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Towards Sustainable Aquaculture: Lessons from Gourami *(Osphronemus goramy)* Aquaculture in Indonesia Within a Global Context

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ABSTRACT

Aquaculture now supplies over half of the fish consumed worldwide, yet its rapid growth presents trade-offs in environmental stewardship, biosecurity, market efficiency, and climate resilience. This study assessed the sustainability of Indonesian gourami (*Osphronemus goramy*) aquaculture and identifies strategic interventions to improve system performance. Employing Multidimensional Scaling (MDS) integrated with the Analytical Hierarchy Process (AHP), data from 25 farms in Kemranjen, Banyumas (Central Java) were analyzed across four key dimensions—technical, economic, socio-institutional, and environmental. The resulting sustainability index of 59.69 classifies the system as "moderately sustainable," with notable heterogeneity among dimensions. Technical practices are functional yet limited by inconsistent access to quality inputs, while economic performance is constrained by inadequate capital and elongated marketing chains. The socio-institutional dimension, particularly farmer group organization, demonstrates relative strength and acts as an enabling factor. In contrast, environmental sustainability remains weakest, hindered by land conversion pressures, insufficient waste and water management, suboptimal biosecurity, and climate-related stressors. Leverage analysis identifies high-impact actions: regulating land conversion and managing carrying capacity, improving financial access, strengthening the distribution of certified inputs, digitizing marketing networks, and institutionalizing biosecurity and climate adaptation. Comparative insights from Vietnam, Bangladesh, and European recirculating aquaculture systems (RAS) highlight that targeted incremental improvements, supported by participatory governance, can yield substantial sustainability gains without imposing excessive costs. This study provides policymakers, investors, and practitioners with an empirically grounded framework and an actionable roadmap to transition Indonesian gourami aquaculture from a "moderate" toward a "high" level of sustainability.

INTRODUCTION

Aquaculture has become one of the fastest-growing food production sectors worldwide, contributing significantly to global food security and livelihoods. In 2022, aquaculture supplied more than 50% of fish for human consumption, a proportion projected to rise further as capture fisheries stagnate **(FAO, 2022)**. However, this rapid expansion also raises major sustainability concerns, including environmental degradation, biosecurity risks, market inequality, and the vulnerability of small-scale producers to climate change. For example, Vietnam's pangasius industry has been challenged by effluent discharge and biosecurity failures **(Nhu *et al.*, 2016)**, while Bangladeshi carp farming faces recurrent climate shocks and limited financial access **(Dompreh *et al.*, 2025)**. In contrast, aquaculture systems in Europe have adopted advanced technologies such as Recirculating Aquaculture Systems (RAS), which enhance productivity while reducing ecological footprints **(Mihály-Karnai *et al.*, 2025)**. These diverse cases demonstrate that the pursuit of aquaculture sustainability is a truly global concern, shaped by ecological, economic, and institutional contexts.

Against this backdrop, Indonesia plays a strategic role as one of the top aquaculture-producing nations. Within Indonesia, gourami *(Osphronemus goramy)* is a high-value freshwater species with cultural and economic significance. In Kemranjen District, Banyumas Regency, Central Java, Indonesia, gourami aquaculture reached a production of 472,063kg in 2023, contributing 11.6% of the regency's total output **(BPS, 2023)**. At an average price of IDR 50,000 per kg, this sector generated revenues exceeding IDR 23 billion, positioning gourami as a cornerstone of the local economy. Yet, this contribution is shadowed by critical challenges, including water quality degradation, aquaculture waste, inefficient feed use, and reliance on superior seed stock **(Nugraha *et al.*, 2022; Pouil *et al.*, 2024)**. Beyond its contribution to local income generation, gourami aquaculture also functions as a multiplier sector that stimulates upstream and downstream economic activities, including feed production, seed supply, transportation, and fish processing.

Despite its economic importance, most sustainability assessments of Indonesian aquaculture remain focused on technical and economic indicators, with limited attention to environmental and socio-institutional dimensions. Multidimensional approaches such as Multidimensional Scaling (MDS), complemented by the Analytical Hierarchy Process (AHP), provide powerful tools to integrate ecological, economic, social, and institutional aspects, thereby identifying leverage attributes for targeted interventions **(Garlock *et al.*, 2024; Nurhabib *et al.*, 2024)**. Previous studies across agriculture and fisheries confirm the utility of this framework in capturing complex sustainability dynamics **(Garcia *et al.*, 2014)**.

In light of these global and local challenges, a comprehensive sustainability assessment of gourami aquaculture in Kemranjen is not only essential for improving local practices but also valuable for generating lessons applicable to broader contexts. By situating Indonesian gourami farming within global sustainability debates, this study seeked to highlight shared challenges, identify leverage points, and propose strategies that align with international best practices for advancing inclusive and sustainable aquaculture.

MATERIALS AND METHODS

Literature review

1. Global growth and sustainability tensions in aquaculture

Aquaculture now supplies more than half of fish for human consumption and is central to food security, yet rapid expansion has amplified concerns over environmental externalities, biosecurity risks, market inequities, and climate vulnerability **(FAO, 2022)**. Comparative evidence shows that sustainability performance varies widely across countries and production systems, shaped by differences in ecological settings, technologies, and institutions **(Garlock *et al.*, 2024)**. These global contrasts underscore the need for context-sensitive assessments that still speak to shared leverage points.

2. Comparative lessons from Asia and Europe

In Vietnam, intensive pangasius systems highlight how certification and effluent control can alter environmental footprints, though improvements are uneven without strong enforcement and farmer capability **(Nhu *et al.*, 2016)**. In Bangladesh, smallholders face climate shocks and financing constraints that influence intensification choices and sustainability trajectories **(Dompreh *et al.*, 2025)**. By contrast, European carp systems adopting recirculating aquaculture systems (RAS) demonstrate how technology can simultaneously reduce ecological impacts and improve profitability, offering useful—but capital-intensive—benchmarks for developing regions **(Mihály-Karnai *et al.*, 2025)**.

3. Indonesian freshwater aquaculture and the case for gourami

Indonesia ranks among top aquaculture producers, with freshwater commodities supporting rural livelihoods. For gourami (*Osphronemus goramy*), recent work documents key production constraints—feed costs, variable seed quality, and waste management—while also signaling innovation avenues such as alternative feed resources **(Nugraha *et al.*, 2022; Pouil *et al.*, 2024)**. Despite economic importance, many studies remain technicist, providing limited integration of environmental and socio-institutional factors that ultimately condition adoption, compliance, and scaling of good practices.

