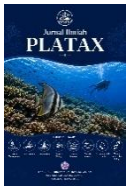
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Prioritas Strategi Pengembangan Budidaya Ikan Nila (*Oreochromis niloticus*) Semi-Intensif di Kawasan Pertambangan Berbasis AHP, Kabupaten Halmahera Tengah

AHP-Based Prioritisation of Development Strategies for Semi-Intensive Nile Tilapia (*Oreochromis niloticus*) Farming in a Mining-Affected Area, Central Halmahera Regency

Running title: AHP Strategy Priorities for Tilapia in Halmahera Tengah

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Abstract

Nile tilapia (*Oreochromis niloticus*) farming is a growing livelihood in Central Halmahera Regency, where nickel mining raises fish demand but may also threaten shared water resources. Choosing among development strategies requires weighing economic, technical, environmental, and institutional considerations, yet such multi-criteria priorities have rarely been quantified for mining-affected smallholder farms. This study aimed to prioritise development strategies for semi-intensive tilapia farming and to test how robust the ranking is to changes in criteria weights. From January to April 2026, 40 purposively selected farmers in the Weda Tengah and Weda Selatan sub-districts and ten experts were surveyed. Eighteen strategy alternatives, derived from a strengths–weaknesses–opportunities–threats analysis reported elsewhere, were grouped into four operational strategies and ranked with the Analytic Hierarchy Process (AHP) under four criteria. Production improvement ranked first under every criterion and overall (global weight 0.532), followed by institutional strengthening (0.231), water-quality management (0.160), and production cost efficiency (0.077); consistency ratios were below 0.10. In recalculated weight scenarios, production improvement stayed first, and the second rank changed only when the environmental criterion exceeded about 66% of the total weight. Simulating 80% survival and a feed conversion ratio of 1.30 raised annual profit by 114.2% and net present value by 147.1% above a feasible but thin baseline (revenue–cost ratio 1.07). The priorities reflect expert judgement and rest on assumed technical targets; scale expansion was not evaluated.

Keywords: analytic hierarchy process; development strategy; mining area; Nile tilapia; sensitivity analysis

Abstrak

Budidaya ikan nila (*Oreochromis niloticus*) merupakan mata pencaharian yang berkembang di Kabupaten Halmahera Tengah, tempat pertambangan nikel meningkatkan permintaan ikan tetapi juga berpotensi mengancam sumber daya air bersama. Pemilihan strategi pengembangan menuntut pertimbangan aspek ekonomi, teknis, lingkungan, dan kelembagaan, namun prioritas multikriteria seperti itu jarang dikuantifikasi pada usaha pembudidaya kecil di wilayah terdampak pertambangan. Penelitian ini bertujuan memprioritaskan strategi pengembangan budidaya ikan nila semi-intensif dan menguji kekokohan peringkat terhadap perubahan bobot kriteria. Pada Januari–April 2026, sebanyak 40 pembudidaya terpilih secara purposif di Kecamatan Weda Tengah dan Weda Selatan serta sepuluh pakar disurvei. Delapan belas alternatif strategi, yang diturunkan dari analisis *strengths–weaknesses–opportunities–threats* yang dilaporkan di tempat lain, dikelompokkan menjadi empat strategi operasional dan diberi peringkat dengan *Analytic Hierarchy Process* (AHP) pada empat kriteria. Peningkatan produksi menempati peringkat pertama pada setiap kriteria dan secara keseluruhan (bobot global 0,532), diikuti penguatan kelembagaan (0,231), pengelolaan kualitas air (0,160), dan efisiensi biaya produksi (0,077); rasio konsistensi di bawah 0,10. Pada skenario bobot hasil perhitungan ulang, peningkatan produksi tetap pertama, dan peringkat kedua berubah hanya ketika kriteria lingkungan melebihi sekitar 66% dari total bobot. Simulasi kelangsungan hidup 80% dan rasio konversi pakan 1,30 meningkatkan keuntungan tahunan sebesar 114,2% dan *net present value* sebesar 147,1% di atas kondisi awal yang layak tetapi bermargin tipis (rasio penerimaan–biaya 1,07). Prioritas ini mencerminkan penilaian pakar dan bertumpu pada target teknis yang diasumsikan; perluasan skala tidak dievaluasi.

