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Research Article

Effects of Dietary Ginger (*Zingiber officinale*) Powder on Growth Performance, Feed-Related CO_2e Intensity, Economic Returns, and Management Decisions in African catfish (*Clarias gariepinus*) Farming

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Abstract | Aqua farming is under pressure to simultaneously improve the efficiency of production and lessen environmental impact. The objectives of this study are to evaluate graded levels of commercial ginger (*Zingiber officinale*) rhizome powder as an inclusion in the dietary amounts fed to juvenile African catfish (*Clarias gariepinus*) and convert the biological results into a means of making management and economic decisions based on the results of the study. Four isonitrogenous diets were prepared to contain 0, 5, 10 or 15 g ginger/kg feed (0, 0.5, 1.0 and 1.5%). Juveniles (mean initial weight 5.2 g) were reared in pond-based cages for 90 days (four replicates per diet). Growth indices, feed conversion ratio (FCR), and survival were measured. Feed-related CO_2e intensity was estimated as a relative comparison using a fixed aquafeed emission factor; this does not constitute a full life-cycle assessment and assumes that upstream emissions from ginger processing are negligible at the inclusion levels used. The study also applied a partial-budget analysis to evaluate the potential impact of the relative differences in FCR on economic returns based on an assumed commercial benchmark FCR. Compared with the control group, ginger-supplemented fish showed significantly greater maximum weight gain (151.8 g in the control vs. 197.6–206.0 g at 5–10 g/kg; $p < 0.001$) and a modest improvement in feed conversion ratio (approximately 0.8–1.1% lower than the control), with no effect on survival. Accordingly, feed-related CO_2e intensity declined proportionally (≈1% relative reduction at 5–10 g/kg), with little additional benefit at 15 g/kg. Logistic growth modelling predicted the shortest time to reach 200 g at 10 g/kg (84 days) compared with 5 or 15 g/kg (92–95 days). The responses plateaued at approximately 10 g/kg of ginger. Dose–response patterns commonly observed for phytogenic additives support the concept of context-specific optimal responses. Based on the findings of this study, moderate ginger inclusion (5–10 g/kg) can be used to support improved growth performance and possibly somewhat lower feed-related CO_2e intensity and modestly improve economic returns; however, economic outcomes are context-dependent and should be interpreted cautiously when extrapolating from experimental to commercial scale FCRs.

Keywords | *Clarias gariepinus*, Ginger powder, Phytogenic feed additive, Growth performance, Feed-related CO_2e intensity

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INTRODUCTION

Phytogenic feed additives from plants intended for low rates of inclusion in aquaculture are also advocated to enhance the performance and resilience of fish while reducing the use of antibiotics and other synthetic inputs (Galina *et al.*, 2009; Langi *et al.*, 2024). Phytogenic additives, as products of herbal origin, have attractive biological and practical properties; they can be found in many parts of the world and act on various targets (digestion, immunity, stress physiology) and are thus promising agents for sustainable intensification under conditions of scarce inputs and low profit margins (Galina *et al.*, 2009; Langi *et al.*, 2024). Within this context, the African catfish, *Clarias gariepinus*, is of particular importance. This species is widely and intensively cultured, with 'supermarkets' of catfish ponds and tanks on the continent. Reviews exist on nutritional requirements, robust culture performance and its economic importance (FAO, 2025). In Nigeria alone, the value chain is made up of hundreds of thousands of producers (FAO Fisheries Department, 2025). The economic weight of feed is considerable: in intensive aquaculture, feeds typically account for 60–80% of total operating costs, so even small improvements in FCR can be reflected in reduced production costs (Ayustaningwarno *et al.*, 2024).

Ginger (*Zingiber officinale*) is among the leading candidates. Its primary phenolic components, gingerols and shogaols, confer antioxidant, anti-inflammatory, and immunomodulatory activities that can enhance growth, health, and nutrient utilisation in fish by modulating redox and inflammatory signalling pathways, gut structure and function, and the microbiota; processing conditions influence the relative abundance and biological activity of these compounds (Samota *et al.*, 2024; Edo *et al.*, 2025; Ashry *et al.*, 2023). Across several finfish species (tilapia, rohu carp, rainbow trout, striped catfish), ginger provided as powder, extract, or oil has been shown to support increased growth rates, enhanced digestive enzyme activity, and improved disease resistance, often at low inclusion levels (0.5–1.0%) suitable for more commercial use (Ahmed *et al.*, 2023; Nya and Austin, 2009; Rawat *et al.*, 2022; Ansah and Frimpong, 2015; Wei *et al.*, 2023, 2025). Less relevant studies have employed purified ginger extracts or essential oils, which may be biologically effective but financially inaccessible for many smallholders. Furthermore, many trials stop short of examining economic viability or providing practical guidance on dosing and timing for farmers. In earlier research on striped catfish (*Pangasianodon hypophthalmus*) (Ashry *et al.*, 2023), feeding ginger improved growth rate, digestive enzyme activity, and antioxidant capacity. This paper examines the effects of feeding ginger to African catfish (*Clarias gariepinus*) raised in pond-based cage systems and evaluates overall performance using both feed-related CO_2e intensity and farm-based economic analyses.