4. Multidimensional frameworks for sustainability appraisal

Multidimensional Scaling (MDS) has been widely used to distill complex attribute spaces into interpretable indices and ordinations for fisheries and agriculture, beginning with rapfish **(Pitcher & Preikshot, 2001; Kavanagh & Pitcher, 2004)** and adapted for broader farming contexts **(Garcia *et al.*, 2014)**. When coupled with the Analytical Hierarchy Process (AHP), MDS outputs gain decision-relevance through explicit weighting and priority setting, enabling composite judgments and policy targeting **(Asro *et al.*, 2024; Aritonang *et al.*, 2025; Kustanti & Mahmudi, 2025; Neka *et al.*, 2025)**. This MDS–AHP pairing is increasingly favored where data are heterogeneous, indicators mix qualitative–quantitative inputs, and stakeholder participation is essential.

5. Environmental management: waste, biosecurity, and climate resilience

Across low-to-middle income contexts, chronic issues involve nutrient loading from effluents, suboptimal waste treatment, and weak biosecurity, all of which depress productivity and raise ecological risks **(Nhu *et al.*, 2016)**. Climate variability further compounds disease dynamics and water quality stressors, pressuring smallholders to adopt monitoring and adaptive infrastructure **(Dompreh *et al.*, 2025)**. Evidence from RAS and biofilter applications suggests that tailored, incremental upgrades—rather than wholesale technology swaps—can yield meaningful environmental gains in resource-constrained settings **(Mihály-Karnai *et al.*, 2025)**.

6. Socio-institutional and market dimensions

Institutional capacity—farmer group performance, extension effectiveness, and rule enforcement—reliably differentiates sustainability outcomes, even when biophysical conditions are similar **(Garcia *et al.*, 2014; Garlock *et al.*, 2024)**. For Indonesia, marketing frictions, access to capital, and uneven diffusion of standards (e.g., CBIB/GAP) remain binding constraints; strengthening collective action and information access can shorten chains and raise margins **(Nugraha *et al.*, 2022)**. These findings align with leverage points commonly identified in multidimensional diagnostics: finance, market access, information/extension, and organizational quality.

7. Knowledge gaps and contribution of this study

Three gaps persist in the gourami literature: (i) limited integration of environmental and socio-institutional dimensions with technical–economic metrics; (ii) scarce leverage analysis that identifies high-impact attributes for policy action; and (iii) weak linkage between local evidence and international comparators to inform transferable lessons. Addressing these, the present study applies an MDS–AHP framework to Kemranjen's gourami aquaculture, quantifies sustainability status across multiple dimensions, identifies leverage attributes, and situates findings against cross-country insights (Vietnam, Bangladesh, Europe). The aim was to furnish locally grounded yet globally relevant guidance for accelerating a just and ecologically sound transition in smallholder freshwater aquaculture.

Research location

This study was conducted at 25 gourami aquaculture sites in Kemranjen District, Banyumas Regency, Central Java (Fig. 1). Kemranjen covers an area of 62.90 km² and is one of the 27 districts in Banyumas, with an estimated population of 75,037 inhabitants **(BPS, 2024)**. The 25 sites were selected to represent variations in land conditions, cultivation techniques, and business scales. The district's geographic setting and supporting infrastructure provide a representative basis for analyzing the sustainability of gourami aquaculture in the area.

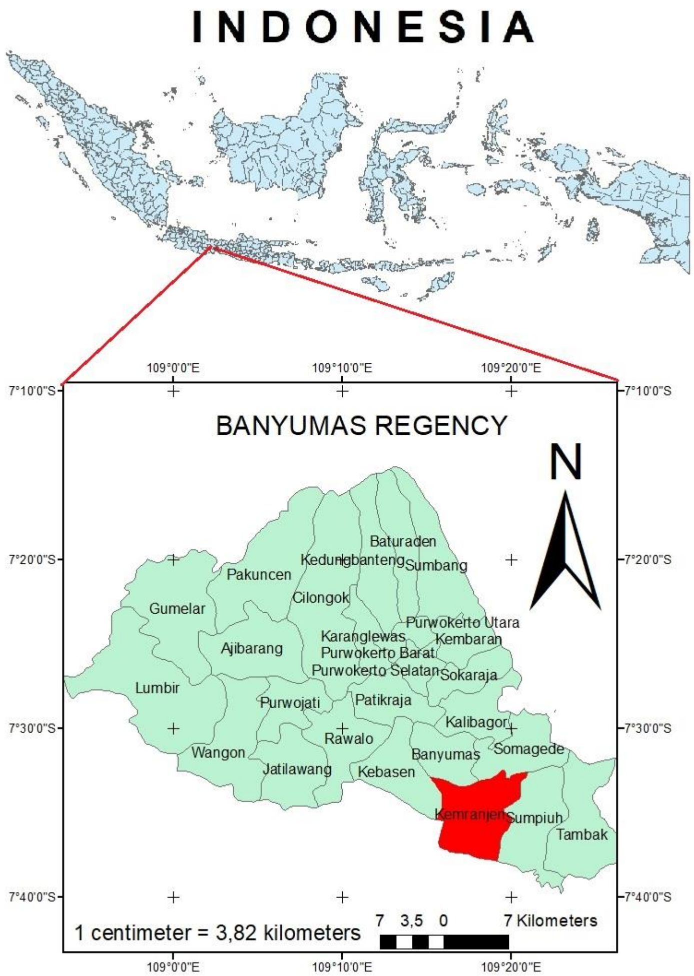

Fig. 1. Research location in Kemranjen District, Banyumas Regency, Central Java Province, Indonesia

Sampling technique and data collection

Data collection was carried out through direct field observations and the distribution of structured questionnaires as supporting instruments. Questionnaires were used to supplement information not readily captured during field observations **(Arsanti *et al.*, 2020)**. Two types of questionnaires were employed: an MDS questionnaire to collect data on sustainability dimensions and an AHP questionnaire to gather priority-setting data.

The sampling approach applied was non-probability sampling, whereby respondents were selected based on the researchers' judgment **(Christine *et al.*, 2012)**. Consequently, not all individuals in the population had an equal probability of being selected **(Sugiyono, 2016)**. Respondents for the AHP survey were aquaculture experts with educational backgrounds in fisheries and at least 10 years of professional or research experience in the field. Their expertise was assessed based on academic qualifications, work experience, and scientific publications. According to **Saaty (1993)**, the minimum number of experts required is two, with quality being more critical than quantity. For instance, **Arrington *et al.* (2015)** utilized three experts in their AHP research. In this study, AHP respondents were asked to provide pairwise comparisons of elements using a 1–9 scale, where 1 indicates equal importance and 9 indicates extreme importance **(Morgan, 2017)**.

Methods

1. Determination and assessment of sustainability attributes

Sustainability attributes and indicators were identified across five key dimensions: technical, economic, socio-institutional, and environmental. The selection process was guided by literature and expert consultation, including practitioners and academics **(Pitcher & Preikshot, 2001; Nuryadin *et al.*, 2015)**. Attributes were scored on a scale of 0–2, where 0 = poor (least favorable for sustainability), 1 = moderate, and 2 = good (most favorable for sustainability).