Kata kunci: analisis sensitivitas; ikan nila; kawasan pertambangan; proses hierarki analitik; strategi pengembangan

1. Introduction

Aquaculture plays a strategic role in strengthening food security, raising farmer incomes, and easing pressure on capture fisheries, and remains one of the fastest-growing food-production sectors worldwide (Samy-Kamal, 2026), though its continued expansion also raises environmental-sustainability considerations that must be managed alongside productivity gains (Boyd et al., 2020). Nile tilapia (*Oreochromis niloticus*) is among the leading freshwater aquaculture species, valued for its fast growth, environmental tolerance, and broad market acceptance (El-Sayed, 2020), and continues to attract technological and economic interest as farming systems intensify across tropical developing countries

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(Arumugam et al., 2023). Because tilapia culture depends almost entirely on the continuous availability of freshwater ponds, rivers, and groundwater, any disturbance to freshwater resources could threaten both production and the livelihoods that depend on it, a concern that becomes particularly acute in regions where aquaculture must coexist with extractive industries such as mining. In Central Halmahera Regency, North Maluku Province, semi-intensive Nile tilapia farming has become increasingly important following the rapid expansion of the nickel mining industry, which has drawn an influx of migrant workers and created strong, stable demand for consumption fish.

This market opportunity, however, has not been fully realised. Earthen-pond Nile tilapia farming in the regency continues to face limited adoption of improved cultivation practices, dependence on external seed supply, restricted access to capital, and weak farmer institutions, which participatory capacity-strengthening programmes for fish-farmer groups elsewhere in Indonesia have been shown to help address (Sunarti et al., 2025), while mining activity itself may reduce the availability and quality of shared water resources, a pattern already documented in the Halmahera region, where nickel mining was found to disturb nearshore fishing grounds in East Halmahera (Sarianto et al., 2016), as well as in a mining-affected river basin in Brazil (Marques et al., 2022). Elsewhere, participation in farmer groups and targeted aquaculture development programmes has been shown to raise smallholder tilapia productivity and returns substantially, underscoring the potential value of institutional strengthening as a development lever rather than a purely organisational goal (Gichuki et al., 2024). Previous studies have examined the financial feasibility of tilapia farming enterprises (Burad-Méndez et al., 2023; Hidayat et al., 2025) and SWOT-based strategy formulation, including a recent analysis combining strengths–weaknesses–opportunities–threats (SWOT), Internal Factor Evaluation (IFE), and the Quantitative Strategic Planning Matrix (QSPM) for a medium-scale tilapia agribusiness in West Java (Faturokhman et al., 2026), largely as separate exercises, but relatively few studies have used multi-criteria decision analysis to prioritise among such strategies within a single, mining-affected setting.

A companion article on the same farmer sample reported the baseline technical and financial performance of the farms and the strengths–weaknesses–opportunities–threats (SWOT) and TOWS analysis that produced the strategy alternatives (Iriyanto et al., 2026). The present article uses those results only as inputs and asks a different question: which strategy should be prioritised, under which criteria, and how stable is that ranking? It applies the Analytic Hierarchy Process (AHP) with four criteria, tests the ranking against changes in the criteria weights, and simulates the financial effect of the top-ranked strategy. Specifically, this study aims to (1) rank four strategy alternatives for semi-intensive Nile tilapia farming in Central Halmahera Regency using AHP, (2) test the robustness of the ranking to changes in criteria weights, and (3) estimate the financial effect of implementing the priority strategy relative to the baseline.

2. Materials and Methods

2.1. Study period and location

This study was conducted from January to April 2026 in the Weda Tengah (approximately 0°28′–0°32′N, 127°50′–127°57′E) and Weda Selatan (approximately 0°08′–0°14′N, 127°52′–127°55′E) sub-districts, Central Halmahera Regency, North Maluku Province, the areas with the highest concentration of semi-intensive Nile tilapia farmer groups in the regency and directly adjacent to the nickel mining industrial area. The semi-intensive system practised in these sub-districts uses earthen ponds that rely mainly on natural pond productivity from local water sources, supplemented by commercial pelleted feed; farmers generally source fingerlings externally rather than from local hatcheries and rear the fish for a 4–6-month culture period (typically five months, with two harvest cycles per year) before harvest. This applied, descriptive-analytical study (Creswell & Creswell, 2018) drew its population from all active semi-intensive Nile tilapia farming households in the two sub-districts (76 households), from which 40 respondents were purposively selected based on meeting all of the following criteria: a minimum of two years of farming experience, application of the semi-intensive system, group membership, and a minimum pond area of 200 m^2; all eligible farmers meeting these criteria were included, up to the target of 40. Ten experts, comprising three fisheries office staff, two extension officers, two academics, and three senior farmers, were additionally selected through purposive and snowball sampling for the AHP assessment; the three senior farmers on this expert panel were selected separately from, and are not among, the 40 farmer respondents surveyed above. The farmer sample, expert panel, and survey are those of the companion article (Iriyanto et al., 2026), where sampling and data collection are described in detail.

