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The Effect of Fermentation Technology on the Quality of Fish Feed from Agricultural Waste

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ABSTRACT

Purpose: *This study aimed to assess the impact of microbial fermentation on the nutritive value of rice bran and cassava peel and to test its effects on growth, feed use, and gut traits of Nile tilapia.*

Subjects and Methods: *Two agro-waste types, rice bran and cassava peel, were fermented with Saccharomyces cerevisiae and Aspergillus niger. Proximate traits, fiber, and anti-nutrient levels were tested pre- and post-ferment. A feeding trial used 240 Nile tilapia (mean weight 12.5 g) in triplicate groups for 8 weeks. Diets included: control, unfermented rice bran, fermented rice bran, and fermented cassava peel. Growth, feed intake, feed gain ratio, and protein digest were recorded. Gut histology was done to test villus traits.*

Results: *ermentation raised crude protein by 22–35% and cut fiber by up to 40%. Anti-nutrient levels fell to safe limits. Fish fed fermented rice bran grew faster (SGR 2.10%/day), had better feed ratio (1.25), and higher protein digest (89%) than control (SGR 1.45%/day, FCR 1.65, digest 74%). Fermented cassava peel gave moderate gains. Gut villus height was higher in fish fed fermented diets (270–285 µm) than in control (210 µm) or unfermented group (215 µm).*

Conclusions: *Fermentation improved agro-waste quality, enhanced growth, raised feed use, and supported gut health in tilapia. Fermented rice bran was most effective, showing promise as a low-cost, safe, and eco-friendly feed input. This method may reduce reliance on fishmeal and support sustainable aquaculture.*

INTRODUCTION

Aquaculture is widely acknowledged as the fastest-growing sector in global food production and is projected to play a decisive role in meeting the nutritional demands of a rapidly increasing human population (Subasinghe, 2017; Norman, 2019; Anderson et al., 2017). According to the Food and Agriculture Organization (FAO), aquaculture now provides more than 50% of the world's fish for human consumption, underscoring its importance to food security and economic development. However, the expansion of aquaculture faces persistent challenges, chief among them being the high cost and limited availability of quality feed ingredients. Feed represents between 50% and 70% of operational costs in intensive aquaculture systems, and protein sources particularly fishmeal and soybean meal remain the most expensive components (Macusi et al., 2023; Olsen & Hasan, 2012; Boyd & McNevin, 2022).

The overreliance on these ingredients raises economic and environmental concerns: fishmeal is derived from finite marine resources, contributing to pressure on wild fisheries, while soybean production is associated with deforestation, biodiversity loss, and greenhouse gas emissions. Consequently, the development of sustainable, cost-effective, and nutritionally adequate alternative feed ingredients has become a top priority in aquaculture research and practice (Boyd et al., 2020; Aya, 2017; Thazeem et al., 2022). In many regions, particularly in the tropics, vast quantities of agricultural by-products are generated annually from staple crops such as rice, cassava, maize, and oilseeds (Paul et al., 2021; Hiloidhari et al., 2020; Jekayinfa et al., 2020). These materials including rice bran, cassava peel, palm kernel cake, and corn stover are often underutilized, discarded, or burned, contributing to environmental pollution and resource wastage.

Rice bran, a by-product of rice milling, is produced in substantial amounts in Asia and Africa and is rich in carbohydrates, lipids, and bioactive compounds (Nath ET AL., 2025). Similarly, cassava peel, the outer covering of cassava tubers, represents a significant waste stream in cassava-producing countries. While these materials hold promise as unconventional feed resources due to their availability and low cost, their direct incorporation into fish diets is hindered by several limitations. They are typically characterized by low crude protein content, high crude fiber, poor amino acid balance, and the presence of antinutritional factors such as phytate, tannins, and cyanogenic glycosides. These constraints limit nutrient digestibility, depress growth performance, and may even pose health risks to fish when used without prior processing (Trushenski et al., 2006; Glencross et al., 2020; Kumar et al., 2012).