2. Sustainability index

The sustainability index was calculated on a scale from 0% (poor) to 100% (good). Systems with an index >50 were categorized as sustainable, while those with an index <50 were considered unsustainable. Four levels of sustainability status were defined: poor, less sustainable, moderately sustainable, and good (Table 1) **(Marzuki *et al.*, 2013; Nuryadin *et al.*, 2015)**.

Table 1. Sustainability status of aquaculture systems

Index	Category
0–25	Unsustainable
26–50	Less sustainable
51–75	Moderately sustainable
76–100	Highly sustainable

Source: **(Marzuki *et al.*, 2013; Nuryadin *et al.*, 2015)**.

3. MDS ordination

Ordination analysis was performed using the Multidimensional Scaling (MDS) technique, which employs Euclidean distance to map objects in two- or three-dimensional space **(Fauzi & Anna, 2005)**. The Euclidean distance formula is expressed as:

$$d_{ij} = \sqrt{\sum_{k=1}^{n} (xik - xjk)^2}$$

The spatial configuration of objects was obtained by regressing the Euclidean distance d_{ij} against the observed data O_{ij}.

4. Sensitivity (Leverage) analysis

Sensitivity analysis was applied to identify the most influential attributes. An attribute was considered sensitive if its removal from the model resulted in significant changes in ordination outcomes. Attribute influence was measured using the *Root Mean Square (RMS)* value, with higher RMS values indicating greater sensitivity to sustainability outcomes **(Fauzi & Anna, 2005)**.

5. Monte Carlo analysis, stress value, and coefficient of determination (R^2)

Monte Carlo analysis was conducted to evaluate errors associated with respondent judgment, scoring variability, and data entry. Results were deemed stable if the difference between Monte Carlo and MDS indices was <1 **(Kavanagh & Pitcher, 2004)**. Model reliability was tested using the *Stress* value and coefficient of determination (R^2).

The Stress value was calculated as follows **(Alder *et al.*, 2000)**:

$$S = \sqrt{\frac{\sum(d_{ij} - d^{\wedge}{}_{ij})^2}{\sum d^2{}_{ij}}}$$

A model is considered reliable when Stress <0.25 and R^2 approaches 1 (100%) **(Pitcher & Preikshot, 2001)**.

6. Multidimensional weighting

To derive a multidimensional sustainability index, weighting was applied using a modified Analytical Hierarchy Process (AHP) approach **(Budiharsono, 2014)**. Experts and stakeholders conducted pairwise comparisons among sustainability dimensions. The resulting weights were multiplied by the index of each dimension, and the sum of these values yielded the multidimensional sustainability index.

7. Formulation of policy strategies using AHP

The Analytical Hierarchy Process (AHP) is a decision-making tool designed to address complex multi-criteria problems by structuring them into hierarchical levels consisting of interrelated factors and criteria **(Saaty, 1993)**. AHP has been widely applied in diverse fields such as business, governance, and social development to establish policy priorities **(Chen *et al.*, 2023)**. In this study, AHP was employed to rank and prioritize the key policy strategies necessary for advancing sustainable aquaculture. The method involves constructing pairwise comparison matrices, where respondents assign relative importance scores. To ensure validity, the Consistency Ratio (CR) must be calculated to verify the logical consistency of the responses, with a CR value not exceeding 0.10 **(Sambah & Miura, 2014)**. The CR is derived using the following formula:

$$CR = \frac{\text{CI}}{\text{RI}}\ dan\ CI = \frac{(\lambda\text{max} - \text{N})}{(\text{N} - 1)}$$

Where, CR is the consistency ratio, CI is the consistency index, RI is the random consistency index, N is the metric comparison size and λmax is the largest eigenvalue.

RESULTS

1. Technical dimension

The sustainability analysis of the technical dimension of gourami aquaculture in Kemranjen District, Banyumas Regency, using the Multidimensional Scaling (MDS) approach yielded an average score of 54.74%, placing it in the “moderately sustainable” category (Table 2). This score indicates that, from a technical perspective, gourami aquaculture in the area has a reasonably solid foundation, although several aspects still require improvement.

To test the stability and accuracy of the MDS results, Monte Carlo analysis was conducted. The simulation produced an average score of 51.61%, which is slightly lower than the MDS results. The difference between the two methods was –3.13%, suggesting that the variation remains within an acceptable range. This implies that the results are relatively stable and suitable for use as a decision-making reference.

Table 2. Sustainability scores for the technical dimension

Respondent	MDS Analysis (%)	Monte Carlo Analysis (%)	Difference (%)
SR	16.44	54.11	37.67
MVR	51.54	52.72	1.18
IM	51.54	50.90	0.64
SP	51.88	53.18	1.30
NA	53.13	53.22	0.09
TF	58.56	52.52	6.04
HT	56.82	51.67	5.16
SH	59.10	51.65	7.45
BS	59.59	52.81	6.78
SK	47.33	52.69	5.36
AS	71.03	53.36	17.67
MM	49.03	52.19	3.16
SP	53.36	52.33	1.02
SK	45.46	51.26	5.79
SD	61.99	50.90	11.09
BD	60.48	51.54	8.94
ISB	60.48	50.14	10.34

RI	68.04	52.98	15.06
ISSR	71.94	50.44	21.50
ST	53.61	51.53	2.08
SDK	81.68	52.59	29.08
ASTR	71.83	51.12	20.71
AR	25.07	52.57	27.50
WT	71.70	51.78	19.92
MMA	54.79	51.95	2.84
Average	**56.26**	**52.09**	**4.17**

