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(Research Article)

Effects of input fermentation and feed extrusion on the production performance of Nile tilapia (*Oreochromis niloticus* Linnaeus, 1758) reared in hapa enclosures

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Abstract

This study was conducted at the fish farm Agro-fish farming company (SAP Mé), located in the south-eastern region of Côte d'Ivoire (6°09'06''N, 3°44'32''W). Twelve enclosures were installed in a fertilized pond to assess the impact of input fermentation and feed extrusion on the production performance of Nile tilapia (*Oreochromis niloticus*). Four dietary treatments were tested, each composed of 50% rice bran and 50% wheat bran: P50 (untreated), PF50 (fermented), G50 (extruded), and FG50 (fermented and extruded). Fish with an initial average weight of 202 ± 2 g were fed for 100 days at a rate of 3% of their body weight. The results revealed a progressive improvement in zootechnical and economic performance depending on the treatment applied. The FG50 diet yielded the highest daily weight gain (DWG: 1.96 ± 0.16 g/day), the lowest feed conversion ratio (FCR: 2.98 ± 0.3), and a 51.04% reduction in feed cost per unit of weight gain compared to the control diet (P50). Both extrusions alone (G50) and fermentation alone (PF50) also enhanced growth and efficiency indicators, though to a lesser extent. Carcass analysis showed increased protein and lipid content, along with reduced moisture, indicating improved nutritional value. Overall, the integration of technological processes such as fermentation and extrusion into fish diets can enhance productivity and profitability in aquaculture, while promoting the use of locally available agricultural resources.

Keywords: Aquaculture; Feed Efficiency; Local Resources; Technological Processes; Profitability**.**

1. Introduction

Aquaculture in West Africa is increasingly recognised as a strategic lever for addressing food security challenges, reducing rural poverty, and creating sustainable employment opportunities [1,2]. In Côte d'Ivoire, the sector has experienced steady growth, particularly through semi-intensive fish farming systems (52%), which are predominantly practised in fertilised ponds [3]. Nile tilapia (*Oreochromis niloticus*) is the most commonly farmed species due to its hardiness, rapid growth, tolerance to variable environmental conditions, and strong market acceptance both locally and regionally [4,5,6]. However, the sustainable development of this sector is hindered by several structural constraints, notably the high cost of imported feeds and limited mastery of feed formulation technologies [7,8]. In extensive and semi-intensive systems, the use of imported extruded feeds-although nutritionally effective-remains economically inaccessible for most producers, resulting in high production costs and retail prices that exceed those of commonly consumed fish species [9,10]. In response, a large proportion of fish farmers in Côte d'Ivoire (71%) rely on locally available agricultural by-products such as rice and maize bran, used either alone or in combination (52% rice bran, 7% low-grade rice flour, and 28% rice/maize mixtures), often supplemented with organic fertilisers [3]. Nonetheless, the direct use of these raw by-products in fish feed leads to low feed efficiency and limited productivity, primarily due to the presence of antinutritional factors such as tannins, phytates, lectins, and insoluble fibres, which impair nutrient

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digestibility and absorption [11,12]. To overcome these limitations, the identification and enhancement of local feed sources, combined with appropriate technological treatments, offer a sustainable, economically viable, and environmentally responsible solution [13,14]. Among the most promising processes are fermentation and extrusion. Fermentation, whether microbial or enzymatic, facilitates the hydrolysis of macromolecules, significantly reduces antinutritional compounds, and improves the bioavailability of nutrients and energy [15,16,17]. Extrusion, on the other hand, promotes starch gelatinisation, protein denaturation, microbial load reduction, and enhances the palatability and shelf-life of formulated feeds [18,19,20]. When combined, these processes transform raw materials into functional ingredients tailored to the physiological needs of fish species, while optimising their nutritional value. From an economic perspective, several studies have shown that integrating these technologies into feed formulation significantly reduces the cost of feeding per unit of weight gain, while maintaining or even improving fish growth performance [21,8]. This approach enhances the value of local agricultural inputs, reduces dependence on imported resources, and strengthens the resilience of farming systems against fluctuations in international markets [22,23]. In this context, the present study aims to evaluate the combined impact of fermentation and extrusion of local agricultural by-products on the nutritional, zootechnical, and economic performance of Nile tilapia (*Oreochromis niloticus*). The central hypothesis is that applying these processes will enable the formulation of balanced, isoproteic diets that are accessible, sustainable, and adapted to the constraints of tropical environments and the socio-economic realities of West African aquaculture.