The optimum use of ginger in the diets of African catfish remains uncertain. There are many conflicting reports on how ginger affects fish based on the stage of life (juveniles or on-growing) as well as the level up to which benefit is gained or plateaued. An example would include studies indicating an optimum level for growth between 1 and 2% of the diet, while higher levels did not result in greater growth and decreased survival (Mbokane and Moyo, 2022; Wei *et al.*, 2023). Therefore, it appears that this optimum is dependent upon species and context. In addition, the use of ginger may improve growth and feed conversion rates; however, in terms of return on investment, the increased weight gain and improved feed conversion rates may be offset by the higher cost of the additive relative to feed and fish prices in practice. Several authors have indicated that there can be large increases in the benefit-cost ratios associated with the use of herbal additives; for example, one study indicated that the profit per kg of fish was nearly three times higher with the addition of ginger to the diet at 0.2% (Wei *et al.*, 2024). Variables such as feed cost, fingerling cost, and market price, as well as inclusion level, will determine the outcomes. Lastly, it would be helpful if recommendations on the usage of ginger were to include consideration of dosage throughout the crop cycle, as well as comparison between biological benefits and economic considerations.

This study was undertaken to investigate how graded inclusion of commercial ginger powder (0, 5, 10, and 15 g/kg) in the diet of juvenile African catfish affected growth, feed conversion, and associated economic outcomes (feed cost per kg gain, net profit per kg fish, and benefit–cost ratio). In addition, we sought to derive a decision model for producers based on growth modelling and profit analysis to assist in selecting ginger inclusion levels appropriate to specific production goals. We hypothesised that growth and feed efficiency would increase up to an optimal inclusion level, beyond which effects would show diminishing returns or decline, and that relatively lower inclusion levels would yield the best economic performance by improving profit without substantially increasing feed cost. By combining biological responses with simple economic principles, we aimed to generate practical recommendations for African catfish production using ginger-based feed additives.

MATERIALS AND METHODS

Culture system and experimental design

The experiment was a completely randomised design with four levels of commercial powdered ginger (0, 5, 10 and 15 g/kg feed) in four replicates. Juvenile African catfish (mean initial weight 5.2 g) were randomly stocked at 50 fish/m^3 into net cages suspended in a 24 m^2 concrete pond (water depth up to 500 mm). Continuous inflow- overflow maintained acceptable water quality (temperature 25–28 °C; dissolved oxygen 3.5–6.8 mg/L; pH 7.2–7.5; total ammonia nitrogen ≤0.5 mg/L; nitrite ≤0.1 mg/L) during the 90-day trial. Fish were hand-fed to apparent satiation twice daily (09:00 and 16:00), with ration size adjusted to biomass every 15 days to avoid under- or over-feeding. All procedures complied with institutional and national guidelines for animal care and use and were approved by the Animal Care and Use Committee (IACUC) of Chiang Mai Rajabhat University, Thailand (approval number CMRU-IAD 009/2565).

Diet preparation and feeding

Basal diets were isonitrogenous and isoenergetic, based on a 30% crude protein commercial pelleted catfish feed. Commercial ginger powder (dried *Z. officinale* rhizome, containing ≥5% gingerol) was included at 0 (control), 5, 10 or 15 g/ kg by top-coating pelleted feed with a gelatinised starch–fish oil binder (the control diet to which binder and oil had been added without ginger). This had the following specifications as brown powder, bulk density 0.3–0.6 g/ mL, 98% passing 80-mesh, active ingredient gingerol ≥5%, water-soluble and pH (1% w/v suspension) 4.0–6.0. All diets were prepared fresh and air-dried to promote adhesion of the topcoat. Feeding was in accordance with the husbandry schedule; ration sizes were reset to biomass every 15 days so that the fish could be fed to apparent satiation without waste.

Sampling and growth indices

Fish were collected at random and weighed individually to compute the following performance indices: weight gain = final weight − initial weight; average daily gain (ADG) = (final weight − initial weight)/90 days; specific growth rate (SGR), % per day = [ln(final) − ln(initial)] × 100/90 days. Feed conversion ratio (FCR) was calculated as feed consumed (g)/weight gain (g). Survival (%) was calculated as 100 × (final number of fish/initial number of fish).

Growth curve modelling for decision support

To express growth dynamics in terms of farm-ready triggers, we fitted the logistic equation: $W(t)=K/[1+\exp(-r(t-t_0))]$

Where $W(t)$ is the predicted weight on day t, K is the carrying capacity (asymptotic weight), r is the intrinsic growth rate coefficient, and t_0 is the inflection time (days). Non-linear least-squares regression was performed on mean weights on days 0, 15, 30, 45, 60, 75, and 90 for each diet. Goodness-of-fit was assessed using R^2 and residual inspection. From the fitted parameters, two derived quantities were calculated: (i) time-to-target (the number of days until fish reached 200 g body weight, a relevant juvenile harvest size) and (ii) maximum absolute growth rate ($K \cdot r/4$), which occurs at $W = K/2$ (the inflection point). These logistic growth metrics underpin the growth-model branch of the decision tree.