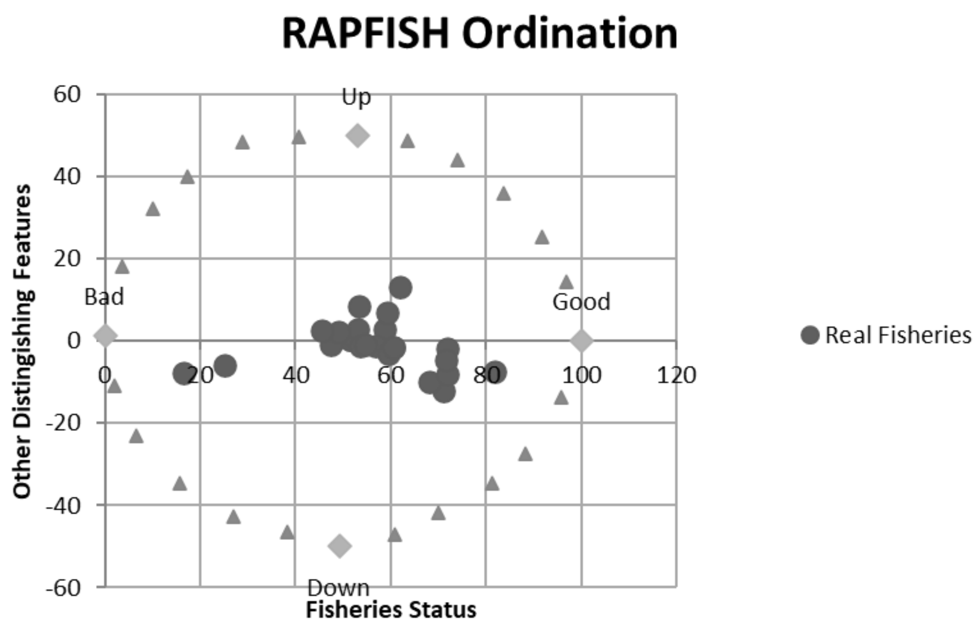

Fig. 2. Distribution of sustainability scores for the technical dimension

Notably, several attributes or respondents exhibited large discrepancies between MDS and Monte Carlo scores, such as SR with a difference of 35.46%, and attributes such as SDK, ASTR, ISSR, and WT, all of which showed substantial variations (Fig. 2). These discrepancies suggest inconsistencies in respondent perceptions or uncertainties in technical data related to those attributes. Such inconsistencies may arise from limited field information or differing technical understandings among aquaculture practitioners. Conversely, most attributes showed relatively small differences (<10%), suggesting that respondent perceptions were fairly consistent and that the technical data collected were sufficiently reliable.

Overall, these findings indicate that the technical aspects of gourami aquaculture in Kemranjen are moderately stable and supportive of sustainability. However, improvements are still required in attributes with large discrepancies, including enhancing data quality, improving farmers' technical knowledge, and conducting continuous monitoring of field conditions. Such efforts will help ensure that the sustainability of gourami aquaculture in the region can be optimized over the long term.

Based on the leverage analysis of the technical dimension, not all attributes contributed equally to improving sustainability status (Fig. 3). The attribute with the highest leverage value was the availability and accessibility of production inputs. This finding underscores that improving access to equipment, raw materials, and other essential aquaculture inputs would have the most significant impact on technical sustainability. In addition, feed quality and the availability of frequently used certified seed also showed high leverage values, highlighting their critical role in enhancing productivity and technical efficiency.

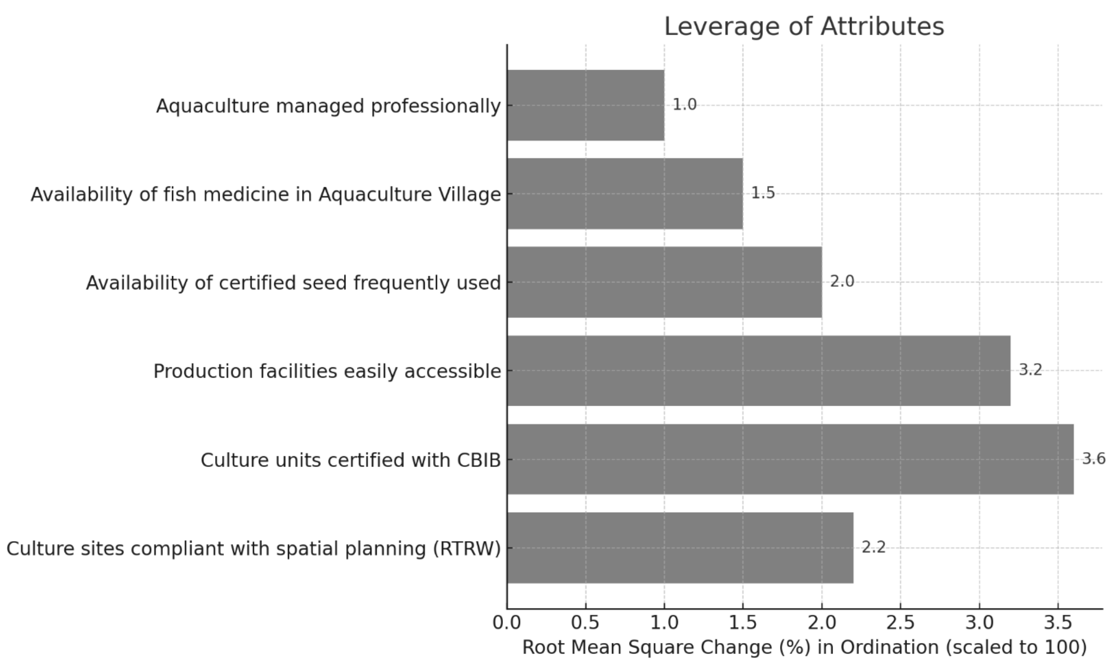

Fig. 3. Leverage values of technical attributes in the sustainability assessment of gourami aquaculture in Kemranjen District

2. Economic dimension

Based on the MDS analysis, the average sustainability index for the economic dimension of gourami aquaculture in Kemranjen District was 45.87%, which falls into the "less sustainable" category (Table 3). This indicates that, economically, gourami aquaculture has not yet fully achieved sustainability, as several challenges remain in marketing, income generation, and product competitiveness. To test the stability of these results, Monte Carlo simulation was performed, yielding an average score of 55.13%, which is higher than the MDS outcome. This suggests that when accounting for uncertainty and data variability, the economic dimension of gourami aquaculture can actually be classified as "moderately sustainable."

Table 3. Sustainability scores for the economic dimension

Respondent	MDS Analysis (%)	Monte Carlo Analysis (%)	Difference (%)
SR	24.84	43.04	18.19
MVR	42.21	42.58	0.38
IM	69.45	43.68	25.76
SP	43.06	44.50	1.45
NA	47.01	44.04	2.97
TF	39.96	42.96	3.00
HT	46.60	40.01	6.59
SH	45.35	41.33	4.02
BS	59.95	43.26	16.68
SK	47.13	42.56	4.58
AS	55.94	40.54	15.41
MM	33.05	42.99	9.94
SP	27.97	39.90	11.92
SK	22.74	43.27	20.53
SD	51.39	42.22	9.17
BD	48.78	42.90	5.88
ISB	48.78	43.62	5.17
RI	57.71	43.72	13.99
ISSR	47.18	43.03	4.15
ST	49.15	43.88	5.28
SDK	44.46	42.66	1.81
ASTR	45.33	42.49	2.85
AR	38.47	41.13	2.66
WT	64.64	43.80	20.84
MMA	49.22	40.33	8.89
Average	**46.02**	**42.58**	**3.44**