2. Materials and methods

2.1. Rearing system and experimental fish

The study was carried out at the Agro-fish farming company (SAP Mé), situated in south-eastern Côte d'Ivoire, approximately 80 kilometres from Abidjan, at geographical coordinates 6°09'06''N and 3°44'32''W. The experiment was conducted in a fertilised pond measuring 10,000 m^2, within which twelve fish enclosures were installed. Each enclosure measured 6 metres in length, 4 metres in width, and 2 metres in height (Length × Width × Height: 6 m × 4 m × 2 m) (Figure 1), and was submerged to a water depth of 1.20 metres, providing a usable volume of 28.8 m^3. The stability of the net cages was maintained using bamboo stakes firmly anchored into the muddy pond bed. The upper rope line was secured 0.80 metres above the water surface with horizontal bamboo poles, while the lower rope line was embedded 0.30 metres deep in a trench excavated in the mud, ensuring watertightness and reducing feed loss. Each enclosure was surrounded by a rigid bamboo lattice frame to prevent feed dispersion and the intrusion of external elements **[24]**. Water supply to the pond was gravity-fed from a 9-hectare retention dam, using SAP Mé's dedicated hydraulic system. This system consisted of a network of PVC pipes; each fitted with fine-mesh mosquito netting (1 mm × 1 mm) at the inlet to prevent the entry of unwanted organisms into the rearing structures

Figure 1 Experimental setup installed in the host pond at the fish farm Agro-Fish Farming Company (SAP Mé): overview of the enclosures [24]

2.2. Experimental diets and preparation

The experimental diets were formulated using two locally available agricultural by-products in Côte d'Ivoire: rice bran (RB) and wheat bran (WB), sourced from regional suppliers. Four distinct diets were developed by combining these ingredients in equal proportions (50% RB, 50% WB) (Table 1), each subjected to a specific technological treatment: P50 (control diet, neither fermented nor extruded), PF50 (fermented, non-extruded), G50 (extruded, non-fermented), and FG50 (fermented then extruded). For diets requiring fermentation (PF50 and FG50), the raw materials were first ground using a hammer mill (DSM 500, Electra, France) equipped with a 1.5 mm sieve, then moistened to 30% water (based on dry weight) and incubated in airtight bags at ambient temperature (28–30 °C) for 72 hours. This natural fermentation process, activated by endogenous microflora, reduces antinutritional factors such as phytates, tannins, and insoluble fibres, while enhancing nutrient digestibility and protein availability [15,16,17]. Fermentation is widely recognised as an effective method for improving the nutritional value of plant-based by-products in aquafeeds, increasing the bioavailability of essential amino acids and mitigating the adverse effects of antinutritional compounds [11,13]. Following fermentation, the mixtures were air-dried for 48 hours and reintegrated into the formulation process. All ingredients, whether fermented or not, were precisely weighed and mixed for 30 minutes in a horizontal mixer (MH-1000, Electra, France; capacity: 500 kg) until a homogeneous blend was achieved. The P50 and PF50 diets were stored as raw meal, bagged immediately after mixing, and kept in a dry, ventilated room. The extruded diets (G50 and FG50) were processed into 3 mm floating pellets using a single-screw extruder (Henan Bedo Machinery DGP-80) (Figure 2) at a temperature of 140 °C and a throughput of 3.6 kg/min. This thermal process promotes starch gelatinisation, protein denaturation, microbial load reduction, and improves feed palatability [18,19,20]. Extrusion is widely used in aquafeed production due to its ability to produce stable, digestible, and floating pellets, while enhancing shelf-life and reducing feed losses [10,21]. After extrusion, the pellets were naturally dried for 48 hours, packed in 25 kg bags, and stored on wooden pallets in a ventilated room. The bromatological characteristics of the diets were analysed by Techna Nutrition Laboratory (France) using standard AOAC methods [25].

Table 1 Composition of the formulated diets (g/100 g of feed as distributed), proximate composition (% dry matter) and essential amino acid profile (% of protein) of experimental diets used for the culture of Nile tilapia (*Oreochromis niloticus*)

Parameters	**P50**	**PF50**	**G50**	**FG50**	**Tilapia Requirement***
Inclusion level of ingredients in the diet (g /100 g of diet as fed)					
Rice bran (%)	50	50	50	50	—
Wheat bran (%)	50	50	50	50	—
Proximate composition (% dry matter)					
Dry matter (%)	88.6	88.6	88.6	88.6	—
Crude protein (%)	14.85	15.40	15.10	15.80	—
Lipids (%)	9.15	9.60	9.80	10.20	—
Fibre (%)	13.15	12.40	12.10	11.50	—
Ash (%)	8.95	9.10	8.80	9.00	—
Starch (%)	22.7	22.5	22.8	22.9	—
Nitrogen-free extract (%)	42.5	43.10	44.20	45.50	—
Metabolisable energy (MJ/kg DM)	2.92	2.95	2.98	3.02	—
Essential amino acid profile (% of protein)					
Arginine (%)	7.25	7.30	7.35	7.40	4.0–4.2
Histidine (%)	2.65	2.70	2.75	2.80	1.7
Isoleucine (%)	4.50	4.55	4.60	4.70	3.1
Leucine (%)	6.35	6.40	6.45	6.50	3.4
Lysine (%)	4.25	4.30	4.35	4.40	5.1–5.7