Assessment of economic viability

Feed cost per kg of fish produced was estimated from diet cost (USD/kg feed) and an assumed commercial-scale FCR. Across the 90-day period, FCR values measured in the experimental fish were numerically high because fish were fed to apparent satiation in small research cages; therefore, these absolute values are not necessarily representative of well-managed commercial systems. However, relative differences in FCR among treatments (approximately 0.8–1.1% lower for the 10 g/kg diet than the control) were informative for comparing diets under identical conditions. To place these relative differences into a more realistic economic context, we adopted a benchmark farm-scale FCR of 1.93 for the 10 g/kg diet and applied the observed relative FCR differences to treatment costs. Accordingly, the economic analysis is a partial-budget illustration that focuses on feed and additive costs and is context-dependent; it should not be extrapolated to other farms without recalculation using local prices and on-farm performance data. Diet cost (USD/kg feed) included the marginal cost of ginger powder at each inclusion. Net profit per kg fish was calculated as:

$$\textit{Net profit (USD/kg fish)} = \textit{Farm-gate fish price} - \textit{Feed cost per kg gain}$$

Where feed cost per kg gain = benchmark FCR × diet cost for scenario. The benefit–cost ratio (BCR) was calculated as revenue per kg fish (farm-gate price) divided by feed cost per kg gain.

In the base scenario we used a basal feed price of USD 1.00/ kg, ginger powder price of USD 3.00/kg, and farm-gate fish price of USD 2.00/kg. Other variable costs (labour, energy etc.) were assumed to be constant across treatments and not included in per-kg comparisons. The economic analysis is thus a partial-budget style comparison focused on feed and additive costs.

Sensitivity analysis

To test the sensitivity of our conclusions to fluctuating input prices, we varied prices of key inputs around our base scenario and recalculated profit per kg fish for the 10 g/ kg diet, keeping all biological parameters constant. We increased the price of ginger powder by +10%, +20% and +30% relative to our base price and reduced the basal feed price by 10%. We present the resultant diet cost (USD/kg feed), feed cost per kg gain, profit per kg fish and change in profit (Δ versus base scenario). Since feed typically accounts for 60–80% of operating costs on African aquaculture farms, we are interested in how price changes affect profit, especially in terms of feed and additive prices. Absolute profit numbers will vary among farms according to how they are structured, so we intend the results to be rather illustrative and indicative scenarios rather than predictive universal truths.

Decision tree framework

Outputs from the economic analysis (profit, BCR, sensitivity results) and growth modelling (K, r, t_0, time-to-target 200 g, and maximum growth rate K·r/4) were combined with observed size-class responses (interval-specific ADG/SGR and FCR by age) to develop the decision-tree framework. The framework has three interacting branches: (i) a profit-based branch that evaluates the economic viability of ginger use at prevailing prices of feed, ginger, and fish; (ii) a growth-model branch that uses logistic parameters and time-to-target to identify the growth window in which supplementation provides the greatest biological opportunity; and (iii) a management branch that adjusts ginger inclusion through the production cycle according to fish size and health status.

In practice, we use these branches to determine when to start ginger supplementation, adjust the dose, taper it, or stop it. For example, the tree may start at 5 g/kg if the cohort is small or underperforming, increase to 10 g/kg during the main growth window, and allow only short pulses of 15 g/kg for 10–15 days when stress or disease risk is indicated (e.g., deteriorating water quality or clinical signs). The decision tree is presented as a transparent heuristic tool rather than a validated management protocol. It requires on-farm validation and should be recalibrated to local production conditions, feed formulations, and prevailing prices before prescriptive use.

Feed-related CO_2e intensity

The sustainability assessment was expanded by estimating a feed-related greenhouse-gas intensity (kg CO_2e per kg liveweight gain) for each treatment using the treatment-specific FCR and an emission factor for the compound aquafeed. Under the assumption that non-feed emissions (e.g., infrastructure and energy use) were similar for all treatments, CO_2e intensity was calculated as CO_2e intensity = FCR × EF_feed. We used EF_feed = 1.2 kg CO_2e/kg feed, representing a conservative value reported for comparable applications. This approach is intended as a relative comparison between dietary strategies rather than a full life-cycle assessment. Upstream emissions associated with ginger processing were assumed negligible at the inclusion levels used (maximum 15 g/kg feed), and readers should not extrapolate the absolute CO_2e values to commercial cradle-to-gate footprints without a complete LCA.

The purpose of this study's carbon footprint analysis was to compare the various types of dietary systems rather than as an extensive LCAs (Lifetime Cycle Assessments) of these dietary systems. The emphasis was on the feed portion of each diet's life cycle; it was assumed that each diet had an equal level of usage of the same energy sources, management practices and infrastructure, thus any absolute number for emissions should be interpreted cautiously. Nevertheless, the results from the differing dietary systems represent the relative efficiencies of each system's ability to convert feed into usable energy.

Statistical analyses

Treatment effects of ginger powder level (0, 5, 10 and 15 g/kg) on final weight, weight gain, ADG, SGR, FCR and survival were analysed using one-way ANOVA. Where ANOVA indicated significance (α= 0.05), Duncan's multiple range test was conducted for pairwise comparisons. Percentage data were arcsine-square root transformed where necessary to meet assumptions of normality and homoscedasticity; percentage means are presented untransformed for clarity. Data presented as mean ± SEM, based on replicate tank values.

RESULTS

Production system and water quality

The cage culture system in the pond produced stable conditions over the whole of the 90-day trial. Water chemistry was within acceptable limits for African catfish and did not differ significantly among treatments. There was no sign of disease or stress in any group. Survival ranged from 87.5 to 91.0% across treatments (not significantly different, p>0.05). Morning dissolved oxygen readings were typically 4–6 mg/ L, total ammonia nitrogen <0.5 mg/ L (nitrite <0.1 mg/ L), and pH level stable between 7.0–7.5 (morning to afternoon).