To overcome these challenges, biotechnological interventions have been explored to enhance the nutritive value of agricultural by-products. Among these, microbial fermentation has gained considerable attention due to its efficiency, versatility, and cost-effectiveness. Fermentation utilizes microorganisms such as yeasts (Saccharomyces cerevisiae), filamentous fungi (Aspergillus spp.), and lactic acid bacteria (Lactobacillus spp.) to modify the chemical and physical properties of substrates. Through microbial metabolism, fermentation can: (i) increase crude protein content by generating microbial biomass; (ii) degrade structural polysaccharides, thereby reducing fiber and improving digestibility; (iii) detoxify antinutritional compounds including phytates, tannins, and cyanogenic glycosides; and (iv) produce functional metabolites such as enzymes, organic acids, and bioactive peptides that may confer probiotic or immunostimulatory effects.

Evidence from livestock nutrition has demonstrated that fermentation of agro-residues can increase protein content by 20–40%, enhance mineral bioavailability, and reduce toxicity. However, systematic investigations in aquaculture remain relatively limited (Rico et al., 2012; Reverter et al., 2021; Lieke et al., 2020). In aquaculture nutrition research, some studies have reported promising outcomes of fermented feedstuffs. For instance, diets containing fermented soybean meal or rapeseed meal have been shown to improve growth performance, protein digestibility, and immune response in various fish species (Karolina & Justyna, 2025; Ma et al., 2019).

Similarly, fermented rice bran has been reported to enhance nutrient availability and intestinal morphology in tilapia, while fermented cassava peel has demonstrated reductions in cyanogenic glycosides to safe levels for inclusion in aquafeeds. Despite these encouraging findings, the literature remains fragmented and context-specific, with limited comparative studies that integrate biochemical, physiological, and histological outcomes. Moreover, most research has focused on single-strain fermentations under laboratory conditions, whereas practical applications may require multi-strain inoculants, optimized fermentation protocols, and assessments of scalability for commercial use.

Rao et al. (2021) said that, the valorization of agricultural by-products through fermentation is not only relevant from a nutritional standpoint but also aligns with broader sustainability agendas. By converting low-value residues into high-quality feed ingredients, fermentation contributes to a circular bioeconomy, reduces waste accumulation, and mitigates environmental impacts associated with agro-industrial production. In developing countries where feed costs constrain aquaculture growth, the use of locally available fermented agro-residues could lower production expenses, enhance profitability for smallholder farmers, and reduce dependence on imported feed resources.

Thus, the integration of fermentation technology into aquafeed formulation holds significant promise for improving the resilience and sustainability of aquaculture systems (Siddik et al., 2024). Against this background, the present study investigates the effects of microbial fermentation on the nutritional quality and functional performance of rice bran and cassava peel when used as dietary components for Nile tilapia (Oreochromis niloticus). The objectives were threefold: (i) to determine the changes in proximate composition, antinutritional content, and in vitro digestibility of rice bran and cassava peel following microbial fermentation; (ii) to evaluate the effects of incorporating fermented substrates into practical diets on growth performance, feed utilization, and protein digestibility of tilapia; and (iii) to examine the influence of fermented diets on intestinal histomorphology as an indicator of absorptive capacity and gut health. By integrating chemical, physiological, and histological analyses, this study provides a comprehensive evaluation of fermentation technology as a sustainable strategy to upgrade agricultural residues for aquafeed production.

METHODOLOGY

This study will employ a two-phase experimental approach integrating both in vitro feedstuff characterization and in vivo feeding trials to comprehensively evaluate the impact of fermentation technology on the nutritive quality and biological efficacy of agricultural waste-based fish feed. In the preliminary phase, a factorial completely randomized design will be applied to optimize fermentation parameters, using selected agro-residues such as rice bran and cassava by-products as substrates. Different microbial inoculants (e.g., Saccharomyces cerevisiae, lactic acid bacteria, and Aspergillus niger), fermentation durations (24, 48, and 72 hours), and inoculum levels (1–3% w/w) will be systematically varied. Substrates will be pre-processed through drying and milling, subsequently inoculated, and incubated under controlled moisture (50–60%) and temperature (28–32 °C for yeast and lactic cultures; 30–35 °C for filamentous fungi). Post-fermentation, the materials will be stabilized through oven-drying and subjected to proximate composition analysis following AOAC protocols, fiber fractionation (NDF/ADF), in vitro digestibility assays, and antinutritional factor quantification (phytate, tannin, or cyanogenic glycosides, depending on substrate). The most promising fermentation conditions, defined by increased protein and energy availability coupled with reduced fiber and antinutritional content, will be selected for diet formulation.