2.2. Data collection

Primary data were collected through structured Likert-scale questionnaires and farm-level numerical data from the 40 farmers, semi-structured interviews with experts and extension officers to verify SWOT factors, and pairwise-comparison questionnaires using the Saaty 1–9 scale (Saaty, 1990) completed by the 10 experts. All respondents were adults who gave informed verbal consent before data collection (see Ethics approval and consent to participate). The same questionnaires and interviews supplied the data used in the companion article (Iriyanto et al., 2026). Secondary data were obtained from the Central Halmahera Regency Fisheries Office, the Ministry of Marine Affairs and Fisheries, and relevant published literature.

2.3. Data analysis

Respondent characteristics, technical performance (survival rate, SR, and feed conversion ratio, FCR), and the financial baseline (Revenue–Cost [R/C] Ratio, Net Present Value [NPV], Internal Rate of Return [IRR], Net Benefit–Cost [Net B/C] Ratio, and Payback Period [PP], assuming a five-year business lifespan and a 10% discount rate, with switching-value sensitivity analysis; Nurhidayati et al., 2024; Nurmalina et al., 2018) were calculated as described in the companion article (Iriyanto et al., 2026) and are used here only as inputs. Internal and external factors identified through literature review and questionnaire-based interviews were validated by an expert panel with the Content Validity Ratio, then weighted and rated by the 40 farmers in Internal Factor Analysis Summary and External Factor Analysis Summary matrices (Rangkuti, 2019). Eighteen strategy alternatives derived from the TOWS Matrix (Weihrich, 1982) were thematically clustered into four operational alternatives, a simplification adopted because AHP pairwise comparisons become progressively harder for experts to judge consistently as the number of alternatives increases.

The four alternatives were prioritised using AHP across a three-level hierarchy comprising the goal, four criteria (economic, technical, environmental, and institutional), and the alternatives (Saaty, 1990; Saaty, 2008). Ten experts completed pairwise comparisons on the Saaty 1–9 scale; their judgements were aggregated with the geometric mean (the default aggregation method of Expert Choice) and synthesised in Expert Choice software (version 11.5; Expert Choice LLC, Arlington, VA, USA). Individual judgement sets exceeding the Consistency Ratio threshold of 0.10 were returned to the respective expert for revision before aggregation.

The robustness of the ranking was examined by recalculating global priorities as the weighted sum of the per-criterion priorities (Table 2) under alternative criteria-weight scenarios: equal weights; the weight of each criterion raised by 50% with the other weights rescaled proportionally; and each criterion set to 70% with the others at 10% each. The environmental weight at which the second and third ranks would exchange was also located by raising it in steps of 0.1 percentage points while rescaling the other weights proportionally. Because the calculation uses the published, rounded per-criterion priorities, the recalculated global values may differ slightly (by up to 0.004) from those reported by Expert Choice.

Because the four-month data-collection period (January–April 2026) did not span a complete five-month grow-out cycle, technical and financial data were collected retrospectively: each farmer

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reported production, cost, and revenue figures for the most recently completed full harvest cycle together with typical annual performance, a standard approach in cross-sectional farm-household surveys (Creswell & Creswell, 2018), with respondents encouraged to refer to feed-purchase and sales records where available to reduce recall bias. The figures therefore represent respondent-reported typical performance rather than data verified against production records. The priority strategy was finally simulated against the baseline financial model by setting SR at 80% and FCR at 1.30, benchmarks for well-managed semi-intensive culture (El-Sayed, 2020), while holding stocking density, selling price, pond area, and investment constant, to compare feasibility indicators before and after implementation.

Declaration of AI use. During the preparation of this manuscript, the authors used an AI-based writing assistant (Claude, Anthropic) for manuscript drafting, language editing, reference formatting, literature searches for supplementary citations, and checking conformity with the journal template. The tool was not used to design the study, collect or analyse the research data, or interpret the results. All scientific content, data analyses (SWOT, AHP, and financial feasibility calculations), and conclusions are the sole responsibility of the authors. Every AI-suggested reference was checked by the authors against the publisher record or DOI, and the authors reviewed, verified, and edited all AI-assisted text and take full responsibility for its accuracy and integrity.