Growth performance and feed utilisation

Initial body weights did not differ between treatments (5.31–5.15 g, p = 0.26), confirming successful randomisation at stocking. From day 15 onward, ginger-supplemented diets produced consistently larger fish than the control (Table 1). On day 90, body weight in the control group averaged 151.8 g, whereas fish fed 5, 10, and 15 g ginger/kg diet averaged 197.6, 206.0, and 192.0 g, respectively (p < 0.001). The 10 g/kg diet produced the highest final weight, but all ginger-supplemented diets yielded significantly higher final weights than the control and did not differ among themselves.

Cumulative weight gain over 90 days showed the same pattern. Control fish gained 146.5 g, whereas fish fed diets containing 5 and 10 g ginger/kg gained 192.4 g and 200.7 g,

Table 1: Growth performance and feed utilisation of African catfish (*Clarias gariepinus*) fed diets containing different levels of commercial ginger powder over a 90-day culture period.

Age	Ginger level (g/kg)				SEM	p value
	0	5	10	15		
Body weight (g)						
Initial weight	5.31	5.13	5.31	5.15	0.042	0.260
15 days	31.23^{b}	31.67^{b}	33.66^{b}	38.21^{a}	0.600	<0.001
30 days	51.77^{b}	70.04^{a}	70.47^{a}	66.93^{a}	1.182	<0.001
45 days	63.01^{b}	77.52^{a}	76.95^{a}	78.85^{a}	1.316	<0.001
60 days	104.47^{c}	137.06^{ab}	141.65^{a}	127.02^{b}	2.178	<0.001
75 days	143.60^{c}	169.57^{b}	189.41^{a}	171.05^{b}	2.547	<0.001
90 days	151.78^{b}	197.56^{a}	206.03^{a}	192.03^{a}	2.911	<0.001
Body weight gain (g)						
0-15 days	25.92^{b}	26.54^{b}	28.35^{b}	33.06^{a}	0.565	<0.001
0-30 days	46.46^{b}	64.91^{a}	65.17^{a}	61.78^{a}	1.153	<0.001
0-45 days	57.70^{b}	72.39^{a}	71.65^{a}	73.70^{a}	1.284	<0.001
0-60 days	99.16^{c}	131.93^{ab}	136.35^{a}	121.88^{b}	2.147	<0.001
0-75 days	138.29^{c}	164.44^{b}	184.10^{a}	165.90^{b}	2.516	<0.001
0-90 days	146.47^{b}	192.43^{a}	200.73^{a}	186.88^{a}	2.883	<0.001
Average daily gain (g/day)						
0-15 days	1.73^{b}	1.77^{a}	1.89^{a}	2.20^{a}	0.038	<0.001
0-30 days	1.54^{b}	2.16^{a}	2.17^{a}	2.05^{a}	0.038	<0.001
0-45 days	1.28^{b}	1.61^{a}	1.59^{a}	1.64^{a}	0.029	<0.001
0-60 days	1.65^{c}	2.20^{ab}	2.27^{a}	2.03^{b}	0.036	<0.001
0-75 days	1.84^{c}	2.19^{b}	2.46^{a}	2.21^{b}	0.034	<0.001
0-90 days	1.63^{b}	2.14^{a}	2.23^{a}	2.08^{a}	0.032	<0.001
Feed intake (g/day)						
15 days	1.56^{b}	1.59^{b}	1.69^{b}	1.91^{a}	0.030	<0.001
30 days	2.59^{b}	3.50^{a}	3.53^{a}	3.35^{a}	0.059	<0.001
45 days	3.15^{b}	3.88^{a}	3.85^{a}	3.95^{a}	0.066	<0.001
60 days	5.23^{c}	6.58^{ab}	7.09^{a}	6.35^{b}	0.109	<0.001
75 days	7.18^{c}	8.48^{b}	9.47^{a}	8.55^{b}	0.127	<0.001
90 days	7.59^{b}	9.88^{a}	10.30^{a}	9.61^{a}	0.146	<0.001
Feed conversion ratio						
15 days	0.91^{a}	0.90^{b}	0.89^{b}	0.87^{c}	0.002	<0.001
30 days	1.67^{a}	1.62^{b}	1.63^{b}	1.63^{b}	0.002	<0.001
45 days	2.46^{a}	2.41^{c}	2.42^{b}	2.41^{c}	0.002	<0.001
60 days	3.16^{a}	3.12^{c}	3.12^{c}	3.13^{b}	0.002	<0.001
75 days	3.89^{a}	3.86^{b}	3.85^{c}	3.87^{b}	0.001	<0.001
90 days	4.66^{a}	4.62^{c}	4.61^{c}	4.63^{b}	0.001	<0.001
Specific growth rate (%/day)						
15 days	11.69^{c}	12.01^{bc}	12.22^{b}	13.26^{a}	0.075	<0.001
30 days	5.85^{c}	6.01^{bc}	6.11^{b}	6.63^{a}	0.037	<0.001
45 days	5.07^{b}	5.76^{a}	5.71^{a}	5.67^{a}	0.029	<0.001
60 days	4.12^{c}	4.50^{a}	4.42^{b}	4.52^{a}	0.019	<0.001
75 days	3.96^{c}	4.36^{a}	4.37^{a}	4.25^{b}	0.017	<0.001
90 days	3.66^{c}	3.88^{b}	3.96^{a}	3.87^{b}	0.012	<0.001
Survival rate (%)	87.86	89.75	88.75	89.88	0.302	0.402

Values with different superscript letters (a, b, c) in the same row differ significantly ($p < 0.05$).

respectively. Fish fed 15 g/kg gained 186.9 g more than the control ($p < 0.001$). In summary, ginger at 5–10 g/kg produced total gains 31–37% higher than the control, while fish fed 15 g/kg grew 28% more than the control. ADG over the full period increased from 1.63 g/day to 2.14–2.23 g/day across ginger treatments ($p < 0.001$). SGR over 0–90 days increased from 3.66%/day (control) to 3.88, 3.96, and 3.87%/day for the 5, 10, and 15 g/kg diets, respectively ($p < 0.001$). The highest SGR was observed in the 10 g/kg group.