Methionine (%)	1.90	2.00	2.10	2.20	2.1–2.8
Phenylalanine (%)	4.25	4.30	4.35	4.40	3.8
Threonine (%)	3.25	3.30	3.35	3.40	3.8
Tryptophan (%)	1.80	1.85	1.90	1.95	1.0
Valine (%)	5.00	5.05	5.10	5.20	2.8

P50 (unfermented, non-extruded); PF50 (fermented, non-extruded); G50 (extruded, unfermented); FG50 (fermented and extruded); * Essential Amino Acid Requirements **[26].**

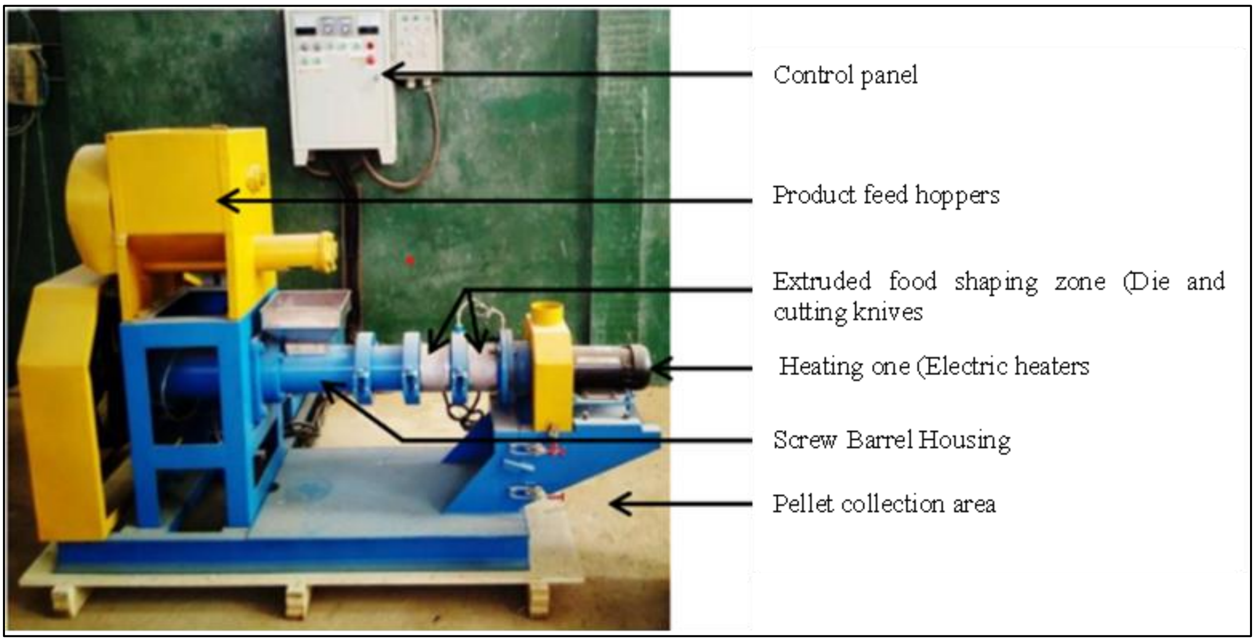

Figure 2 Single-screw extruder "DGP-80" used for the production of extruded pellets

2.3. Experimental protocol and procedures

The experiment lasted 100 days and was carried out in two distinct cycles. Trials focused on Nile tilapia (*Oreochromis niloticus*), a species widely used in aquaculture due to its robustness and rapid growth [27]. Selected fish had an initial mean weight of 219 ± 2 g. Individuals were distributed across 12 enclosures (hapas) installed in a fertilised pond, at a stocking density of 1.7 fish/m^2. To prevent uncontrolled reproduction within the enclosures, each rearing unit was supplemented with *Hemichromis fasciatus* predators, accounting for 5% of the total stock, in accordance with the standard practices of the Agro-Fish Farming Company (SAP Mé). The pond was fertilised with poultry manure at a rate of 0.10 kg/m^2 two weeks prior to stocking, and subsequently every two weeks at a dose of 120 kg/ha, following recommended guidelines to stimulate natural aquatic productivity [28,29]. Prior to fish introduction, enclosures were cleaned using seine netting to remove residual fauna. Stocking was carried out by individually weighing 30 fish per enclosure to assess initial uniformity. Target stocking density was achieved through grouped weighings of 2–3 fish, allowing for precise distribution across enclosures. During the trial, four distinct dietary treatments were evaluated, each corresponding to a specific combination of technological processes: • P50: control diet, neither fermented nor extruded • PF50: fermented diet, not extruded • G50: extruded diet, not fermented • FG50: fermented and extruded diet. These diets were designed to assess the impact of processing methods on the zootechnical performance of *Oreochromis niloticus*, considering the potential effects of fermentation on nutrient digestibility [15,17] and extrusion on feed stability and palatability [18,20]. Fish were manually fed three times daily (09:00, 11:00 and 14:00) at a feeding rate of 3.8% of live body weight, six days per week, in accordance with recommendations for fish of this size [21]. Growth monitoring was performed biweekly on a sample of 20 fish per enclosure (approximately 48% of the population), allowing feed rations to be adjusted based on weight progression. At the end of the trial, all fish were harvested early in the morning, counted, and individually weighed. A sample of 30 individuals per enclosure was retained for statistical analysis.