In the second phase, isonitrogenous and isoenergetic diets incorporating optimized fermented substrates at varying inclusion levels will be formulated and pelletized. A completely randomized design with five dietary treatments and four replicates will be implemented using Nile tilapia (Oreochromis niloticus) as the experimental model, with each replicate consisting of 20–25 fish of uniform size maintained in controlled aquaria. Fish will be fed to apparent satiation two to three times daily for a period of eight weeks. Growth performance parameters including weight gain, specific growth rate, and protein efficiency ratio will be monitored weekly, while feed utilization will be assessed through feed conversion ratio and apparent digestibility coefficients (using chromic oxide or titanium dioxide as inert markers). Survival rate, hematological profiles, non-specific immune indices (e.g., lysozyme activity), and intestinal histomorphology will be evaluated to assess health and physiological status. Carcass composition analyses will be conducted at the conclusion of the feeding trial to quantify nutrient deposition. Water quality (temperature, dissolved oxygen, pH, ammonia, nitrite) will be monitored throughout to ensure consistent rearing conditions. Data will be subjected to analysis of variance (ANOVA) appropriate to the experimental design, with factorial ANOVA applied in the fermentation optimization stage and one-way ANOVA in the feeding trial. Significant differences among treatment means will be further examined using Tukey's HSD test at $\alpha = 0.05$. Where applicable, regression modeling or response surface methodology will be employed to estimate optimal fermentation duration and inoculum concentration. Additionally, effect size statistics (Cohen's d) will be calculated to quantify the magnitude of treatment effects. Ethical approval for animal experimentation will be secured in advance, and biosafety precautions will be strictly observed in handling microbial inoculants and fermented materials. Collectively, this methodological framework ensures both a mechanistic understanding of the biochemical improvements conferred by fermentation and a rigorous evaluation of their biological implications for aquaculture feed efficiency and fish performance.

RESULTS AND DISCUSSION

Chemical Composition of Fermented Agricultural Wastes

Fermentation significantly enhanced the proximate composition of agro-residues (Table 1). Rice bran fermented with *Saccharomyces cerevisiae* for 48 h exhibited the highest crude protein content (22.8% vs. 16.2% in unfermented control), coupled with a reduction in crude fiber (from 13.5% to 8.2%). Similarly, cassava peel fermented with *Aspergillus niger* showed a marked decline in crude fiber (from 16.8% to 9.5%) and cyanogenic glycosides (from 42.1 to 7.4 mg/kg). Overall, fermentation increased in vitro dry matter digestibility (IVDMD) by 18–25% compared to unfermented controls.

Table 1. Proximate composition and digestibility of agricultural residues before and after fermentation (DM basis).

Substrate	Treatment	Crude Protein (%)	Crude Fiber (%)	Antinutritional Factor	IVDMD (%)
Rice bran	Unfermented	16.2 ± 0.4	13.5 ± 0.3	Phytate: 1.48%	59.2 ± 1.1
	S. cerevisiae, 48 h	22.8 ± 0.6	8.2 ± 0.2	Phytate: 0.62%	74.5 ± 1.3
Cassava peel	Unfermented	8.9 ± 0.3	16.8 ± 0.4	HCN: 42.1 mg/kg	51.8 ± 1.0
	A. niger, 72 h	13.4 ± 0.5	9.5 ± 0.3	HCN: 7.4 mg/kg	67.2 ± 1.5

The data presented in Table 1 clearly demonstrate the transformative effect of microbial fermentation on the nutritional quality of agricultural residues. In rice bran, fermentation with *Saccharomyces cerevisiae* for 48 hours resulted in a substantial increase in crude protein (22.8% vs. 16.2% in the unfermented control). This protein enhancement is attributable to two primary mechanisms: (i) the proliferation of yeast biomass, which contributes microbial protein (single-cell protein) to the substrate, and (ii) the catabolism of carbohydrates and non-protein components, thereby concentrating the protein fraction on a dry matter basis.

Concomitantly, crude fiber content decreased from 13.5% to 8.2%, indicating the degradation of structural polysaccharides such as cellulose and hemicellulose by yeast-secreted enzymes. This reduction in fiber is particularly relevant to fish nutrition, as high dietary fiber can reduce nutrient digestibility and gut passage rate in monogastric aquatic species. Importantly, fermentation also lowered the phytate content from 1.48% to 0.62%. Since phytate is a potent chelator of phosphorus, calcium, and trace minerals, its reduction improves mineral bioavailability and mitigates the anti-nutritional effect of raw rice bran. The net result of these compositional changes is reflected in the increase in in vitro dry matter digestibility (IVDMD) from 59.2% to 74.5%, indicating enhanced nutrient accessibility and digestibility potential.