Feed intake did not differ between treatments at the start of the trial but diverged as the fish grew. Mean daily feed intake averaged across days 0–90 was 7.59 g in the control group and 9.88, 10.30, and 9.61 g for the 5, 10, and 15 g/kg diets, respectively ($p < 0.001$), likely reflecting the larger body masses attained with ginger. When expressed as FCR over the entire trial, values were numerically high (range 4.61–4.66) across treatments; however, ginger diets improved FCR significantly ($p < 0.001$). Cumulative FCR decreased from 4.66 in the control to 4.62 and 4.61 at 5 and 10 g/kg, and 4.63 at 15 g/kg ($p < 0.001$), representing an approximate 0.8–1.1% reduction in feed required per unit of growth relative to the control diet. Survival was high (87.9–89.9%) and did not differ among treatments ($p = 0.40$), indicating that ginger powder at up to 15 g/kg did not compromise viability.

Feed-related CO_2e intensity

Using treatment-specific FCR values, we estimated feed-related greenhouse-gas intensity (kg CO_2e per kg liveweight gain) to be lowest for the 5–10 g/kg ginger groups because of their slightly improved feed efficiency relative to the control. Using this comparative calculation, ginger inclusion at 5–10 g/kg was estimated to reduce CO_2e intensity by approximately 1% relative to the control, whereas 15 g/kg provided no further improvement, confirming the plateau observed in FCR.

Logistic growth modelling

Logistic growth models were fitted to time-weight data for each diet (Table 2). The asymptotic weight parameter (K) was lowest in the control group (184 g) and higher in ginger-supplemented treatments (232–247 g), suggesting greater growth potential with ginger inclusion. The intrinsic growth rate coefficient (r) was highest for the 10 g/kg diet (0.050 day^{-1}) and lowest for 15 g/kg (0.045 day^{-1}), with the control and 5 g/kg diets intermediate (0.048–0.049 day^{-1}). Based on these parameters, fish fed 10 g/kg ginger were estimated to reach 200 g in about 84 days, whereas those fed 5 or 15 g/kg were estimated to approach 200 g in 92–95 days. Under the model, the control group (K= 184 g) was not expected to reach 200 g within the same period. Consistent with these patterns, the maximum absolute growth rate (K·r/4) at the logistic inflection was greatest for 10 g/kg (3.10 g/day) and lowest for the control (2.20 g/day), with intermediate values for 5 and 15 g/kg. Overall, inclusion of ginger at 10 g/kg maximised growth rate and predicted progression to 200 g under the present culture conditions.

Table 2: Logistic growth model parameters (K, r, t_0, Time-to-Target and K·r/4) for African catfish (*Clarias gariepinus*) fed diets containing different levels of commercial ginger powder.

Diet (ginger, g/kg^{-1})	K (g)	r (per day)	t_0 (days)	Time to 200 g (days)	K·r/4 (g/day)
0	184.0	0.048	54.0	10.0	2.20
5	232.3	0.048	54.0	4.60	2.78
10	247.2	0.050	55.0	6.40	3.09
15	235.0	0.045	56.0	3.20	2.64

Economic performance and sensitivity analysis

Because feed costs normally dominate operating costs in catfish culture, economic comparisons focused on feed cost per kg gain, based on the benchmark FCR and assumed ingredient prices. Under baseline parameters (basal feed: US$1.00/kg; ginger: US$3.00/kg; farm-gate fish price: US$2.00/kg), diet costs increased slightly with ginger inclusion (US$1.00, 1.02, 1.03, and 1.05/kg feed for 0, 5, 10, and 15 g ginger/kg). Using the benchmark FCR of 1.93 for the 10 g/kg diet, feed cost per kg gain was approximately US$1.97 in the base case (Table 3). Under these assumptions, all diets were close to breakeven at the farm-gate price; however, ginger diets had a slight edge because of their lower FCR. At 5–10 g/kg, feed cost per kg gain was about 1% lower than the control. Because absolute profit margins are small in the base scenario and depend on the assumed benchmark FCR and price set, the reported profit values should be treated as illustrative rather than predictive of commercial profitability. These economics were generated by applying the relative experimental FCR differences to an assumed benchmark farm-scale FCR and should be recalculated with farm-specific FCR and local prices before decision-making.

Table 3: Sensitivity analysis of feed cost and net profit per kilogram of African catfish (*Clarias gariepinus*) fed the 10 g/kg ginger diet under changes in ginger powder and base feed prices.