2.4. Water quality assessment

The physico-chemical quality of water within the rearing enclosures was monitored using three key indicators: dissolved oxygen, temperature, and pH, to characterise the environmental conditions associated with each dietary treatment. Measurements were taken weekly on-site between 06:00 and 07:00 using a HANNA Instruments HI 83141 multiparameter device (for pH and temperature) and a HI 9146 oximeter (for dissolved oxygen). Regular monitoring was essential to maintain optimal conditions for fish growth and to prevent stress caused by physico-chemical fluctuations [30,31].

2.5. Economic evaluation

The economic analysis of the experimental diets (P50, PF50, G50, and FG50) aimed to assess their profitability within aquaculture production systems, taking into account the costs associated with raw materials, transport, processing (fermentation, extrusion), and packaging. The cost of feed per kilogram of weight gain served as the primary indicator for comparing treatments, providing insight into the economic efficiency of processed diets relative to the control [10,14]. Cost calculations included ingredient prices, logistical expenses, and charges related to feed manufacturing and packaging [32]. The comparison of technological modalities sought to identify cost differences per unit of growth and the percentage reductions achieved through the application of extrusion and/or fermentation. This approach enabled an evaluation of the extent to which these processes could contribute to better control of feed expenditure and economic optimisation of fish production.

2.6. Zootechnical and nutritional parameters assessment

Fish performance was assessed using the following indicators: • Weight gain (WG) = Final weight – Initial weight • Average daily gain (ADG) = WG / Duration of rearing • Survival rate (%) = (Final number / Initial number) × 100 • Specific growth rate (SGR, %/day) = [(Ln Wf – Ln Wi) / Duration] × 100 • Feed conversion ratio (FCR) = Quantity of dry feed / Fresh weight gain • Protein efficiency ratio (PER) = Weight gain / Protein intake • Carbohydrate content (%) = 100 – (% moisture + % protein + % lipid + % fibre + % ash) • Metabolisable energy (ME, MJ/kg DM) = 3.95 + [0.0544 × % lipid] – [0.0887 × % fibre] – [0.0408 × % ash] **[33]** • Cost per unit of weight gain = Feed price per kg × FCR • Cost reduction rate (%) = 100 × [(Non-extruded cost – Extruded cost) / Non-extruded cost] • Production increase rate (%) = 100 × [(Extruded yield – P50 yield) / P50 yield]

2.7. Statistical analysis

The effects of dietary treatments on water quality and growth performance were analysed using zootechnical and physico-chemical parameters. Data normality was verified using the Kolmogorov–Smirnov test, validating the use of parametric analyses. Statistical processing was performed using three-way ANOVA, incorporating the effects of diet, rearing structure, experimental period, and their interactions. Analyses were conducted using SPSS software (version 20). Where significant effects were observed, one-way ANOVA was applied to refine results, followed by multiple comparisons using Tukey's HSD test. The significance threshold was set at 5%.

3. Results

3.1. Proximate composition of experimental diets

The comparative analysis of the P50, PF50, G50, and FG50 diets reveals structured differences based on the processing treatments applied, namely fermentation and extrusion. All diets share an identical base composition, consisting of 50% rice bran and 50% wheat bran, allowing the comparison to focus specifically on the effects of technological processing. Dry matter content remained constant across all diets at 88.6%, indicating stability in feed moisture levels. Crude protein content increased progressively with treatment: 14.85% in P50, rising to 15.40% with fermentation alone (PF50), 15.10% with extrusion alone (G50), and peaking at 15.80% with the combined fermentation–extrusion process (FG50). This upward trend was mirrored in lipid content, which rose from 9.15% in P50 to 10.20% in FG50, with intermediate values for PF50 (9.60%) and G50 (9.80%). Fibre content decreased in parallel, from 13.15% in P50 to 11.50% in FG50, reflecting a gradual reduction in indigestible fractions. Ash content showed slight variation, with the highest value in PF50 (9.10%) and the lowest in G50 (8.80%), while P50 and FG50 recorded similar levels (8.95% and 9.00%, respectively). Starch content remained relatively stable across treatments, ranging from 22.5% to 22.9%, with no significant variation.