3. Results

The 40 farmers (87.5% male; 80.0% with two to three years of farming experience) operated earthen ponds averaging 662.5 m^2, with a stocking density of 13.13 fish/m^2, an SR of 75.13%, and an FCR of 1.42 (Iriyanto et al., 2026). Nile tilapia production recorded by the Central Halmahera Regency Fisheries Office rose from 62.20 tonnes in 2022 to 99.21 tonnes in 2025 (59.50%), with a decline in 2024 (from 91.44 to 87.03 tonnes). The baseline business was financially feasible (NPV Indonesian rupiah [IDR] 27,035,572; IRR 35%; Net B/C Ratio 1.71; PP 2.22 years) but had a thin margin (R/C Ratio 1.07; profit IDR 9,188,117 per year on revenue of IDR 138,450,000) and could tolerate a feed-price increase of 10.25% or a selling-price decrease of 5.15% before NPV reached zero (Iriyanto et al., 2026). The SWOT analysis placed the business in Quadrant I and the TOWS Matrix generated 18 strategy alternatives (5 SO, 5 WO, 4 ST, 4 WT), which were grouped into four operational alternatives: production improvement, institutional strengthening of fish farmer groups (Kelompok Pembudidaya Ikan, Pokdakan), water-quality management, and production cost efficiency.

The AHP hierarchy comprised a goal, four criteria, and these four alternatives (Figure 1). The synthesis of ten experts' pairwise comparisons produced criteria weights of 43.9% (economic), 21.2% (technical), 20.1% (environmental), and 14.8% (institutional), with a Consistency Ratio of 0.01 (Table 1).

The production-improvement alternative obtained the highest weight under every criterion: economic (54.0%), technical (53.1%), environmental (50.5%), and institutional (54.8%). Institutional strengthening ranked second under the economic, technical, and institutional criteria (26.6%, 21.7%, and 18.3%, respectively), whereas water-quality management ranked second under the environmental criterion (23.3%). Production cost efficiency consistently obtained the lowest weight (7.0–9.7%) (Table 2; Figure 2). All per-criterion Consistency Ratios were below 0.10 (economic 0.01; technical 0.0003; environmental 0.03; institutional 0.0005). The global synthesis ranked production improvement first (weight 0.532), followed by institutional strengthening (0.231), water-quality management (0.160), and production cost efficiency (0.077), with an Overall Inconsistency Ratio of 0.01.

Production improvement remained first in all nine recalculated weight scenarios (Table 3). Its global weight ranged from 0.515 (environmental criterion at 70%) to 0.541 (institutional criterion at 70%), and its lead over the next alternative was at least 0.27 under every single criterion (Table 2). Institutional strengthening stayed second and production cost efficiency fourth in all scenarios except one: with the environmental criterion at 70%, water-quality management (0.209) overtook institutional strengthening (0.196). In the stepwise search, the second and third ranks exchanged only when the environmental weight rose from 20.1% to about 66%.

The simulation assumed an SR of 80% (from 75.13%) and an FCR of 1.30 (from 1.42), with stocking density, selling price, and pond area held constant and no additional capital outlay. Under these assumptions, production increased by 6.5% (2,769 to 2,948 kg) and revenue by 6.5% (IDR 138,450,000 to IDR 147,424,464), whereas profit rose by 114.2% (IDR 9,188,117 to IDR 19,680,094). Of the IDR 10,491,977 increase in profit, approximately 86% (IDR 8,974,464) was attributable to the SR-driven increase in revenue and approximately 14% (IDR 1,517,512) to the FCR-driven reduction in variable (feed) cost. The NPV increased by 147.1% (IDR 27,035,572 to IDR 66,808,418), the IRR rose from 35% to 67%, the Net B/C Ratio from 1.71 to 2.75, and the PP shortened from 2.22 to 1.38 years. Post-implementation sensitivity thresholds rose to 25.99% (feed price) and 11.95% (selling price) (Table 4).