Scenario	Diet (10 g/kg) cost ($ per kg feed)	Feed cost ($ per kg gain)	Profit ($ per kg fish)	Δ vs-Base
Base	1.020	1.970	0.031	–
Ginger +10 %	1.023	1.974	0.026	−0.005
Ginger +20 %	1.026	1.981	0.019	−0.012
Ginger +30 %	1.029	1.986	0.014	−0.017
Feed −10 %	0.921	1.780	0.223	+0.192

To assess how resilient this advantage might be to changing input prices, a cursory sensitivity analysis was performed for the 10 g/kg diet (Table 3, Figure 1). Increasing the assumed ginger price from US$3.00 to 3.30, 3.60, and 3.90/kg (10, 20, and 30% increases) raised the cost of the diet slightly (from US$1.020 to 1.023, 1.029, and 1.036/kg feed, respectively) and only marginally increased feed cost per kg gain (from US$1.970 to 1.974–1.986). Profit per kg fish therefore fell from US$0.031 in the base case to 0.026, 0.019, and 0.014 at ginger prices of +10, +20, and +30%, respectively. Cutting basal feed price by 10% (to US$0.90/kg) reduced the cost of the 10 g/kg diet to US$0.921/kg feed and decreased feed cost per kg gain to US$1.78, increasing profit per kg fish to about US$0.223 (Δ +0.192 vs. the base scenario). Overall, moderate movements in ginger price had little effect on diet economics, whereas changes in bulk feed price strongly affected profitability. Under these assumptions, ginger supplementation did not radically alter net profit but improved feed efficiency enough at 5–10 g/kg to be attractive where feed costs are relatively high.

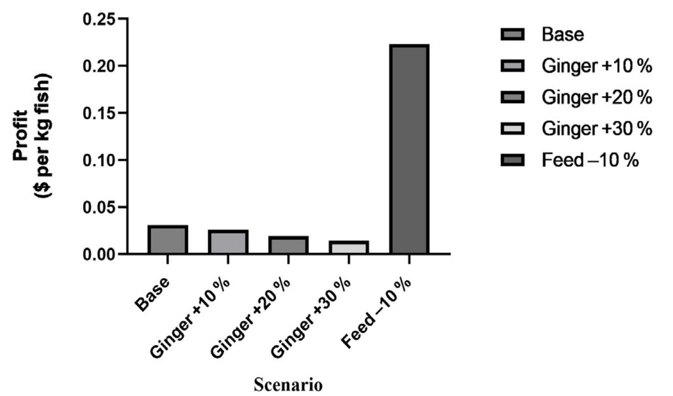

Figure 1: Net profit per kg fish under varying ginger and feed cost scenarios.

Decision-tree model for ginger inclusion

We constructed a decision tree to translate the combined growth and economic results into simple recommendations for ginger inclusion (Figure 2). The first decision node asks whether ginger use is economically reasonable at current prices. Under the baseline example and sensitivity analysis (Table 3), the 10 g/kg ginger diet was marginally profitable, and even a 20–30% increase in ginger price resulted in only small declines in profit per kg fish. In contrast, changes in bulk feed price had a far greater impact. Accordingly, the profit-based branch recommends ginger supplementation when feed is relatively expensive and the farm can maintain a small positive margin at 5–10 g/kg inclusion. As such, the tree should be interpreted as a heuristic decision aid and requires on-farm validation before it is used as a prescriptive management protocol.

Conditional on economic viability, the second tier of the tree considers fish size and growth phase and, using logistic parameters (Table 2) and size-class performance, recommends doses. For small fish (<50 g) or cohorts growing below the expected curve, the tree recommends starting at 5 g/kg to encourage a growth flush at limited extra cost. For fish in the main growth window (approximately 50–150 g, near the logistic inflection where $K \cdot r/4$ is maximal), the recommended dose is 10 g/kg, because this treatment produced the highest K and r values and the shortest time-to-target 200 g.

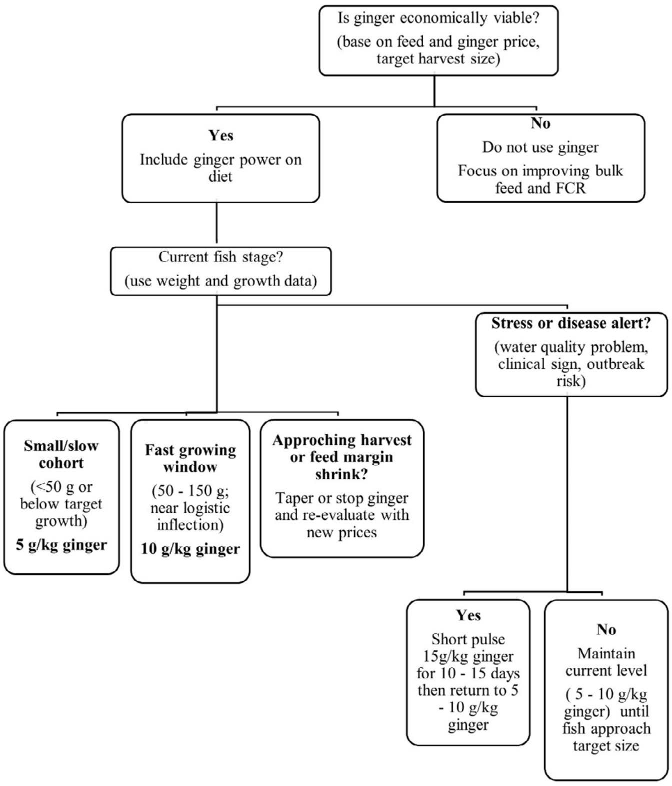

Figure 2: Decision-tree flowchart for selecting ginger powder inclusion levels based on fish growth stage and economic criteria.