Nitrogen-free extract increased steadily from 42.5% in P50 to 45.50% in FG50, indicating an enhancement in the available energy fraction. This trend was confirmed by metabolisable energy values, which rose from 2.92 MJ/kg DM in P50 to 3.02 MJ/kg DM in FG50, with intermediate values for PF50 (2.95 MJ/kg DM) and G50 (2.98 MJ/kg DM). The profile of essential amino acids also showed gradual improvement. Arginine increased from 7.25% in P50 to 7.40% in FG50; histidine from 2.65% to 2.80%; isoleucine from 4.50% to 4.70%; leucine from 6.35% to 6.50%; lysine from 4.25% to 4.40%; methionine from 1.90% to 2.20%; phenylalanine from 4.25% to 4.40%; threonine from 3.25% to 3.40%; tryptophan from 1.80% to 1.95%; and valine from 5.00% to 5.20%. Overall, the comparison of diets according to processing treatments reveals a consistent progression in nutritional parameters, with coherent transitions from untreated to fermented, extruded, and combined formulations.

3.2. Water quality

The results show that the physico-chemical quality of the water varied depending on the dietary treatments applied (Table 2).The FG50 diet (fermented and extruded) yielded the highest mean concentration of dissolved oxygen at 3.62 ± 0.10 mg/L, followed by G50 (extruded, non-fermented) at 3.50 ± 0.20 mg/L. PF50 (fermented, non-extruded) recorded an intermediate value of 3.35 ± 1.80 mg/L, while P50 (neither fermented nor extruded) showed the lowest concentration at 3.12 ± 0.20 mg/L. Temperature differences between treatments were minimal. FG50 recorded a mean of 27.40 ± 0.66 °C, slightly lower than PF50 at 27.60 ± 1.20 °C. G50 and P50 showed values of 27.46 ± 1.80 °C and 27.48 ± 2.00 °C, respectively. In contrast, pH measurements revealed more pronounced differences in the opposite direction. FG50 exhibited the lowest pH value at 7.24 ± 0.56, followed by G50 at 7.45 ± 0.80, PF50 at 8.64 ± 0.06, and P50 with the highest pH at 9.20 ± 0.66. These findings demonstrate a differentiated evolution of water quality parameters in response to the processing treatments applied to the diets.

Table 2 Physico-chemical water parameters

Diet	Dissolved Oxygen (mg/L)	Temperature (°C)	pH
P50	3.12 ± 0.20^a	27.48 ± 2.00^a	9.20 ± 0.66^a
PF50	3.35 ± 1.80^a	27.60 ± 1.20^a	8.64 ± 0.06^b
G50	3.50 ± 0.20^b	27.46 ± 1.80^a	7.45 ± 0.80^c
FG50	3.62 ± 0.10^b	27.40 ± 0.66^a	7.24 ± 0.56^c

Values with different superscript letters within the same column indicate statistically significant differences ($p < 0.05$). ± indicates the standard deviation around the mean; Superscript letters (^{a}, ^{b}, ^{c}) denote statistically distinct groups. Values sharing the same letter within a given column are not significantly different from one another. Diet codes: P50 (unfermented, non-extruded); PF50 (fermented, non-extruded); G50 (extruded, unfermented); FG50 (fermented and extruded)

3.3. Growth performance

Table 3 Growth performance and feed utilization efficiency of *Oreochromis niloticus* reared on experimental diets over a 100-day period

Diet	Final Weight (g)	Weight Gain (g)	ADG (g/day)	FCR	PER	Survival Rate (%)
P50	312.8 ± 9.6^a	110.8 ± 9.6^a	1.11 ± 0.22^a	6.37 ± 0.4^a	1.60 ± 0.09^a	97.33 ± 2.3^a
PF50	336.4 ± 10.2^b	134.4 ± 10.2^b	1.34 ± 0.21^b	5.25 ± 0.3^b	1.24 ± 0.11^b	97.67 ± 2.0^a
G50	357.6 ± 15.8^c	155.6 ± 15.8^c	1.56 ± 0.21^c	3.70 ± 0.2^c	1.46 ± 0.11^c	100.00 ± 0.0^a
FG50	398.2 ± 12.4^d	196.2 ± 12.4^d	1.96 ± 0.16^d	2.98 ± 0.3^d	1.76 ± 0.07^d	98.67 ± 2.1^a