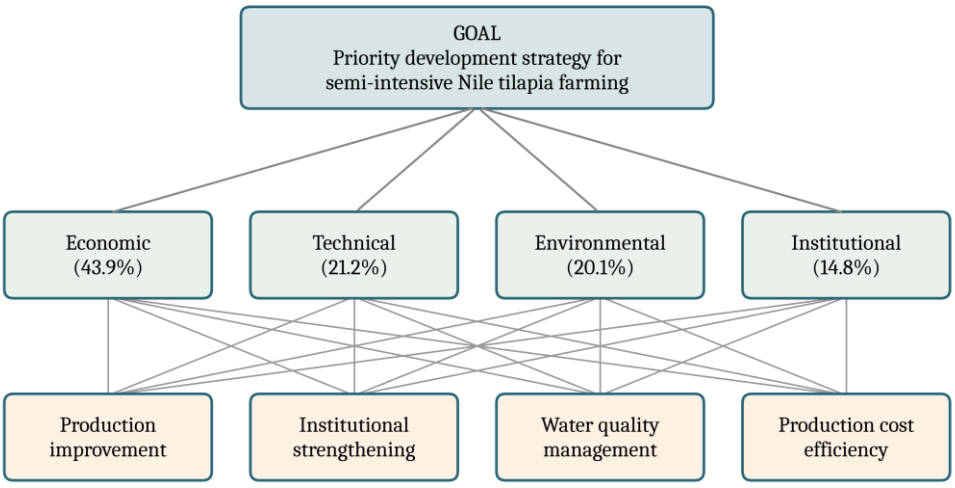


Figure 1. AHP Hierarchical Structure for Determining the Priority Development Strategy for Nile Tilapia Farming.

Table 1. Priority Weights of Nile Tilapia Farming Development Criteria

Criteria	Weight (%)	Rank
Economic	43.9	1
Technical	21.2	2
Environmental	20.1	3
Institutional	14.8	4

Note: Inconsistency Ratio = 0.01.

Table 2. Strategy Alternative Priorities by Criterion and Global Priority

Strategy alternative	Economic (%)	Technical (%)	Environmental (%)	Institutional (%)	Global (%)	Rank
Production improvement	54.0	53.1	50.5	54.8	53.2	1
Institutional strengthening of Pokdakan	26.6	21.7	18.5	18.3	23.1	2
Water quality management	12.4	16.3	23.3	17.2	16.0	3
Production cost efficiency	7.0	8.9	7.7	9.7	7.7	4

Note: Consistency Ratio per criterion: economic 0.01; technical 0.0003; environmental 0.03; institutional 0.0005; Overall Inconsistency Ratio (global) 0.01. Pokdakan = Kelompok Pembudidaya Ikan (fish farmer groups).

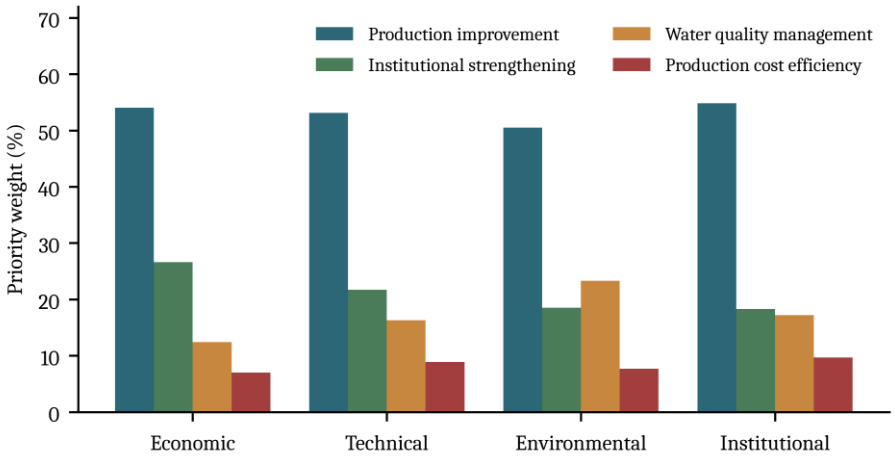


Figure 2. Strategy Alternative Priorities by Criterion.

