

9. Recent Advances, Challenges, Opportunities, Product Development, and the Sustainability of Agricultural Wastes as Feed Ingredients in Aquaculture

Sanat Chandravanshi¹, Debtanu Bera² Joshi Sharon J³, Kashvi Kajal⁴, kadam Bihari⁵

¹*Department of Aquatic Animal Health Management, College of Fisheries, CAU (I) Lembucherra, Agartala - 799 210, Tripura, India.*

²*Department of Aquaculture, Tamil Nadu Dr J. Jayalalithaa Fisheries University*

³*Centre for Aquaculture, Sathyabama Institute of Science and Technology, Chennai*

⁴*Erasmus Mundus Joint Master's in Aquaculture, Environment and Society (ACES-STAR), University of Highlands and Islands, Inverness, IV2 3JH, United Kingdom*

⁵*College of Fisheries, ANDUAT, Kumarganj, Ayodhya, UP 224229*

1. Introduction

Aquaculture is the fastest-growing food production sector globally, projected to supply two-thirds of the world's food fish by 2030 (FAO, 2020). However, this growth hinges on the sustainability and cost-effectiveness of feed ingredients, which represent over 50% of operational costs in aquaculture. Traditionally, aquafeeds have relied heavily on fishmeal and fish oil sourced from wild-caught fish. The limited availability of these marine resources, along with rising demand and volatile market prices, jeopardises the industry's long-term viability (Tacon & Metian, 2015). Consequently, there is a pressing need to identify alternative sustainable protein and lipid sources.

Agricultural wastes, comprising various crop residues, agro-industrial by-products,

and animal manures, are a largely untapped resource. Their conversion into feed ingredients not only addresses the feed crisis but also alleviates environmental pollution from waste disposal. Embracing a circular economy model, which focuses on minimising waste and enhancing resource efficiency, is essential in this regard. This review synthesises current research on the utilisation of agricultural waste in aquaculture feeds, highlighting technological advancements, challenges, emerging opportunities, and product development pathways. Ultimately, the goal is to promote a resilient and environmentally sustainable aquaculture industry that can meet future food demands without compromising the health of the planet.

2. Recent Advances in Agricultural Waste Utilisation

Significant progress has been achieved in converting various agricultural wastes into viable aquaculture feed ingredients. This advancement primarily hinges on innovative processing technologies that unlock the nutritional potential of these materials. Raw agricultural wastes generally contain complex carbohydrates (e.g., lignin, cellulose), anti-nutritional factors (ANFs), and low crude protein content, which restrict their direct application in aquafeeds. Contemporary processing techniques aim to enhance nutrient bioavailability, deactivate ANFs, and improve the physical properties of the feed, such as palatability and water stability.

2.1. Categories of Agricultural Wastes

Agricultural wastes encompass a heterogeneous collection of materials with distinct nutritional and chemical profiles, broadly classified into three categories:

- **Crop Residues:** These non-edible remnants of crops after harvesting include rice husks, wheat bran, corn stover, and sugarcane bagasse. They are typically rich in fibre but have a low protein content and high lignin levels, necessitating processing to improve digestibility.

- **Agro-industrial By-products:** These are residues from food and beverage processing. This category includes brewery spent grains, distillery by-products, fruit and vegetable pomace, and oilseed cakes (e.g., soybean meal, canola meal, sunflower cake) after oil extraction. These by-products are typically more nutrient-dense than crop residues, offering a good source of protein and residual lipids.
- **Animal Manures:** While not directly used as a feed ingredient in its raw form due to safety concerns and low digestibility, animal manures (e.g., poultry litter, swine manure) can be a substrate for indirect feed production. This is commonly seen in pond fertilisation, where it promotes the growth of natural food organisms (algae, zooplankton), or in insect bioconversion systems, where it serves as a substrate for insect larvae.

2.2. Processing Technologies

The raw form of many agricultural wastes presents nutritional and physical limitations. Advanced processing technologies are crucial for overcoming these hurdles and converting waste into a high-quality feed ingredient.