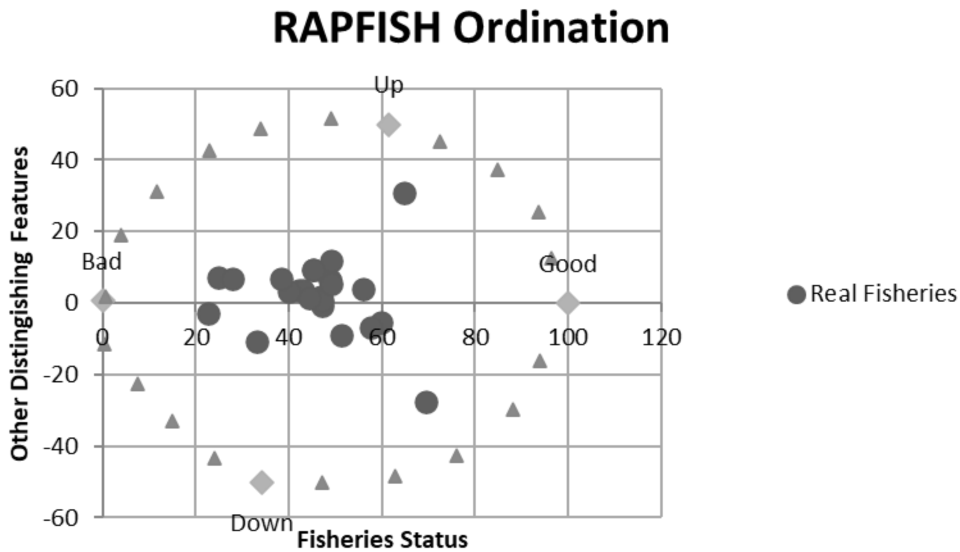

Fig. 4. Distribution of sustainability scores for the economic dimension

The difference between the two analytical methods averaged 9.26%, reflecting notable variations in perceptions or actual economic conditions in the field. Some attributes or respondents showed particularly large discrepancies, such as SR (31.45%), SK (33.08%), and SP (27.62%). These gaps indicate inconsistencies in respondent perceptions or fluctuations in economic performance across certain aquaculture units (Fig. 4). Conversely, some attributes displayed very small differences, such as AS with only –0.94%, suggesting that the data and perceptions related to this attribute were relatively stable and reliable.

Overall, most respondents demonstrated higher Monte Carlo scores compared with MDS, implying that the economic potential of gourami aquaculture could be enhanced through improvements in business management, market access, and the use of technology.

The leverage analysis of the economic dimension further revealed that attributes contributed unequally to changes in economic sustainability status (Fig. 5). The attributes with the highest leverage were: (i) ease of access to business capital, (ii) utilization of digital platforms for marketing, and (iii) the length of the marketing chain. These three factors exert the strongest influence on economic sustainability, and their improvement should be considered a top priority.

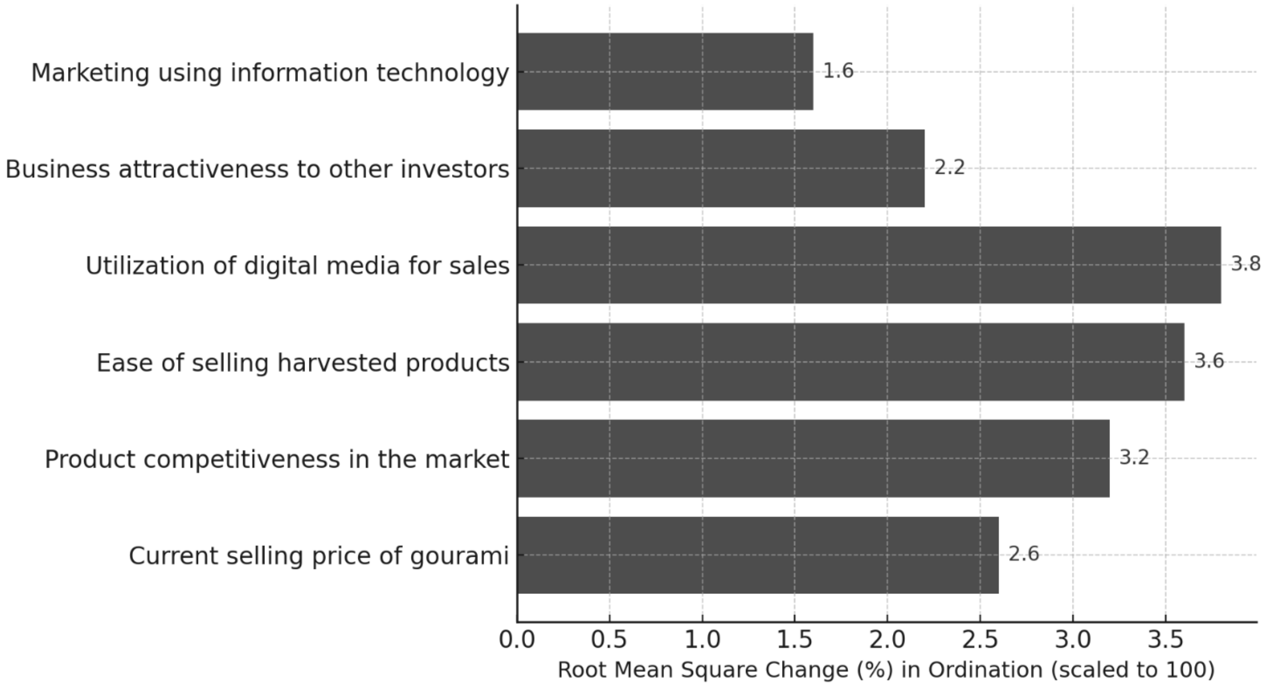

Fig. 5. Leverage values of economic attributes in the sustainability assessment of gourami aquaculture

3. Social-institutional dimension

The social-institutional dimension is one of the key pillars supporting the sustainability of gourami aquaculture. The Multidimensional Scaling (MDS) analysis revealed an average sustainability index score of 57.64% for this dimension, placing it in the "moderately sustainable" category (Table 4). This indicates that community participation, the role of farmer groups, collaboration among business stakeholders, and government support are functioning adequately, although there remain challenges in several social-institutional aspects that need strengthening.

To test the stability of these results, a Monte Carlo simulation was conducted, yielding an average score of 74.71%, which falls into the "sustainable" category. This suggests that, accounting for uncertainty and variability in field data, the social-institutional sustainability potential of gourami aquaculture in this area is relatively strong and stable.

The average difference between the MDS and Monte Carlo results was 17.06%, indicating variability in respondent perceptions or inconsistencies in how social-institutional aspects are viewed. Some respondents showed significant score differences, such as SR with a 44.23% gap, SK with 32.00%, and AS with 33.35% (Fig. 6). These large discrepancies suggest inconsistent perceptions or unequal social and institutional experiences in the field, particularly concerning community participation, institutional support, and access to information and assistance.

In contrast, several respondents displayed minimal differences between the MDS and Monte Carlo results, such as SD with only a –1.62% difference, and IM and MMA with differences below 5%. This indicates that in certain business units or community groups, social-institutional aspects are functioning well, stable, and experienced equitably.