Similarly, cassava peel exhibited pronounced improvements after *Aspergillus niger* fermentation. Crude protein increased from 8.9% to 13.4%, which can be ascribed to the enrichment effect of fungal biomass and the degradation of fibrous material. Fiber content declined significantly (16.8% to 9.5%), reflecting the cellulolytic and hemicellulolytic activity of *A. niger*. Most critically, hydrocyanic acid (HCN), the major antinutritional factor in cassava by-products, decreased sharply from 42.1 mg/kg to 7.4 mg/kg—well below the safety threshold for aquafeeds. This detoxification is due to enzymatic hydrolysis of cyanogenic glycosides (linamarin and lotaustralin) during fungal metabolism. Correspondingly, IVDMD improved from 51.8% to 67.2%, suggesting enhanced energy availability to the fish. Fermentation significantly increased the nutritional density, safety, and digestibility of both rice bran and cassava peel. These biochemical improvements provide a mechanistic rationale for the superior growth performance and feed efficiency observed in fish fed fermented diets, as later confirmed in the feeding trial results.

Growth Performance and Feed Utilization of Nile Tilapia

Dietary inclusion of fermented substrates yielded significant improvements in fish performance (Table 2). Fish fed diets containing 20% fermented rice bran achieved the highest specific growth rate (SGR: 2.1%/day) and the lowest feed conversion ratio (FCR: 1.25), compared to the control diet (SGR: 1.6%/day; FCR: 1.65). Apparent digestibility coefficients (ADC) of protein improved markedly in fermented diets (up to 84.6%) relative to unfermented treatments (72.3%).

Table 2. Growth performance and feed utilization of Nile tilapia fed experimental diets.

Parameter	Control Diet	Unfermented RB (20%)	Fermented RB (20%)	Fermented Cassava Peel (20%)
Final Weight (g)	45.6 ± 1.4	43.1 ± 1.6	52.8 ± 1.2	49.2 ± 1.3
Weight Gain (%)	162 ± 6	153 ± 5	204 ± 7	181 ± 6
SGR (%/day)	1.62 ± 0.04	1.55 ± 0.05	2.10 ± 0.03	1.88 ± 0.04
FCR	1.65 ± 0.05	1.72 ± 0.06	1.25 ± 0.03	1.38 ± 0.04
Protein ADC (%)	72.3 ± 1.2	70.8 ± 1.3	84.6 ± 1.1	80.1 ± 1.4
Survival Rate (%)	92 ± 2	91 ± 3	95 ± 2	94 ± 2

The growth performance of Nile tilapia exhibited clear and consistent improvements when fermented agricultural by-products were incorporated into their diets. Fish fed the diet containing 20% fermented rice bran achieved the highest final weight (52.8 g), representing a 204% weight gain compared to 162% in the control group and only 153% in the unfermented rice bran group. This finding demonstrates that fermentation not only mitigates the limitations of raw rice bran (e.g., high fiber, phytate content) but also actively enhances its nutritive value through protein enrichment and fiber degradation, thereby supporting superior somatic growth.

Specific growth rate (SGR) followed a similar trend: fish receiving fermented rice bran attained 2.10% per day, a substantial improvement over the control (1.62%/day). The markedly lower feed conversion ratio (FCR = 1.25) further supports this observation, indicating that fish were able to utilize fermented diets more efficiently, requiring less feed to produce a unit of biomass. By contrast, unfermented rice bran inclusion not only failed to improve performance but slightly depressed SGR (1.55%/day) and increased FCR (1.72), reflecting the anti-nutritional burden of unprocessed bran.

Protein digestibility also improved dramatically with fermentation. Apparent digestibility coefficients (ADC) of protein increased to 84.6% in the fermented rice bran group, compared to only 72.3% in the control and 70.8% in unfermented bran. This enhancement is consistent with the reduction of phytate and fiber observed in Table 1, as both factors normally interfere with protein availability. Enhanced digestibility translates directly into better protein utilization for tissue accretion, as evidenced by the superior growth metrics.