Values with different superscript letters within the same column indicate statistically significant differences ($p < 0.05$). ± indicates the standard deviation around the mean; Superscript letters (^{a}, ^{b}, ^{c},^{d}) denote statistically distinct groups. Values sharing the same letter within a given column are not significantly different from one another. Diet codes: P50 (unfermented, non-extruded); PF50 (fermented, non-extruded); G50 (extruded, unfermented); FG50 (fermented and extruded)

At the end of the 100-day rearing period, the zootechnical performance of *Oreochromis niloticus* was assessed across four dietary treatments distinguished by the technological processes applied: P50 (unfermented, non-extruded), PF50 (fermented, non-extruded), G50 (extruded, unfermented), and FG50 (fermented and extruded). Comparative analysis revealed a structured progression in growth indicators, feed efficiency, and survival rates according to the processing method. The P50 diet, which underwent no processing, yielded the lowest values across all measured parameters, with a final mean weight of 312.8 ± 9.6 g, weight gain of 110.8 ± 9.6 g, average daily gain (ADG) of 1.11 ± 0.22 g/day, protein efficiency ratio (PER) of 1.6 ± 0.09, feed conversion ratio (FCR) of 6.37 ± 0.4, and a survival rate of 97.33 ± 2.3%. The introduction of fermentation in the PF50 diet led to notable improvements, with final weight increasing to 336.4 ± 10.2

g, weight gain to 134.4 ± 10.2 g, ADG to 1.34 ± 0.21 g/day, and a reduction in FCR to 5.25 ± 0.3. PER was 1.24 ± 0.11, and survival reached 97.67 ± 2%. Extrusion alone in the G50 diet resulted in further enhancement, with final weight reaching 357.6 ± 15.8 g, weight gain 155.6 ± 15.8 g, ADG 1.56 ± 0.21 g/day, PER 1.46 ± 0.11, FCR 3.70 ± 0.2, and a maximum survival rate of 100%. The combined fermentation and extrusion treatment in FG50 produced the highest performance values: final weight of 398.2 ± 12.4 g, weight gain of 196.2 ± 12.4 g, ADG of 1.96 ± 0.16 g/day, PER of 1.76 ± 0.07, FCR of 2.98 ± 0.3, and survival rate of 98.67 ± 2.1%. These results demonstrate a gradual and coherent improvement in zootechnical performance across the dietary treatments, with clear transitions from unprocessed to partially and fully processed diets.

3.4. Economic evaluation

The comparative economic analysis of the P50, PF50, G50, and FG50 diets, differentiated by fermentation and extrusion processes, revealed structured variations in both economic and zootechnical parameters. The P50 diet, unprocessed, had the lowest production cost at 86.0 CFA francs/kg, with no additional costs for fermentation or extrusion. It recorded an FCR of 6.37 and a feed cost per unit of weight gain of 547.82 CFA francs/kg. Introducing fermentation in PF50 increased the production cost to 88.5 CFA francs/kg, including a fermentation cost of 2.5 CFA francs/kg. This treatment reduced the FCR to 5.25 and the feed cost per weight gain to 464.63 CFA francs/kg, representing a 15.19% reduction compared to P50. Extrusion alone in G50 resulted in a production cost of 87.5 CFA francs/kg, including 18.5 CFA francs/kg for extrusion. The FCR dropped to 3.70, and the feed cost per weight gain to 323.75 CFA francs/kg, a 40.90% reduction relative to P50. The FG50 diet, combining both treatments, had the highest production cost at 90.0 CFA francs/kg, incorporating fermentation and extrusion costs. However, it achieved the lowest FCR (2.98) and feed cost per weight gain (268.2 CFA francs/kg), reflecting a 51.04% reduction compared to P50.

Table 4 Economic effectiveness of *Oreochromis niloticus* reared on experimental diets over a 100-day period

Parameters	**P50**	**PF50**	**G50**	**FG50**
Labour cost for powdered feed (CFA/kg)	1.5	1.5	1.5	1.5
Fermentation cost (approximate) (CFA/kg)	0.0	2.5	0.0	2.5
Extrusion cost (CFA/kg)	0.0	0.0	18.5	18.5
Total production cost per kg of feed (CFA)	86.0	88.5	87.5	90.0
Feed Conversion Ratio (FCR)	6.37	5.25	3.70	2.98
Feed cost per kg of weight gain (CFA)	547.82	464.63	323.75	268.20
Cost reduction compared to P50 (%)	—	15.19	40.90	51.04

P50 (unfermented, non-extruded); PF50 (fermented, non-extruded); G50 (extruded, unfermented); FG50 (fermented and extruded).