Table 3. Sensitivity of Global Strategy Priorities to Criteria Weights

Scenario	Weights E / T / Env / I (%)	PI (%)	IS (%)	WQ (%)	CE (%)	Rank order
Reported (Expert Choice)	43.9 / 21.2 / 20.1 / 14.8	53.2	23.1	16.0	7.7	PI > IS > WQ > CE
Recalculated, reported weights	43.9 / 21.2 / 20.1 / 14.8	53.2	22.7	16.1	7.9	PI > IS > WQ > CE
Equal weights	25.0 / 25.0 / 25.0 / 25.0	53.1	21.3	17.3	8.3	PI > IS > WQ > CE
Economic weight ×1.5	54.0 / 17.4 / 16.5 / 12.1	53.4	23.4	15.5	7.8	PI > IS > WQ > CE
Technical weight ×1.5	39.7 / 28.8 / 18.2 / 13.4	53.2	22.6	16.1	8.0	PI > IS > WQ > CE
Environmental weight ×1.5	39.9 / 19.3 / 27.4 / 13.4	53.0	22.3	16.8	7.9	PI > IS > WQ > CE
Institutional weight ×1.5	40.9 / 19.7 / 18.7 / 20.7	53.3	22.4	16.2	8.1	PI > IS > WQ > CE
Economic weight 70%	70.0 / 10.0 / 10.0 / 10.0	53.6	24.5	14.4	7.5	PI > IS > WQ > CE
Technical weight 70%	10.0 / 70.0 / 10.0 / 10.0	53.1	21.5	16.7	8.7	PI > IS > WQ > CE
Environmental weight 70%	10.0 / 10.0 / 70.0 / 10.0	51.5	19.6	20.9	8.0	PI > WQ > IS > CE
Institutional weight 70%	10.0 / 10.0 / 10.0 / 70.0	54.1	19.5	17.2	9.2	PI > IS > WQ > CE

Note: Global priorities recalculated from the per-criterion priorities in Table 2 and may differ slightly from the values reported by Expert Choice. PI = production improvement; IS = institutional strengthening of Pokdakan; WQ = water quality management; CE = production cost efficiency; E = economic; T = technical; Env = environmental; I = institutional.

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Table 4. Comparison of Business Performance Before and After Implementation of the Priority Strategy

Indicator	Baseline	After strategy	Change
Production (kg)	2,769	2,948	+6.5%
Revenue (IDR)	138,450,000	147,424,464	+6.5%
Profit (IDR)	9,188,117	19,680,094	+114.2%
NPV (IDR)	27,035,572	66,808,418	+147.1%
IRR (%)	35	67	+32 points
Net B/C Ratio	1.71	2.75	+1.04 points
Payback Period (years)	2.22	1.38	0.84 years faster
Feed price switching value (%)	10.25	25.99	+15.74 points
Selling price switching value (%)	5.15	11.95	+6.80 points

Note: Simulation assumes SR = 80% and FCR = 1.30; costs of the management improvements were not included. Baseline values are from the companion article. IDR = Indonesian rupiah; NPV = net present value; IRR = internal rate of return; Net B/C = net benefit–cost; SR = survival rate; FCR = feed conversion ratio.

4. Discussion

The gap between the existing SR (75.13%) and the survival rates commonly reported for well-managed semi-intensive Nile tilapia culture, typically above 80% (El-Sayed, 2020), indicates that meaningful productivity gains remain achievable, primarily through improved survival management (water quality, disease control, and seed quality) rather than through expanding pond area, since the FCR (1.42) already falls within the range commonly reported for semi-intensive systems (1.2–1.5; Boyd & Tucker, 1998). This is consistent with the principle that feed, seed, and water-quality management are the principal technical determinants of pond aquaculture performance (Boyd & Tucker, 1998). The average stocking density (13.13 fish/m^2) also lies within the 10–20 fish/m^2 range recommended for pond culture by Boyd and Tucker (1998).

Although the existing business met all conventional investment feasibility criteria (Nurhidayati et al., 2024), its narrow margin, reflected in an R/C Ratio only slightly above unity and a production level close to the break-even point, indicates limited resilience to shocks. The markedly greater sensitivity of the business to selling-price decreases than to feed-price increases suggests that price stabilisation through marketing partnerships may be at least as important as input-cost control for safeguarding feasibility (Nurmalina et al., 2018).

The Quadrant I position suggests a generally favourable strategic environment, in which internal strengths and external opportunities outweigh weaknesses and threats, warranting a growth-oriented strategy, although the position close to the origin on the strengths–weaknesses axis indicates that this favourable balance is not strongly pronounced (Rangkuti, 2019). This finding parallels evidence from Sunarti et al. (2025), who identified institutional strengthening as central to the success of community-based catfish farming. Such strengthening may be even more relevant where farmers compete with other sectors, here nickel mining, for shared natural resources (Marques et al., 2022; Sarianto et al., 2016). The institutional dimension of this strategic advantage is further supported by evidence from Kenyan tilapia farming, where membership in common-interest groups and participation in aquaculture development programmes raised tilapia returns by over 30% and yields by 6.6%, suggesting that institutional strengthening can translate into measurable productivity gains rather than remaining a purely organisational objective (Gichuki et al., 2024). Because Kenyan smallholders operate in market and institutional settings that differ from those in Halmahera, this evidence supports, rather than directly tests, the present AHP ranking.