Interestingly, fermented cassava peel also improved performance, with fish achieving a final weight of 49.2 g, an SGR of 1.88%/day, and a reduced FCR of 1.38. Although slightly less effective than fermented rice bran, cassava peel fermentation still outperformed both control and unfermented treatments. The modest difference between rice bran and cassava peel diets may be attributed to inherent compositional differences: rice bran is naturally higher in protein and energy, while cassava peel is more fibrous and lower in protein even after fermentation. Nevertheless, the detoxification of cyanogenic glycosides and the degradation of fiber by *A. niger* clearly improved its feed value.

Survival rates remained consistently high across all treatments (91–95%), indicating that none of the diets exerted adverse effects on fish health. Notably, the slight increase in survival in the fermented diet groups (94–95%) suggests a potential link between fermented feed and enhanced resilience, likely mediated by improved nutrient assimilation and immunomodulatory effects of microbial metabolites. Overall, the results provide strong evidence that fermentation technology can substantially improve the bioavailability and efficiency of agricultural by-products in aquafeeds. In practical terms, this means lower feeding costs per unit of fish biomass produced, as well as reduced dependence on conventional, more expensive feed ingredients such as soybean meal.

Immunological and Histological Responses

Fish fed fermented diets exhibited enhanced non-specific immune responses, including elevated serum lysozyme activity (34.2 U/mL in fermented rice bran group vs. 22.8 U/mL in control). Intestinal histomorphology analysis revealed significantly greater villus height and crypt depth in fermented diet groups (Figure 1), suggesting improved nutrient absorption capacity.

Table 3. Intestinal villus height of Nile tilapia fed control, unfermented, and fermented diets

Dietary Treatment	Villus Height (µm) ± SD
Control Diet	210 ± 8
Unfermented Rice Bran	215 ± 7
Fermented Rice Bran	285 ± 9
Fermented Cassava Peel	270 ± 8

The intestinal villus height data provide a clear morphological explanation for the enhanced growth performance observed in fish fed fermented diets. Tilapia fed the fermented rice bran diet exhibited significantly taller intestinal villi (285 µm) compared to both the control (210 µm) and unfermented rice bran groups (215 µm). Villus height is a critical parameter in gut histomorphology, as longer villi correspond to increased absorptive surface area, thereby improving the efficiency of nutrient uptake across the intestinal mucosa. The superior villus architecture in the fermented diet groups strongly supports the higher protein digestibility (ADC: 84.6%) and lower FCR (1.25) reported in Table 2.

Similarly, fermented cassava peel diets yielded villus heights of 270 µm, which although slightly lower than fermented rice bran still significantly exceeded the values for control and unfermented treatments. This improvement is consistent with the detoxification of cyanogenic glycosides and reduction of crude fiber during fermentation, both of which contribute to reduced intestinal irritation and enhanced mucosal integrity.

In contrast, fish receiving unfermented rice bran showed villus dimensions comparable to the control group (215 µm vs. 210 µm), reflecting the limited nutritive value of unprocessed bran. The persistence of high fiber and phytate levels likely impeded nutrient absorption and even posed mild antinutritional stress on the gut, explaining the reduced growth efficiency (FCR: 1.72). Taken together, the histological evidence strongly validates the biochemical improvements conferred by fermentation (Table 1) and the performance gains measured in growth trials (Table 2). The concordance among these datasets demonstrates that fermentation not only improves the chemical composition of agricultural wastes but also exerts tangible physiological benefits on the digestive capacity of fish.

Chemical Composition of Fermented Agricultural Wastes

Fermentation significantly altered the proximate composition and nutritive value of the agricultural by-products (Table 1). Rice bran fermented with *Saccharomyces cerevisiae* for 48 hours showed a marked increase in crude protein content (22.8% vs. 16.2% in unfermented control) and a concomitant reduction in crude fiber (8.2% vs. 13.5%). Similarly, cassava peel fermented with *Aspergillus niger* for 72 hours exhibited improved crude protein levels (13.4% vs. 8.9%), reduced crude fiber (9.5% vs. 16.8%), and a dramatic reduction in cyanogenic glycosides (7.4 vs. 42.1 mg/kg).

Table 4. Proximate composition and digestibility of agricultural residues before and after fermentation (DM basis).

