the region can be drawn from the foundational work of Bairagi *et al.* (2002 and 2004) who demonstrated at institutions in West Bengal that microbial fermentation using fish gut bacteria is a technically simple and highly effective means of improving the nutritional value of diverse plant-based ingredients for rohu. This microbial bioprocessing technology requires only locally available raw materials, basic fermentation equipment and access to fish gut bacteria and can therefore be implemented at community or cooperative scale in rural aquaculture clusters of northeast India without major capital investment.

Conclusion

Agricultural byproducts represent an underutilized resource with significant potential to address the dual challenge of feed cost reduction and sustainability in aquaculture. Rice bran, wheat bran, mustard oil cake, groundnut oil cake, copra meal and cassava have all demonstrated suitability as partial or substantial replacements for conventional fishmeal and energy ingredients in diets for Indian major carps and other freshwater fish species of commercial importance. The primary technical constraints associated with their use, namely anti-nutritional factors and variable nutritional composition, can be substantially mitigated through fermentation, heat treatment, phytase supplementation and rigorous quality control during storage.

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