Table 4. Sustainability scores for the social-institutional dimension

Respondent	MDS Analysis (%)	Monte Carlo Analysis (%)	Difference (%)
SR	29.16	55.07	25.92
MVR	55.73	54.06	1.67
IM	76.38	53.57	22.81
SP	52.40	53.32	0.92
NA	58.20	52.10	6.10
TF	58.68	54.82	3.86
HT	56.29	55.91	0.39
SH	68.75	54.53	14.22
BS	61.98	53.40	8.58
SK	46.94	53.10	6.16
AS	43.36	53.52	10.16
MM	59.55	53.10	6.46
SP	59.04	53.33	5.71
SK	44.53	54.57	10.04
SD	73.47	52.30	21.17
BD	61.09	54.74	6.35
ISB	61.09	54.09	7.00
RI	52.85	53.73	0.87
ISSR	68.77	55.25	13.52
ST	68.13	54.22	13.90
SDK	61.10	53.59	7.50
ASTR	61.10	54.80	6.30
AR	51.02	51.90	0.88
WT	54.27	53.10	1.17
MMA	68.79	53.53	15.26
Average	**58.11**	**53.83**	**4.28**

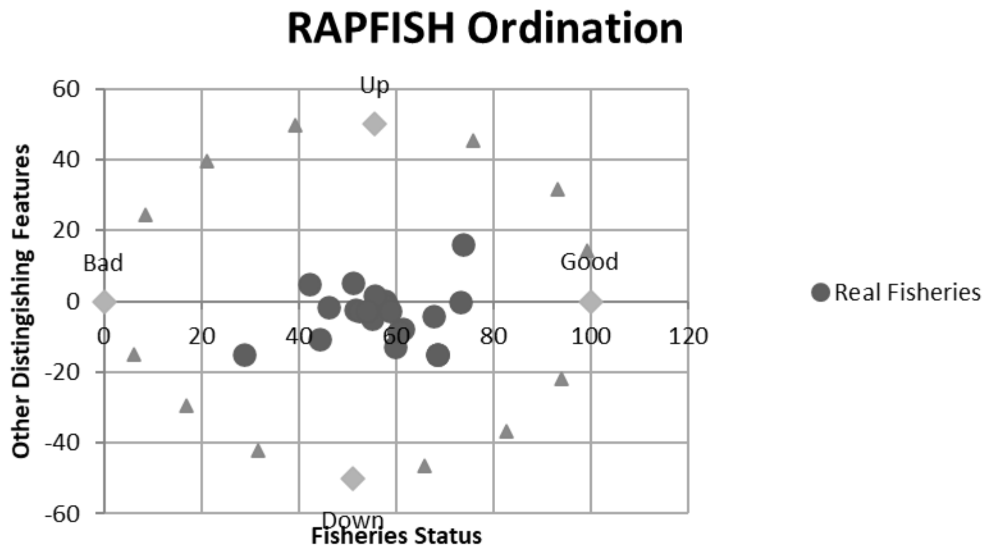

Fig. 6. Distribution of sustainability scores for the social-institutional dimension

Based on the leverage attribute graph for the social-institutional dimension of gourami aquaculture in Kemranjen District, it is evident that each attribute has a varying degree of influence on enhancing social-institutional sustainability (Fig. 7). The attribute with the highest leverage value is the important role of farmer groups in aquaculture activities. This indicates that strengthening the institutional capacity of farmer groups has a significant impact on the social and institutional sustainability of gourami aquaculture, making it a key area for improvement.

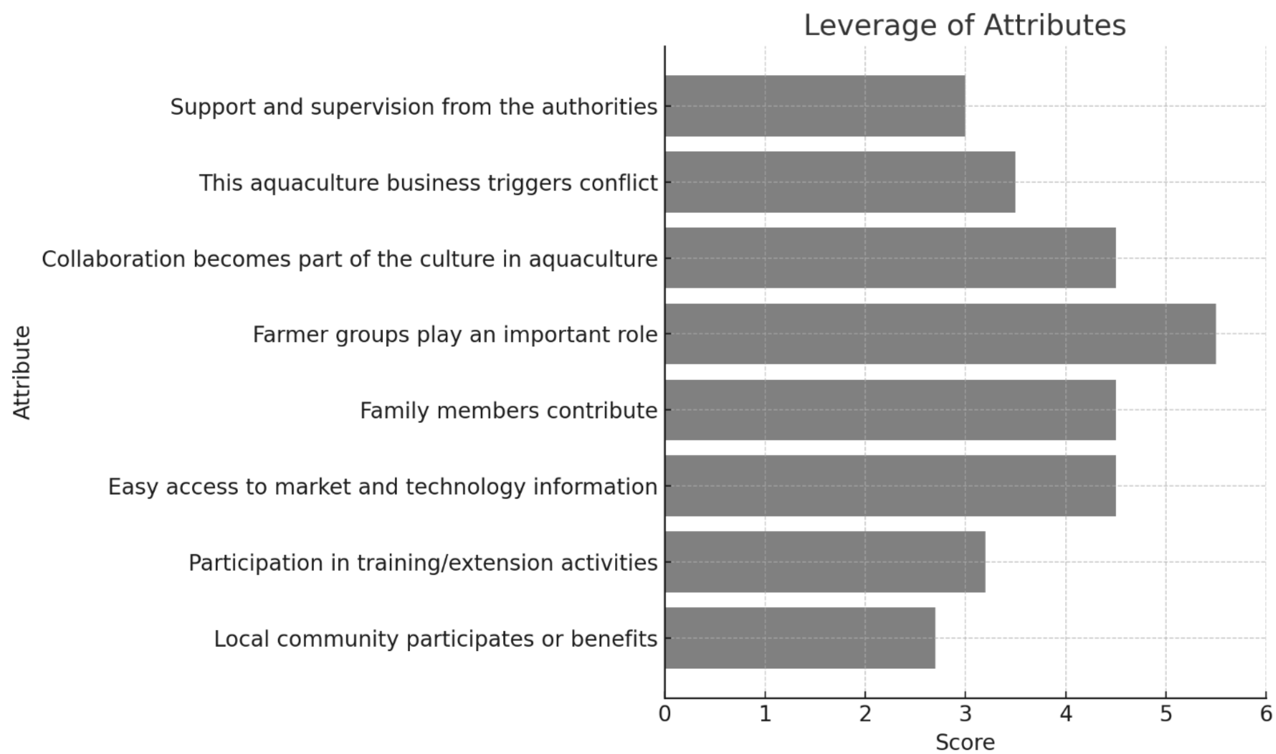

Fig. 7. Leverage values of social-institutional attributes

Furthermore, attributes such as collaboration as a cultural practice in aquaculture, ease of access to market and technology information, and family involvement in aquaculture activities also demonstrate substantial leverage. This means that enhancing collaboration among farmers, improving access to information, and increasing family involvement are crucial contributors to supporting social sustainability.

4. Environmental dimension

The environmental dimension is a critical factor in determining the sustainability of aquaculture, including gourami farming in Kemranjen District. Based on the Multidimensional Scaling (MDS) analysis of ten environmental attributes, the average sustainability index for this dimension was 44.80%, placing it in the "less sustainable" category (Table 5). This result indicates that, from an environmental perspective, gourami aquaculture in the area continues to face multiple challenges, particularly related to water quality management, waste control, biosecurity, and ecosystem carrying capacity.