3.5. Proximate carcass composition of experimental Fish

Table 5 Carcass composition of *Oreochromis niloticus* reared on experimental diets

Treatment	**Moisture (%)**	**Crude Protein (%)**	**Total Lipid (%)**	**Total Ash (%)**	**Total (%)**
Initial State	75.2 ± 0.2	16.4 ± 0.1	7.0 ± 0.2	1.4 ± 0.1	100
P50	74.8 ± 0.3^{a}	17.2 ± 0.3^{a}	6.5 ± 0.1^{a}	1.5 ± 0.2^{a}	100
PF50	74.2 ± 0.2^{b}	17.8 ± 0.2^{b}	6.8 ± 0.1^{b}	1.6 ± 0.1^{a}	100
G50	73.5 ± 0.2^{c}	18.3 ± 0.3^{c}	7.2 ± 0.2^{c}	1.7 ± 0.1^{c}	100
FG50	72.8 ± 0.3^{d}	18.9 ± 0.2^{d}	7.6 ± 0.2^{d}	1.7 ± 0.2^{c}	100

Values with different superscript letters within the same column indicate statistically significant differences ($p < 0.05$). ± indicates the standard deviation around the mean; Superscript letters (^{a}, ^{b}, ^{c}, ^{d}) denote statistically distinct groups. Values sharing the same letter within a row are not significantly different from one another. P50 (unfermented, non-extruded); PF50 (fermented, non-extruded); G50 (extruded, unfermented); FG50 (fermented and extruded).

At the end of the trial, the chemical composition of fish carcasses fed the different diets showed a progressive evolution in response to the applied treatments. Initially, fish exhibited 75.2% moisture, 16.4% crude protein, 7.0% total lipids, and 1.4% ash. After 100 days, the P50 diet resulted in a slight reduction in moisture to 74.8 ± 0.4^{a}%, a moderate increase in protein to 17.2 ± 0.1^{a}%, a decrease in lipids to 6.5 ± 0.3^{a}%, and an increase in ash to 1.5 ± 0.2^{a}%. Fermentation alone (PF50) reduced moisture to 74.2 ± 0.3^{b}%, increased protein to 17.8 ± 0.2^{b}%, lipids to 6.8 ± 0.1^{b}%, and ash to 1.6 ± 0.1^{b}%. Extrusion alone (G50) further reduced moisture to 73.5 ± 0.5^{c}%, increased protein to 18.3 ± 0.3^{c}%, lipids to 7.2 ± 0.2^{c}%, and ash to 1.7 ± 0.1^{c}%. The FG50 diet yielded the most pronounced changes, with moisture at 72.8 ± 0.3^{d}%, protein at 18.9 ± 0.2^{d}%, lipids at 7.6 ± 0.1^{d}%, and ash at 1.7 ± 0.2^{c}%. These results highlight significant and structured transitions in carcass composition, reflecting the increasing impact of technological processing on fish quality.

4. Discussion

This comparative study of the dietary treatments P50, PF50, G50, and FG50 applied to *Oreochromis niloticus* demonstrates that technological processes-fermentation, extrusion, or their combination-exert distinct effects on key parameters including water quality, nutritional composition, zootechnical performance, economic viability, and carcass quality.From the perspective of water physico-chemical quality, processed diets significantly improved oxygenation levels. The FG50 diet, combining fermentation and extrusion, recorded the highest dissolved oxygen concentration (3.62 ± 0.10 mg/L), followed by G50 (3.50 ± 0.20 mg/L), PF50 (3.35 ± 1.80 mg/L), and P50 (3.12 ± 0.20 mg/L). This hierarchy may be attributed to more efficient nutrient assimilation and reduced organic waste, as highlighted by El-Sayed et al. [34], who noted that processing techniques enhance digestive efficiency while lowering pollutant loads. In contrast, temperature differences between treatments were minimal and statistically insignificant, corroborating the findings of Boyd & Tucker [35], who emphasised that temperature is primarily influenced by environmental conditions. pH levels decreased with increasing processing intensity: FG50 showed the lowest value (7.24 ± 0.56), followed by G50 (7.45 ± 0.80), while PF50 and P50 exhibited higher values (8.64 ± 0.06 and 9.20 ± 0.66, respectively). This trend may reflect reduced ammonia emissions and improved environmental stability, as suggested by Li et al. [36]. All diets were formulated using a standard base of 50% rice bran and 50% wheat bran, allowing for isolated assessment of the effects of technological treatments. Dry matter content remained constant at 88.6%, while crude protein levels increased progressively from 14.85% in P50 to 15.80% in FG50. This improvement may be linked to the breakdown of antinutritional factors and the release of more digestible protein fractions [15,37]. Lipid content followed a similar trend, rising from 9.15% to 10.20%, indicating enhanced energy concentration and lipid retention [38]. Fibre content decreased from 13.15% to 11.50%, reflecting the degradation of insoluble fractions through microbial enzymatic activity and polysaccharide gelatinisation [39]. This reduction, coupled with increased metabolisable energy, suggests improved nutrient digestibility [39–41]. Ash content, indicative of total mineral concentration, showed slight variation across treatments, with the highest value in PF50 (9.10%) and the lowest in G50 (8.80%). These differences may reflect varied mineral mobilisation, with fermentation enhancing mineral release and extrusion potentially reducing bioavailability through structural modification [15,34]. Improved mineral availability is generally associated with enhanced digestibility and intestinal absorption [41], supporting the interpretation of these variations in relation to observed zootechnical outcomes. Starch content remained relatively stable, while the progressive increase in nitrogen-free extract and metabolisable energy indicates better carbohydrate utilisation [40,41]. The reduction in fibre, often linked to improved digestibility, reinforces this trend [39]. Additionally, the enrichment in essential amino acids suggests enhanced protein quality, conducive to growth and nutritional efficiency [42].