2.2.1. Fermentation

- **Fermentation** is a robust biological process that uses microorganisms to break down complex organic matter and synthesise new compounds. It is a key

method for enhancing the nutritional value of agricultural wastes.

Table 1 Production of single-cell protein, probiotics

Table 1: Production of single-cell protein, probiotics

Fermentation Type	Microorganism Examples		Benefits of Aquaculture Feeds	
Solid-State Fermentation (SSF)	<i>Aspergillus niger</i> , <i>Rhizopus oryzae</i>		High protein enrichment, ANF reduction	
Submerged Fermentation (SmF)	<i>Saccharomyces cerevisiae</i> , <i>Lactobacillus spp.</i>		Production of single-cell protein, probiotics	

2.2.2. Enzymatic Hydrolysis

Enzymatic hydrolysis utilises specific enzymes to selectively break down complex polymers in agricultural waste into more digestible components. This targeted process operates under mild conditions and can rival fermentation in efficiency for specific applications. For instance, cellulases hydrolyse cellulose from crop residues into glucose, making it readily available for aquatic animals or suitable as a substrate for microbial fermentation. Similarly, proteases break down complex proteins into peptides and free amino acids, enhancing their bioavailability. This highly controllable process significantly increases nutrient release and absorption.

2.2.3. Extrusion and Pelleting

These are thermal and mechanical processes critical for producing physically stable and palatable aquafeeds. Extrusion involves a combination of high

temperatures, pressure, and shear to transform raw ingredients into finished feed pellets. This process has several key benefits:

- **Starch Gelatinisation:** The high heat and pressure cause starch granules to swell and burst, making the carbohydrates much more digestible for aquatic species.
- **Anti-Nutritional Factor Denaturation:** Many heat-labile ANFs, such as trypsin inhibitors in soybean meal and lectins, are denatured and inactivated during the extrusion process, improving nutrient utilisation.
- **Pathogen Elimination:** The high temperatures effectively sterilise the feed, eliminating harmful pathogens and ensuring product safety.

- **Water Stability:** Extruded pellets have a low bulk density and excellent water stability, which is crucial for reducing nutrient leaching in aquatic environments.

2.2.4. Insect Bioconversion

The use of insects, particularly black soldier fly larvae (BSFL), to bioconvert organic wastes into high-protein and lipid-rich biomass is gaining significant traction. This process capitalises on the ability of insect larvae to efficiently consume and grow on a wide range of organic wastes, including food

processed into insect meal and insect oil. The BSFL meal has shown promising results as a direct replacement for fishmeal, while the extracted oil is a viable alternative to fish oil. This process offers an exceptionally efficient waste management solution, converting low-value waste streams into a high-value aquaculture feed ingredient.