A further tier incorporates health and stress alerts. If water quality declines or disease risk rises (e.g., clinical signs or recent active disease), the model allows a short pulse of 15 g/kg ginger for 10–15 days before returning to 5–10 g/kg once conditions stabilise. In the absence of alerts, the current dose (5 or 10 g/kg) is maintained until fish approach harvest size or market prices reduce margins. As fish near the asymptote (K) and growth naturally slows, the tree advises tapering or stopping supplementation to avoid wastage. By connecting the empirical growth response (Table 1), the logistic growth parameters (Table 2), and the partial budget analysis (Table 3), the decision tree translates experimental results into heuristic, farm-level guidance on whether to use ginger, how much, and for how long within a production cycle.

DISCUSSION

Studies on the use of phytogenic additives, like ginger (*Zingiber officinale*) in aquaculture feed, have shown positive effects on the digestive processes of fish, due to the enhancement of their immune response, and a broad range of other benefits, including oxidative stress reduction (Wei *et al*., 2023). In the African catfish, the addition of 2-3% ginger leaf powder to the diet resulted in an increase in the activities of amylase, lipase and protease enzymes as well as a significant increase in feed conversion efficiency and weight gain (Hassan *et al*., 2025). Across other cultured species, comparable improvements in digestive enzyme activity and nutrient utilisation have been attributed not only to secretory stimulation but also to gut morphological changes that increase absorptive surface area, supporting enhanced growth efficiency (Wei *et al*., 2023, 2025).

Our findings are consistent with this literature and therefore do not conflict with prior studies. Under the present conditions, ginger at low inclusion rates (0.5–1.0% of diet; 5–10 g/kg) improved growth performance (final weight, weight gain and specific growth rate) and reduced FCR relative to the control, while survival did not differ among treatments. A lack of survival differences is plausible where baseline mortality is low, and husbandry conditions are controlled. More broadly speaking, the evidence from various catfish systems reveals that few relatively small changes in feed inputs can lead to substantial increases in productive performance. For instance, the use of prepared diets made from locally available raw materials instead of live fish or commercially manufactured feeds increased both growth rates and intestinal enzyme activity in the larvae of Asian stinging catfish (*Heteropneustes fossilis*) and did not cause any adverse effects on survival rates (Khanom *et al*., 2022).

A similar dose–response relationship to the current trial has been shown in striped catfish (*Pangasianodon hypophthalmus*) raised in a more natural environment, as the response was enhanced at the lowest – moderate concentrations of ginger but had a plateau effect at the highest (Ashry *et al*., 2023). In our study, the lesser marginal increase in benefit at the 15 g/kg inclusion may be caused by the saturation of the bioactive effects, for example, maximum stimulation of both the digestive secretion and antioxidant pathway, as well as practical barriers such as palatability, ingestion regulation, or redistribution of nutrients resource use at the higher inclusion ranges. It is typical with most phytogenic compounds to see a plateau of this nature because a lower, intermediate rate of inclusion can be sufficient for capturing most of the biological effects.

The most plausible mechanisms for improved feed utilisation are enhanced digestive performance and improved regulation of oxidative stress. Gingerols and related phenolic compounds have been reported to stimulate digestive secretory activity and digestive enzyme activity, while also supporting antioxidant responses that can mitigate oxidative damage under culture stressors (Wei *et al*., 2023, 2025). Through enhanced digestion and nutrient absorption, improved utilisation allows more efficient conversion of feed into weight gain. This interpretation is consistent with the pattern observed here, where changes in feed intake were small compared with the improvement in FCR, suggesting that ginger primarily improved utilisation efficiency rather than simply increasing appetite.

Beyond growth and FCR, ginger is frequently discussed as an immunomodulatory additive. According to Wei *et al*. (2025), the use of plant-derived feed additives such as ginger has been shown to boost the non-specific immune response and improve susceptibility to disease in aquaculture species. Hassan *et al*. (2025) found that using intermediate levels of dietary ginger in African catfish produced greater post-challenge survival when challenged with bacterial infections. In addition, ginger fed to African catfish increased the levels of antioxidant enzymes such as catalase, glutathione peroxidase and superoxide dismutase. Although the present study did not include a pathogen challenge, the absence of negative effects on survival at up to 15 g/kg and the documented immunostimulant potential support further work that integrates growth optimisation with health-risk management. There is also evidence indicating that the use of plant-based materials can decrease dependence upon chemical products typically employed in aquaculture. Evidence of this practice includes the use of bath applications of leaf extracts from *Ocimum gratissimum* to control *Ichthyophthirius multifiliis* when applied to *Clarias gariepinus*. Those treated with these extracts exhibited a significant reduction in parasite intensity and produced less harm to the environment than those treated with chloramphenicol (Ohanu *et al*., 2024).