Zootechnically, growth performance followed a structured progression. The untreated P50 diet yielded the lowest values: final weight of 312.8 ± 9.6 g, weight gain of 110.8 ± 9.6 g, ADG of 1.11 ± 0.22 g/day, FCR of 6.37 ± 0.4, and survival rate of 97.33%. The introduction of fermentation in PF50 improved performance indicators, with a mean weight gain of 134.4 ± 10.2 g and a reduced FCR of 5.25 ± 0.3. Comparable results were reported by Mones & Isagani [43] in juvenile red tilapia fed fermented banana peel-based diets. Similarly, Barnes et al. [44] observed growth increases of 172–350% in rainbow trout (*Oncorhynchus mykiss*) fed fermented diets. Extrusion alone in G50 led to further improvements, with weight gain of 155.6 ± 15.8 g, ADG of 1.56 ± 0.21 g/day, PER of 1.46 ± 0.11, and FCR reduced to 3.70 ± 0.2.

The FG50 diet achieved the highest performance: weight gain of 196.2 ± 12.4 g, ADG of 1.96 ± 0.16 g/day, PER of 1.76 ± 0.07, FCR of 2.98 ± 0.3, and survival rate of 98.67%, confirming the synergistic effect of combined treatments [36,38]. The observed differences between diets may be attributed to the ability of processing techniques to enhance nutrient bioavailability and reduce digestive losses.

Economically, production costs increased with processing: 86.0 CFA/kg for P50, 88.5 CFA/kg for PF50, 87.5 CFA/kg for G50, and 90.0 CFA/kg for FG50. However, this increase was offset by improved feed efficiency. Feed cost per unit of weight gain decreased from 547.82 CFA/kg in P50 to 268.2 CFA/kg in FG50, a reduction of 51.04%, demonstrating that technological treatments, despite incurring additional costs, enhance overall profitability [10,41]. While fermentation improves biological feed quality at a moderate cost, extrusion enhances feed performance despite higher technical expenses. Their combination in FG50 achieves an optimal balance between production cost and nutritional efficiency.

Finally, carcass composition reflected the impact of diets on fish body quality. Moisture content decreased progressively from 75.2% to 72.8%, while protein increased from 16.4% to 18.9%, lipids from 7.0% to 7.6%, and ash from 1.4% to 1.7%. The P50 diet showed limited improvement, whereas PF50 and G50 demonstrated more pronounced effects linked to fibre degradation and improved nutrient assimilation. The FG50 diet, combining both treatments, yielded the highest protein and lipid levels, indicating flesh densification and optimal nutrient utilisation [15,38]. These findings suggest that technological processing influences not only growth and profitability, but also the final quality of aquaculture products, aligning with current standards for sustainable fish nutrition.

5. Conclusion

In conclusion, fermentation and extrusion emerge as effective technological strategies for enhancing digestibility, growth performance, and economic efficiency in Nile tilapia production. The FG50 diet, integrating both processes, demonstrated superior zootechnical and economic outcomes. These findings support the adoption of innovative practices in aquaculture, promoting more sustainable and competitive production systems. Wider implementation could transform local aquaculture value chains, while future research may further optimise formulations and expand their applications

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

Author contributions

This study was made possible through the joint efforts and active collaboration of all authors: KJ-LB: Led the conceptualization of the study, designed the experimental protocol, conducted data collection and statistical analysis, and drafted the manuscript ; YB: Coordinated fieldwork operations, oversaw sampling procedures and laboratory analyses, and contributed to the critical revision of the manuscript ; YD: Handled data processing, interpreted the results, prepared figures and tables, and conducted the literature review ; BZ: Participated in data collection and contributed to manuscript editing and refinement ; AO: Provided technical support during fish rearing trials and managed logistics at the experimental site.

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