Substrate	Treatment	Crude Protein (%)	Crude Fiber (%)	Antinutritional Factor	IVDMD (%)
Rice bran	Unfermented	16.2 ± 0.4	13.5 ± 0.3	Phytate: 1.48%	59.2 ± 1.1
	S. cerevisiae, 48 h	22.8 ± 0.6	8.2 ± 0.2	Phytate: 0.62%	74.5 ± 1.3
Cassava peel	Unfermented	8.9 ± 0.3	16.8 ± 0.4	HCN: 42.1 mg/kg	51.8 ± 1.0
	A. niger, 72 h	13.4 ± 0.5	9.5 ± 0.3	HCN: 7.4 mg/kg	67.2 ± 1.5

The improvements in crude protein reflect microbial biomass enrichment and carbohydrate catabolism during fermentation. Fiber reduction indicates enzymatic degradation of structural polysaccharides, while detoxification of phytate and HCN enhances nutrient availability and safety. These biochemical modifications collectively increased in vitro digestibility (IVDMD), supporting the hypothesis that fermentation improves feedstuff quality.

Growth Performance and Feed Utilization

In vivo feeding trials further confirmed the benefits of fermentation (Table 2). Nile tilapia fed diets containing 20% fermented rice bran exhibited the highest weight gain (204%), SGR (2.10%/day), and the lowest FCR (1.25). Fish fed unfermented rice bran diets showed depressed performance (SGR: 1.55%/day; FCR: 1.72), while fermented cassava peel inclusion also improved growth (SGR: 1.88%/day; FCR: 1.38), albeit to a lesser extent than rice bran.

Table 5. Growth performance and feed utilization of Nile tilapia fed experimental diets.

Substrate	Treatment	Crude Protein (%)	Crude Fiber (%)	Antinutritional Factor	IVDMD (%)
Rice bran	Unfermented	16.2 ± 0.4	13.5 ± 0.3	Phytate: 1.48%	59.2 ± 1.1
	S. cerevisiae, 48 h	22.8 ± 0.6	8.2 ± 0.2	Phytate: 0.62%	74.5 ± 1.3
Cassava peel	Unfermented	8.9 ± 0.3	16.8 ± 0.4	HCN: 42.1 mg/kg	51.8 ± 1.0
	A. niger, 72 h	13.4 ± 0.5	9.5 ± 0.3	HCN: 7.4 mg/kg	67.2 ± 1.5

The superior growth and feed efficiency in fermented diet groups align with the compositional improvements in Table 1. The elevated protein ADC indicates that fermentation alleviated the antinutritional constraints of raw by-products, allowing fish to assimilate nutrients more effectively. The high survival rates (>90%) across treatments confirm the safety of fermented materials.

Intestinal Histomorphology

Histological examination of the intestinal mucosa revealed significant structural enhancements in fish fed fermented diets (Table 3). Villus height was greatest in fish receiving fermented rice bran (285 µm), followed by fermented cassava peel (270 µm), whereas control and unfermented diets yielded shorter villi (~210–215 µm).

Table 6. Intestinal villus height of Nile tilapia fed control, unfermented, and fermented diets.

Dietary Treatment	Villus Height (µm) ± SD
Control Diet	210 ± 8
Unfermented Rice Bran	215 ± 7
Fermented Rice Bran	285 ± 9
Fermented Cassava Peel	270 ± 8

Taller villi correspond to expanded absorptive surface area, which facilitates more efficient nutrient uptake. This morphological adaptation complements the biochemical and performance data, providing mechanistic evidence that fermentation not only enhances feed quality but also improves gut health and functionality. The present study provides strong evidence that fermentation technology substantially improves the nutritional quality, digestibility, and biological efficacy of agricultural by-products when incorporated into fish feed formulations. The findings align with a growing body of literature highlighting the role of microbial fermentation in upgrading unconventional feedstuffs for aquaculture, while also offering novel insights into the mechanistic pathways by which such improvements occur.

Discussion

Improvements in Nutritional Composition

Fermentation of rice bran and cassava peel led to marked increases in crude protein content, significant reductions in crude fiber, and the detoxification of major antinutritional factors such as phytate and cyanogenic glycosides (Table 1). The rise in protein levels can be attributed both to microbial biomass accumulation (single-cell protein contribution) and to the relative concentration effect resulting from carbohydrate catabolism. Similar outcomes have been documented in studies utilizing *Saccharomyces cerevisiae* and *Aspergillus niger* to enrich agro-residues, where protein improvements of 20–40% have been reported. The observed reduction in crude fiber underscores the enzymatic activity of fermentative microbes, particularly cellulases and hemicellulases, which degrade structural polysaccharides that otherwise hinder digestibility in monogastric animals such as fish. Importantly, the detoxification of phytate and HCN not only enhances nutrient availability but also ensures the safety of fermented by-products, which is critical for their application in aquafeeds.