Integrating quantitative SWOT with AHP, as also demonstrated by Kurttila et al. (2000) in a forest-certification context, allowed the strategy alternatives derived from the TOWS Matrix to be ranked using expert judgement rather than relying on the SWOT quadrant alone. A comparable strategy formulation for a medium-scale tilapia agribusiness in West Java, which used IFE and QSPM rather than AHP to rank alternatives, likewise prioritised internal management strengthening and partnership development over simple output expansion (Faturokhman et al., 2026). Although the production-scale context differs and the present AHP did not evaluate a scale-expansion alternative against which to test this directly, the convergence between these independently derived priorities, despite differing multi-criteria techniques, offers limited external support for prioritising efficiency- and institution-oriented strategies over simple pond-area expansion in smallholder tilapia farming. The first-rank position of the production-improvement strategy under all four criteria, rather than only under the economic criterion, indicates that experts perceived this strategy as delivering balanced benefits, not merely narrow economic gain. AHP has similarly been used elsewhere in Indonesia to prioritise extension strategies for aquaculture farmers through structured expert judgement (Razi, 2016).

The sensitivity results add weight to the AHP ranking. Because production improvement led under every criterion, no re-weighting of the four criteria displaced it, so its first rank depends on the experts' alternative-level judgements rather than on how the criteria were weighted. The only reversal found, between institutional strengthening and water-quality management, would require the environmental criterion to carry about 66% of the total weight, more than three times its elicited value (20.1%), which suggests that the order of the second and third alternatives is fairly stable. The gap between them (0.231 versus 0.160) nevertheless reflects expert perception, not measured water-quality risk, which this study did not assess. The test also does not capture uncertainty in the pairwise judgements themselves, which would require individual-expert data or Monte Carlo simulation of the judgements.

The disproportionate increase in profit relative to the modest increase in production and revenue is better explained as a leverage effect of the thin baseline profit margin (profit ≈ 6.6% of revenue; R/C Ratio 1.07) than as evidence that feed efficiency outweighs output growth: most of the profit gain (about 86%) arises from the SR-driven increase in revenue, and only about 14% from the FCR-driven reduction in variable cost. Because the baseline margin is so thin, even this modest, mostly revenue-driven improvement translates into a large proportional gain in profit. This also clarifies an apparent tension with the AHP results: although the simulated FCR improvement is a technical lever associated with the production-cost-efficiency alternative, which the expert panel ranked lowest in priority, the simulation shows that the leverage this lever exerts on profit is real; the panel's low ranking may reflect the comparatively narrow scope of that alternative relative to the production-improvement alternative, which already subsumes gains in survival and feed performance, rather than a judgement that feed efficiency itself is unimportant. The post-implementation sensitivity thresholds for feed price and selling price both more than doubled relative to baseline, suggesting that efficiency-based strategies can indirectly strengthen a farm's capacity to withstand market volatility, a consideration increasingly relevant as small-scale producers become more exposed to input- and output-price fluctuations. This is consistent with the broader argument that innovation and efficiency gains are a principal way in which aquaculture responds to resource and cost pressures (Asche & Smith, 2018).

These findings may carry practical implications beyond Central Halmahera. As nickel and other critical-mineral mining expands across eastern Indonesia and similar resource frontiers worldwide, smallholder aquaculture systems adjacent to extractive industries may face a recurring tension: mining activity can simultaneously enlarge local protein markets and constrain the water resources on which that same production depends (Marques et al., 2022; Sarianto et al., 2016). The present results suggest that local governments and mining-community development programmes may wish to prioritise technical-efficiency support (improved feed management, seed quality, and pond husbandry training) alongside, rather than instead of, pond-area expansion, since even the modest, largely survival-rate-driven production gain simulated here translated into a disproportionately large financial return because of the thin baseline profit margin. At the same time, the second-rank position of institutional strengthening in the global AHP synthesis indicates that Pokdakan capacity building should not be treated as a secondary, purely social intervention; rather, it may be a necessary complement that enables farmers to adopt and sustain technical improvements, a conclusion consistent with programme evaluations elsewhere (Gichuki et al., 2024). As farmer groups in mining-affected or other resource-frontier regions come under growing pressure to meet more formalised market, governance, or certification requirements, institutional strengthening may also help them adapt to such external demands (Tran et al., 2013). For policymakers allocating corporate social responsibility or regional development funds in mining-affected fisheries and aquaculture areas, these results may support bundled interventions: simultaneous investment in farmer training, group institutions, and water-quality safeguards rather than single-lever programmes focused on production volume alone, although this study did not directly measure water quality or mining impacts and these implications should be treated as tentative.