3. Challenges in Utilising Agricultural Wastes

Despite the substantial potential of agricultural wastes, several significant

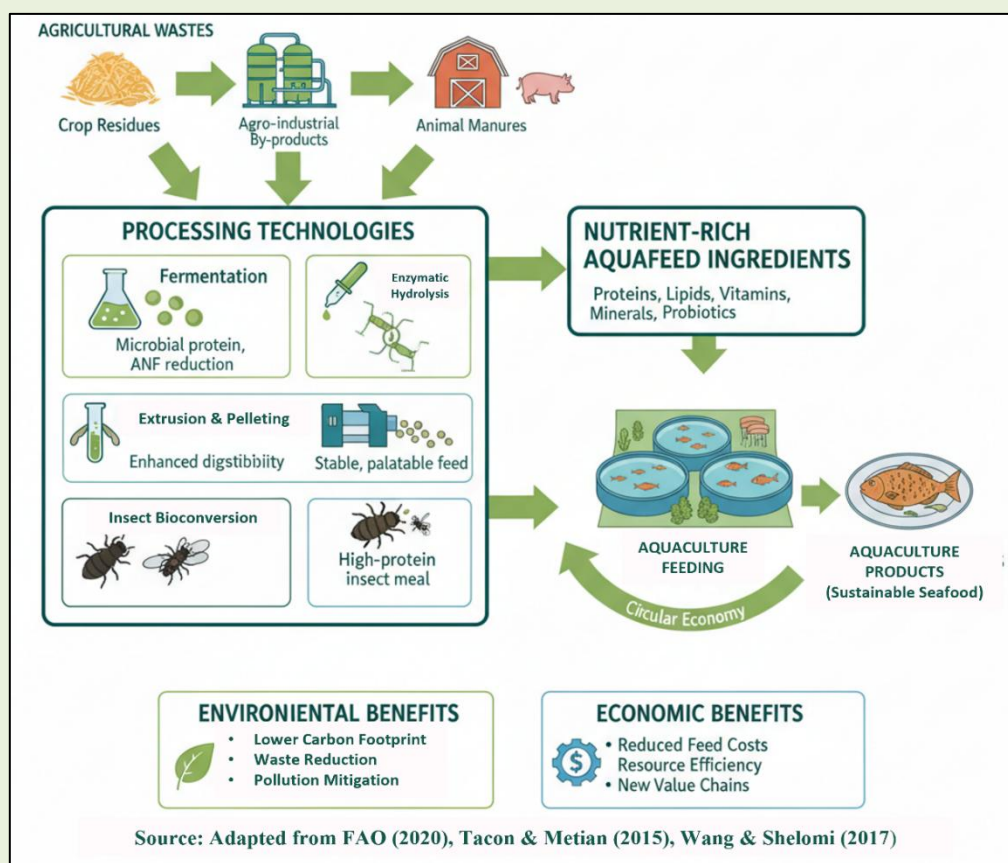


Figure 1: Agriculture Waste Bioconversion: A Circular Aquaculture Feed Model

waste, manure, and crop residues. The resulting larval biomass, which can contain 40-50% crude protein and 25-30% lipids, is

challenges must be addressed for their widespread and sustainable adoption in aquaculture feeds. These hurdles span

nutritional, safety, logistical, and socio-economic dimensions.

3.1. Nutritional Variability and Imbalance

Nutritional Variability and Imbalance

Nutritional variability in agricultural wastes is influenced by factors such as plant species and post-harvest handling. For instance, protein content in rice bran can vary considerably due to milling methods and rice types. This inconsistency complicates feed formulation and can lead to inconsistent animal performance and nutritional deficiencies without standardised quality control.

3.2. Anti-Nutritional Factors (ANFs)

Many agricultural wastes contain anti-nutritional factors (ANFs) that hinder nutrient digestion and may be toxic to aquatic animals. Common ANFs include:

- **Phytates:** Found in cereal grains and oilseed meals, phytates chelate with minerals (e.g., zinc, calcium, phosphorus), making them unavailable for absorption.
- **Trypsin Inhibitors:** Present in legumes and some oilseed meals (e.g., raw soybean meal), these inhibitors block the action of the enzyme trypsin, severely reducing protein digestibility.
- **Tannins:** These polyphenolic compounds bind to proteins, reducing

their digestibility and making the feed less palatable.

- **Lectins:** These proteins can cause gut damage and inflammation, leading to reduced nutrient absorption and overall poor health.
- **Mycotoxins:** Produced by fungi that can grow on improperly stored agricultural wastes, mycotoxins are highly toxic and can cause severe health issues, immunosuppression, and mortality in aquatic species.

3.3. Contaminants and Safety Concerns

Agricultural wastes can harbour contaminants threatening animal and human health, including:

- **Pesticide and Herbicide Residues:** Chemicals used in crop production can accumulate in agricultural wastes.
- **Heavy Metals:** Wastes can absorb heavy metals from the soil or environmental pollution.
- **Pathogenic Microorganisms:** Improperly stored wastes can be a breeding ground for harmful bacteria (e.g., *Salmonella*, *E. coli*) and fungi.

3.4. Supply Chain and Logistics

The seasonal and decentralised nature of agricultural waste generation presents logistical challenges. Collecting, transporting, and storing these low-density

materials can be complex and costly, with high moisture content increasing the risk of spoilage. Efficient collection networks and centralised processing facilities are vital for a sustainable supply chain.