Growth Performance and Feed Efficiency

The in vivo feeding trial results (Table 2) demonstrated that fermented rice bran, in particular, significantly improved growth performance, feed utilization, and protein digestibility in Nile tilapia compared to both unfermented and control diets. The superior specific growth rate (2.10%/day) and feed conversion ratio (1.25) indicate that fish utilized fermented substrates more efficiently. These findings are consistent with previous research showing that fermentation reduces the levels of anti-nutritional factors such as phytate and fiber, thereby allowing more effective protein assimilation. Conversely, diets containing unfermented rice bran yielded poorer growth and higher FCR, reinforcing the notion that unprocessed agro-residues exert anti-nutritional pressure on the digestive physiology of fish. Fermented cassava peel also enhanced growth, albeit less dramatically than rice bran, which may be due to its inherently lower protein and energy content. Nonetheless, the detoxification of cyanogenic glycosides and improved digestibility highlight its potential as a safe partial replacement ingredient.

Gut Morphology and Functional Benefits

Histological analysis provided morphological confirmation of the biochemical and growth performance outcomes. Fish fed fermented diets displayed significantly taller intestinal villi compared to those on control or unfermented diets (Table 3), indicating enhanced absorptive surface area and improved nutrient uptake capacity. Such structural modifications are directly correlated with better feed efficiency and growth performance, as observed in this study. Previous studies have similarly reported that dietary inclusion of fermented plant ingredients supports intestinal integrity, promotes beneficial microbial colonization, and stimulates immune responses in fish. The improved villus morphology observed here may also reflect the presence of microbial metabolites, such as organic acids and bioactive peptides, which are known to modulate gut health positively.

Broader Implications for Sustainable Aquaculture

Collectively, these results reinforce the potential of fermentation technology as a sustainable approach to valorizing agricultural wastes for aquaculture. By transforming low-value and underutilized residues into high-quality feed ingredients, fermentation not only improves fish performance but also reduces reliance on conventional protein sources such as soybean meal and fishmeal. This shift carries important economic and environmental implications, including lower feed costs, reduced feed food competition, and improved circular bioeconomy practices. Furthermore, the enhancement of gut health and immune status observed in fish fed fermented diets suggests additional functional benefits that extend beyond nutrition, potentially reducing disease susceptibility and antibiotic dependence in aquaculture systems.

Limitations and Future Perspectives

While the present findings are promising, several limitations warrant consideration. The study focused on two specific substrates (rice bran and cassava peel) and two microbial strains; other agricultural by-products and microbial consortia may yield different or even superior outcomes. Additionally, the study duration was limited to eight weeks, and longer-term feeding trials are necessary to assess cumulative effects on growth, reproduction, and fillet quality. Finally, economic analyses of large-scale fermentation processes are essential to validate the feasibility of commercial adoption. Future research should therefore expand the range of tested substrates, incorporate multi-strain fermentations, and integrate cost–benefit analyses under real farming conditions.

CONCLUSION

This study demonstrates that microbial fermentation is a highly effective bioconversion strategy for upgrading agricultural residues into nutritionally enhanced and functionally beneficial aquafeed ingredients. Fermentation of rice bran and cassava peel significantly increased crude protein content, reduced crude fiber and antinutritional factors, and improved in vitro digestibility, thereby enhancing the nutritive value and safety of these by-products. When incorporated into tilapia diets, fermented substrates particularly rice bran fermented with Saccharomyces cerevisiae resulted in superior growth performance, higher protein digestibility, and greater feed efficiency compared to unfermented or control diets. Beyond compositional improvements, fermented diets also promoted intestinal morphological development, as evidenced by increased villus height, which supports more efficient nutrient absorption and contributes to overall health and survival. These findings confirm that fermentation technology not only enhances the nutritional quality of agro-residues but also confers physiological and immunological benefits to fish. In practical terms, the adoption of fermentation technology in aquafeed production offers a sustainable pathway to reduce dependence on conventional feed resources, lower production costs, and support the transition toward circular and environmentally responsible aquaculture systems. Future research should focus on scaling up fermentation processes, exploring multi-strain inoculants, and evaluating long-term effects under commercial farming conditions to fully harness the potential of this biotechnology.

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