A Monte Carlo simulation was subsequently conducted to test the stability of the MDS results and to assess data uncertainty. The Monte Carlo analysis yielded an average score of 42.58%, also categorized as "less sustainable," which reinforces the MDS findings. The average difference between the two analyses was –2.22%, indicating that the MDS results are relatively stable, despite some variation in individual respondents' values.

Table 5. Sustainability scores for the environmental dimension

Respondent	MDS Analysis (%)	Monte Carlo Analysis (%)	Difference (%)
SR	23.63	42.58	18.95
MVR	30.91	43.68	12.78
IM	56.89	44.04	12.38
SP	43.62	44.04	0.42
NA	16.14	42.96	26.82
TF	47.44	40.01	7.44
HT	62.50	41.33	21.16
SH	73.35	43.26	30.08
BS	43.37	42.56	0.82
SK	53.59	40.54	13.05
AS	45.33	42.99	2.34
MM	31.94	39.90	7.96
SP	40.47	43.27	2.81
SK	44.75	42.22	2.53
SD	49.87	42.90	6.97
BD	73.60	43.62	29.98
ISB	73.60	43.72	29.88
RI	47.85	43.03	4.82
ISSR	49.08	43.88	5.20
ST	40.13	42.66	2.52
SDK	27.18	42.49	15.30
ASTR	50.88	41.13	9.75
AR	34.13	43.80	9.67
WT	25.06	40.33	15.26
MMA	47.77	42.58	5.19
Average	**45.32**	**42.56**	**2.76**

A closer examination reveals that several respondents or business units exhibited substantial differences between MDS and Monte Carlo scores. For instance, SH showed a difference of –32.11%, BD –30.77%, and ISB –30.06%, indicating either inconsistencies in perception or significant fluctuations in environmental conditions in the field. Conversely, some respondents, such as SP and SK, displayed minimal differences, below 2%, reflecting consistent perceptions and relatively stable environmental conditions (Fig. 8).

Furthermore, most MDS and Monte Carlo scores were below 50%, indicating that aspects such as water quality, waste management, land use, biosecurity implementation, and environmental carrying capacity have not yet been fully addressed according to sustainability principles. External factors, including climate change, rainfall variability, and disease outbreaks, which significantly affect production, also represent substantial real-world challenges.

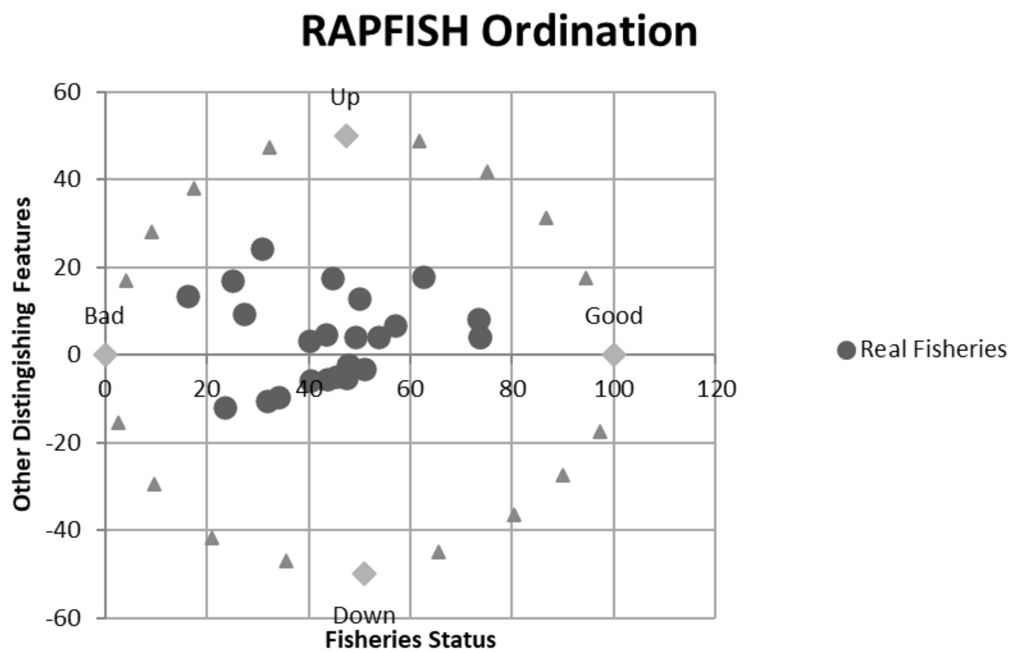

Fig. 8. Distribution of environmental dimension sustainability scores

The leverage analysis of environmental attributes in gourami aquaculture in Kemranjen District indicates that not all attributes exert equal influence on shifts in sustainability status (Fig. 9). Certain attributes contribute more substantially to determining the environmental sustainability status, making them priority areas for improvement. The attribute with the most significant impact is the development and utilization of non-aquaculture land, which exhibits the highest leverage value. This implies that without effective control over land conversion, the environmental sustainability of gourami aquaculture is highly vulnerable.

Additionally, attributes such as adequate environmental carrying capacity, the implementation of biosecurity measures at aquaculture sites, and the significant impacts of climate change also show high leverage. Strengthening these aspects is therefore crucial to maintaining the balance of aquatic ecosystems and enhancing the resilience of the aquaculture system against external disturbances.