This study has several limitations. Because the four-month data-collection period did not span a complete grow-out cycle, technical and financial figures were collected retrospectively from farmer recall rather than from prospectively monitored records, which may introduce recall bias despite efforts to encourage reference to feed-purchase and sales records. All reported technical and financial figures are averages across the 40 respondents; standard deviations, ranges, and the proportion of individual farms operating below the break-even point were not available from the data collected, so the financial feasibility conclusions, strictly speaking, apply to the average farm rather than to every individual business, and farms with below-average performance may not be profitable. Because 80.0% of respondents had only two to three years of experience, close to the two-year inclusion minimum, reflecting the relatively recent expansion of semi-intensive farming in the area, the results chiefly represent relatively new adopters. The financial analysis also relies on a single average selling price (IDR 50,000/kg); because the business was found to be more sensitive to selling-price declines than to feed-price increases, reliance on this single price assumption, rather than on the observed distribution of prices actually received by farmers, is a further source of uncertainty. Water quality and the direct physical impact of nearby mining activity on pond water resources were not measured in this study, so statements regarding mining-related water risk draw on secondary and contextual evidence rather than on-site measurement. For the AHP component, the four strategy alternatives are not fully independent (production improvement and production-cost efficiency both involve feed-related interventions), which departs from the independence assumption underlying standard AHP; in addition, consistency ratios were examined only at the aggregate and per-criterion level, not for each individual expert, and the sensitivity analysis of the criteria weights used the rounded published per-criterion priorities and did not test uncertainty in the pairwise judgements themselves. AHP priorities also rest on the subjective judgements of a small panel of ten experts. The financial impact of the priority strategy was simulated using literature-based technical targets rather than field-validated outcomes, so the projected gains should be interpreted as an upper-bound estimate pending on-farm trials. The sample was limited to 40 farmers in two sub-districts, which may constrain generalisation to other parts of the regency. In addition, the switching-value sensitivity analysis assumed all other cost and revenue parameters remained constant, so compounded shocks (for example, a simultaneous feed-price increase and selling-price decline) were not explicitly modelled and could erode the financial buffers identified here more quickly than either shock considered in isolation. The farmer sample, baseline results, and SWOT–TOWS analysis overlap with the companion article (Iriyanto et al., 2026), so the present findings are a further analysis of the same dataset rather than an independent replication. Finally, the reduction of eighteen TOWS-derived alternatives into four operational strategies, while necessary to keep the AHP pairwise comparisons manageable, involved an element of researcher judgement during thematic clustering.

5. Conclusion

Using AHP on expert judgements, production improvement was the priority development strategy for semi-intensive Nile tilapia farming among the studied farms in Central Halmahera Regency, ranking first under all four criteria (global weight 0.532), ahead of institutional strengthening (0.231), water-quality management (0.160), and production cost efficiency (0.077). No criteria-weight scenario tested displaced the first rank, and the second rank changed only when the environmental criterion dominated. Under assumed technical targets, the strategy substantially raised simulated profit and investment feasibility of a financially feasible but thin-margin baseline. Technical-efficiency improvements, supported by stronger farmer institutions and sound water management, may therefore offer a promising pathway for mining-affected smallholder tilapia farms, alongside rather than in place of scale expansion, which this study did not evaluate. The priorities reflect expert preferences, not demonstrated causal effects.

Competing interests

The authors declare no competing interests relevant to this article.

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Authors' contributions

Adi Iriyanto: Conceptualization, Investigation, Formal analysis, Writing – original draft. Muhammad Irfan: Supervision, Methodology, Writing – review & editing, Project administration. Gamal M. Samadan: Supervision, Data curation, Validation, Writing – review & editing.

Availability of data and materials

The anonymised dataset (survey responses, AHP pairwise-comparison matrices, and the financial feasibility model) supporting the findings of this study will be deposited in a public repository (e.g., Zenodo or Figshare) upon acceptance; prior to that, it is available from the corresponding author upon reasonable request.

Ethics approval and consent to participate

No live animals were used or handled in this study, and no animal experiments were conducted; the research relied solely on questionnaires and interviews. The study did not undergo review by a formal institutional ethics committee, and no ethics approval number is available. Participation was anonymous and limited to adult farmer and expert respondents, who provided informed verbal consent prior to data collection; no identifiable personal or sensitive data were collected.

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