3.5. Palatability and Digestibility

Processed agricultural wastes may still have low palatability or digestibility for particular aquatic species, particularly carnivorous fish. This can result in reduced feed intake and poor growth. Research into flavour enhancers and species-specific dietary formulations is needed to improve acceptability.

3.6. Regulatory Hurdles and Consumer Acceptance

Introducing new feed ingredients from waste materials often encounters regulatory challenges and consumer scepticism. Extensive data on safety and efficacy is required for approval, and clear communication about the safety and benefits of these materials is essential to build trust and acceptance among consumers.

4. Opportunities and Future Directions

Despite significant challenges, the valorisation of agricultural wastes offers numerous opportunities to enhance the sustainability and profitability of the aquaculture sector. Future efforts should emphasise technological advancements,

strategic integration, and supportive policy frameworks.

4.1. Value Chain Integration and Bio-refinery Concepts

Transforming agricultural waste management into comprehensive bio-refinery concepts presents a key opportunity. This approach allows for the simultaneous extraction of multiple high-value products from a single waste source. For example, rice husks can yield digestible fibres for aquafeeds, silica for industrial use, and bio-oil for energy, thus creating a circular, economically viable value chain.

4.2. Precision Nutrition and Feed Formulation

Advancements in nutritional genomics and bioinformatics enable precision nutrition, tailoring feed formulations to the specific needs of aquaculture species. Through detailed nutrient profiling of agricultural waste ingredients, optimised inclusion levels can be determined, thereby maximising growth performance while minimising waste. This approach also facilitates the development of targeted strategies to mitigate the impact of anti-nutritional factors (ANFs).

4.3. Development of Novel and Synergistic Processing Technologies

Future research will focus on developing and combining novel processing

technologies for enhanced efficacy. This includes:

- **Microbial Consortia Fermentation:** Utilising multiple beneficial microorganisms can enhance substrate breakdown and nutrient synthesis.
- **Enzyme Cocktails:** Employing a combination of enzymes to achieve comprehensive hydrolysis of complex agricultural waste matrices.
- **Non-thermal Processing:** Investigating non-thermal methods such as pulsed electric fields or plasma treatment for effective extraction and minimal nutrient degradation.

4.4. Standardisation and Market Development

For the broader adoption of agricultural waste-based feed ingredients, standardisation and market development are crucial. Establishing quality assurance protocols and specific certifications will foster confidence among feed manufacturers. Additionally, market mechanisms, such as carbon credits for waste utilisation, can incentivise investment in these sustainable practices.

4.5. Policy and Regulatory Support

Supportive government **policies and regulatory frameworks** are crucial to accelerate the adoption of these innovations. This includes:

- **Funding for Research and Development:** Investing in research to address the remaining technical challenges.
- **Streamlined Regulatory Approval:** Creating clear and efficient pathways for the approval of new feed ingredients derived from agricultural wastes.
- **Incentives and Subsidies:** Providing financial incentives for farmers and feed producers to adopt these sustainable practices, which can help offset initial capital costs.

5. Product Development Strategies

Developing aquaculture feed ingredients from agricultural waste is a systematic, multi-stage process that transitions from characterisation to commercialisation. A robust strategy is essential to ensure the final product is safe, nutritious, and economically viable.

5.1. Raw Material Characterisation and Pre-processing

The first step involves a thorough characterisation of agricultural waste, including proximate analysis to assess nutritional components such as moisture, protein, lipids, fibre, and ash content. Additional analyses of amino acid profiles, fatty acids, minerals, and vitamins are necessary, alongside screening for anti-nutritional factors (ANFs) and contaminants. Post-characterisation, pre-

processing steps such as cleaning, drying, and grinding are essential to achieve a uniform particle size and moisture level suitable for subsequent processing.

5.2. Small-Scale Processing and Optimisation

Characterised raw materials undergo various processing technologies at a laboratory or pilot scale. This stage focuses on optimising methods, such as fermentation or extrusion, to maximise nutrient availability and inactivate ANFs. Parameters such as substrate concentration and fermentation conditions are fine-tuned for fermentation, while extrusion settings, including barrel temperature and moisture level, are adjusted to enhance pellet quality and digestibility.