However, one of the major economic constraints for the widespread utilization of plant-based products in commercial aquaculture is related to the costs of using the higher recommended rates of phyto extract. We therefore concentrated on lower inclusion levels (≤1.5%) and observed that 0.5–1.0% ginger powder improved growth and, under the assumed price structure, produced small increases in profit per kg fish. Supportively, intermediate inclusion rates typically strike an equal balance of biological advantage and additive expense (Wei *et al*., 2023, 2024); likewise, comparable middle-range targets for some herbal supplement types, for example turmeric and kaffir lime leaf which over 2-3% improved growth, digestive enzyme activity and blood parameters in African catfish (Wei *et al*., 2023, 2024). It should also be noted that nutritional additives may work in concert with other cost/risk reduction methods; for example, altering carbon sources and C:N ratios are associated with improved growth and antioxidant enzyme activity of juvenile *C. gariepinus* during short production cycles (Ikele *et al*, 2022). Given that absolute profit margins under the base scenario are small, the economic analysis should be read as illustrative and context-dependent rather than as a forecast of farm profitability. Readers should re-parameterise the calculations using local feed prices, ginger costs, market prices and farm-level performance.

Contextual interpretation is critical when assessing economic performance and feed conversion ratio (FCR). The absolute FCR observed in this trial was substantially elevated, likely because feeding was less controlled in scaled research cages; therefore, these values do not reflect FCRs typically achieved in commercial production. The most informative outcome is the relative effect size: ginger diets required approximately 0.8–1.1% less feed per unit gain than the control over 90 days. Because feed is typically the dominant variable cost, even small relative improvements can be consequential, particularly when combined with concurrent efficiencies in feed management, water quality, or stocking strategy. Accordingly, we present the economic analysis as illustrative and context-dependent and caution against direct extrapolation of experimental FCRs to commercial-scale systems. The benchmark-FCR approach is used to demonstrate how relative changes may translate into farm outcomes under different price scenarios; in practice, absolute profit margins remain sensitive to bulk feed cost, whereas the direction of biological response is likely to be more robust across moderate price variation.

The decision-tree framework developed here is intended to make these trade-offs more transparent to farmers as a heuristic decision aid rather than as a validated management protocol. Rather than presenting only mean treatment effects, the tree situates ginger use within conditional 'if and then' rules linked to fish size, growth trajectory and prevailing prices, and it includes an option for short, higher dose pulses during periods of stress where immunostimulatory effects may be valuable. However, because the framework is derived from a single trial and simplified partial budget scenarios, on-farm validation and local calibration of cost inputs are needed before it can be used prescriptively. This approach is consistent with previous uses of growth models in decision support for catfish and other species, including profitability calculators and climate-adaptation tools (Ansah and Frimpong, 2015; Mbokane and Moyo, 2022). A practical next step is prospective testing in commercial operations to confirm decision thresholds and to refine the model for regional feeds, management and market conditions. Accordingly, the decision tree should be used as a heuristic decision-support tool; prospective on-farm validation and local calibration are required before it can be treated as a standard management protocol.

Finally, environmental interpretation should be treated cautiously. The feed-related CO_2e estimates used here provide a relative comparison among diets via differences in feed use rather than a full life cycle assessment. Upstream emissions associated with ginger processing were assumed negligible at the low inclusion rates tested, and values should not be interpreted as cradle-to-gate footprints. Nevertheless, because feed production is typically a major contributor to aquaculture greenhouse-gas emissions, the observed improvement in feed conversion implies a directional reduction in feed-associated emissions intensity per unit of fish produced. Relative trends from feeding trials can therefore inform decision-making, provided readers recognise the limits of transferring absolute values from experimental systems to commercial farms. A full cradle-to-farm-gate LCA would be needed to quantify absolute footprints, including upstream emissions from ginger cultivation, drying, milling, and transport.

CONCLUSION

This 90-day pond-cage trial indicates that supplementing juvenile African catfish diets with commercial ginger powder at 5–10 g/kg can improve growth performance and slightly improve feed utilisation without affecting survival. Among the tested levels, 10 g/kg produced the strongest growth response and, in logistic modelling, the shortest predicted time to reach 200 g under the present conditions. Because feed-related CO_2e intensity was estimated directly from FCR, the modest improvement in feed conversion translated into a small relative reduction in feed-related CO_2e intensity; this metric should not be interpreted as a complete life-cycle assessment. The partial-budget economics suggested only marginal gains in net profit under the base scenario, emphasising that economic outcomes are context-dependent and should be recalculated using farm-specific prices and performance. Accordingly, the proposed decision tree is presented as a transparent heuristic framework rather than a validated management protocol, and it requires on-farm validation and local recalibration before prescriptive use in commercial systems.

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NOVELTY STATEMENT

This research is different from standard phytogenic feeding trials because it interrelates graded dietary ginger supplementation (0 to 15g/kg) with a comparison of the green-house gas (CO2e) intensity of feed relative to each level of ginger supplementation, and a partial budget economic assessment based on a hypothetical commercial feed conversion ratio (FCR), thus translating biological results to meaningful outcomes for management. Additionally, this research provides additional decision support by using logistic growth modelling and integrating the biological and economic data into an easy to understand decision logic model for common adjustments to ginger level throughout the entire production cycle.

AUTHOR'S CONTRIBUTION

W.K.: Conceptualization, data curation, formal analysis, investigation, methodology, supervision, project administration, and funding acquisition. A.A., W.P. and W.W.: Formal analysis and investigation. N.K.: Formal analysis and validation N.C.: Formal analysis, investigation and validation. K.M.: Software, validation, writing – original draft, and writing – review & editing. All authors read and approved the final manuscript.

Generative AI and AI-assisted technology statement

AI-assisted tools were used only for language and grammar editing.

Conflict of interest

The authors declare that they have no competing interests. The findings of this study are consistent with the existing literature and do not conflict with the research reported by other authors.

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