5.3. Nutritional Evaluation and Feeding Trials

This is a critical stage that validates the effectiveness of the processed ingredient. It moves from theoretical composition to practical application.

- **In Vitro Studies:** help estimate digestibility using digestive enzymes from target aquaculture species.
- **In Vivo Feeding Trials:** assess the ingredient's impact on growth rates, feed conversion ratios (FCR), survival rates, and nutrient retention across various life stages and environmental conditions. Monitoring animal health,

including immune response and organ histology, is also crucial for identifying potential long-term effects.

5.4. Palatability and Acceptability Assessment

Evaluating the ingredient's palatability is critical, as a nutritious product is ineffective if not consumed. Trials to assess feed intake and behavioural responses in target species involve exploring modifications such as palatability enhancers, pellet size adjustments, and feed texture alterations to optimise intake.

5.5. Safety and Shelf-Life Assessment

Safety assessments are vital and include rigorous testing for microbial loads (e.g., Salmonella, E. coli) and contaminants, as well as shelf-life studies under varying storage conditions. This process monitors nutrient integrity, lipid oxidation, and microbial spoilage to establish a realistic expiry date, ensuring product safety and efficacy.

5.6. Techno-Economic and Market Feasibility Analysis

A comprehensive techno-economic analysis is essential before scaling up production. This analysis assesses the economic viability of processes spanning waste collection to distribution, incorporating cost-benefit analyses, market potential studies, and return-on-investment calculations. Identifying bottlenecks and

strategies to remain competitive with existing feed ingredients is crucial for setting sustainable pricing.

6. Environmental Sustainability

The valorisation of agricultural wastes significantly reduces environmental impact by diverting them from landfills, where they produce methane, and preventing harmful open burning. This shift diminishes the ecological footprint of both agriculture and aquaculture. Additionally, substituting conventional feed ingredients, such as fishmeal and soybean meal, with locally sourced waste lowers the carbon footprint of aquafeed production by reducing dependence on long-distance transportation and energy-intensive production processes. Efficient nutrient cycling ensures that valuable nutrients remain within the food system, thereby maintaining their availability for use.

6.1. Economic Sustainability

The economic benefits of this model are notable, particularly in reducing feed costs, as agricultural waste often serves as a low-cost or free raw material. Given that feed constitutes the most significant portion of aquaculture expenses, this transition enhances resource efficiency, allowing for the creation of profitable value chains. Farmers can generate additional income by selling residues, and new industries can develop around the collection and

processing of these materials. This localised sourcing also enhances food security by lessening dependency on volatile global markets for feed ingredients.

6.2. Social Sustainability

Socially, the emergence of a waste-to-feed industry can stimulate job creation in rural regions, encompassing roles in waste collection, processing, and feed production. This not only improves local livelihoods but also encourages a shift in perception toward viewing by-products as valuable resources rather than waste. This comprehensive approach contributes to several UN Sustainable Development Goals (SDGs), such as SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water).

7. Conclusion

The integration of agricultural wastes into aquaculture feeds is a transformative step toward enhancing the sustainability and resilience of the sector. This article highlights advancements in processing technologies, such as fermentation and insect bioconversion, which help unlock the nutritional value of these undervalued resources, reducing reliance on traditional, resource-intensive feed components like fishmeal and fish oil. Although challenges such as nutrient variability and logistical complexities exist, they underscore the

need for ongoing research and development. A multi-pronged approach is necessary, encompassing technological innovations, strategic integration within a circular economy framework, and supportive policies that incentivise industry adoption. This shift not only mitigates environmental impact by reducing pollution and carbon footprint but also fosters economic sustainability through new value chains and lower production costs, while enhancing social sustainability through job creation and improved food security. Ultimately, this paradigm shift will enable the aquaculture industry to meet the growing global demand for aquatic protein in a manner that is both profitable and environmentally and socially responsible, thereby positioning it as a cornerstone of sustainable global food systems.

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