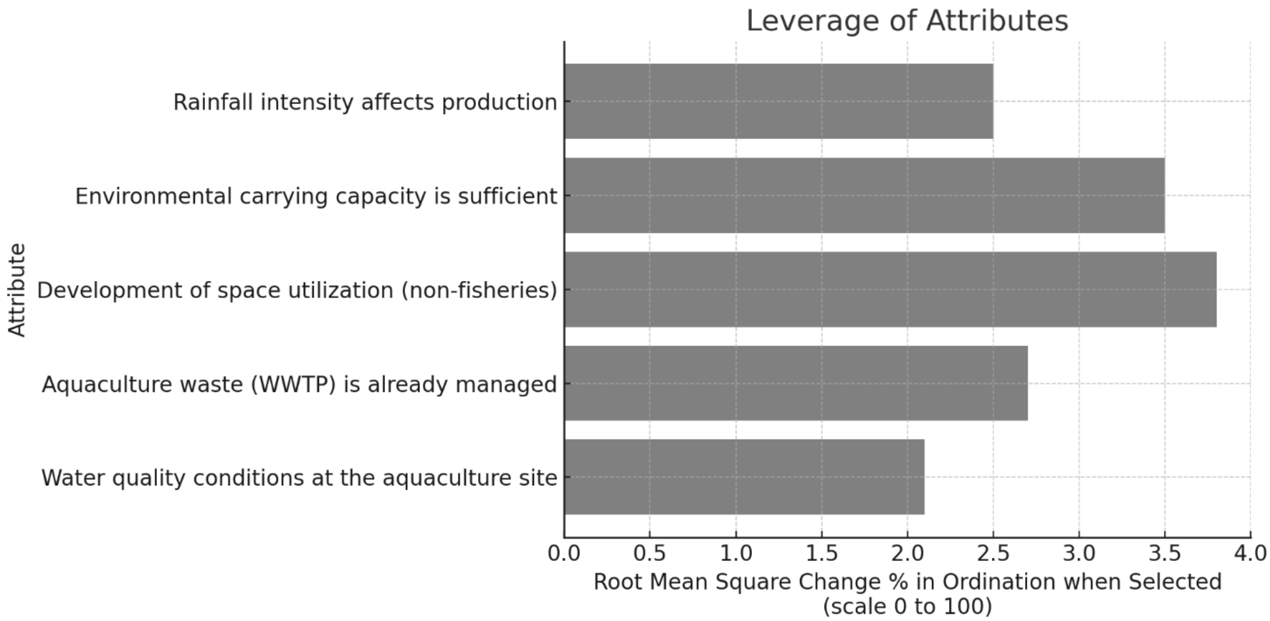

Fig. 9. Leverage of environmental dimension attributes

5. Multidimensional sustainability status

The multidimensional sustainability analysis of gourami aquaculture in Kemranjen District, Banyumas Regency, indicates that, overall, the aquaculture activities in the area fall into the "moderately sustainable" category, with a total score of 59.69 (Table 6). This assessment was conducted by considering four main dimensions: technical, economic, social-institutional, and environmental, each weighted according to its contribution to the overall sustainability of the aquaculture system (Fig. 10).

Table 6. Multidimensional sustainability status

Dimension	Weight	Aspect Score	Weighted Score
Technical	0.20	55.83	11.17
Economic	0.27	56.64	15.29
Social	0.15	61.81	9.27
Environmental	0.38	63.05	23.96
Total	1.00	237.33	59.69

Management status **(Marzuki et al., 2013; Nuryadin et al., 2015)**: Moderately Sustainable.

The four-dimensional analysis was used to determine the overall sustainability status of gourami aquaculture in Kemranjen District. The results indicate that, collectively, the dimensions fall within the moderately sustainable category. Among these, the environmental and social-institutional dimensions scored the highest (Fig. 10). Therefore, targeted improvements in the attributes within these dimensions are necessary to elevate the system to a "highly sustainable" level.

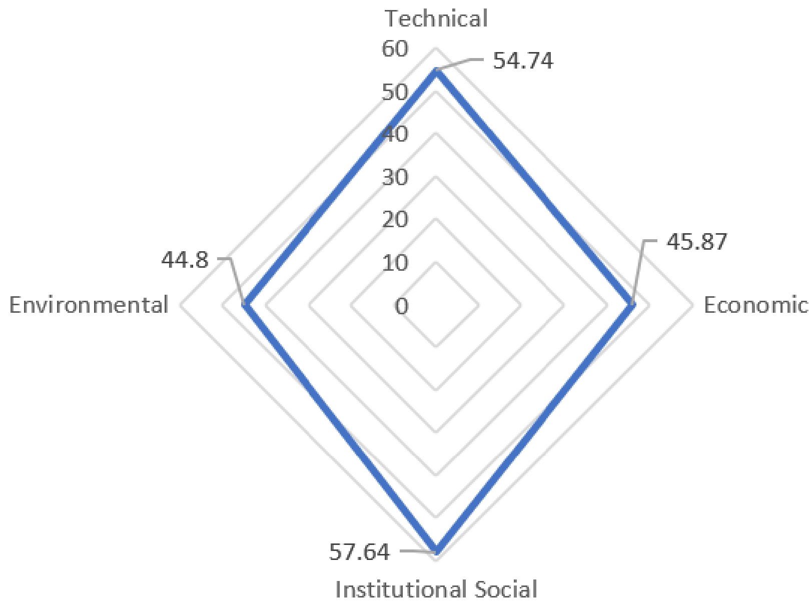

Fig. 10. Sustainability index radar diagram

Based on the obtained results, the Stress values for each dimension are as follows: technical dimension 0.19, economic dimension 0.19, social-institutional dimension 0.22, and environmental dimension 0.20 (Table 7). All Stress values are below the threshold of 0.25, which, according to **Kruskal and Wish (1978)**, indicates a low level of distortion. This suggests that the configuration of points (attributes) in the multidimensional space is adequately accurate. Lower Stress values indicate a better representation of the data in the MDS visualization.

Furthermore, the coefficient of determination (R^2) for each dimension also shows high values: 0.88 for the technical, economic, and environmental dimensions, and 0.86 for the social-institutional dimension. R^2 values approaching 1 indicate that the MDS model can explain most of the data variability effectively. Therefore, the MDS analysis results can be considered valid and suitable for decision-making related to the sustainability of gourami aquaculture in the study area.

The number of iterations required to reach convergence or stability in all dimensions was three, indicating that the MDS optimization process was efficient and quickly achieved stable results. The relatively low number of iterations suggests that the data used were consistent, allowing the modeling process to reach final results without extensive repetition.

Table 7. MDS analysis results for key sustainability statistics

Statistic	Technical	Economic	Social-Institutional	Environmental
Stress	0.19	0.19	0.22	0.20
R^2	0.88	0.88	0.86	0.88
Iterations	3	3	3	3

DISCUSSION

Global–local connections

Table (8) presents comparative evidence on sustainability challenges and solutions in aquaculture across multiple contexts. The findings make it clear that the difficulties faced in Kemranjen District are not isolated but mirror broader global patterns.

Table 8. Comparative sustainability challenges and solutions in aquaculture across contexts

Country	Species	Method/ Focus	Main Challenges	Solutions/ Recommendations	References
Indonesia	Gourami (*Osphronemus goramy*)	Utilization of floating macrophytes as alternative feed	Dependence on commercial feed; high costs	Use of local macrophytes as environmentally friendly feed	**(Pouil *et al.*, 2024)**
Indonesia	Gourami (*Osphronemus goramy*)	Reproduction (gonadal development and sexual maturation)	Limited physiological data for broodstock management	Monitoring gonadal maturity for superior seed production	**Purnamasari *et al.*, 2025**
Vietnam	Gourami (*Osphronemus goramy*)	Study of trematode parasites in gourami ponds	Parasite infection from snails → reduced fish health	Biosecurity management and pond sanitation	**Thien *et al.*, 2023**
Global (57	Various (global	Sustainability analysis of	Variations in	Global standards → benchmarking	**Garlock *et al.*, 2024**

countries)	pisciculture)	social, economic, and environmental aspects (API framework)	sustainability performance across countries	and adoption of best practices	
Indonesia	Various (Indonesian aquaculture)	Fuzzy cognitive mapping for aquaculture governance	Governance complexity; stakeholder conflicts	Participatory approach in governance	**Nagel *et al.*, 2024**

In Indonesia, dependence on commercial feed continues to raise production costs, driving the search for alternative feed strategies. The use of floating macrophytes has been proposed as an environmentally friendly and cost-effective solution that could reduce reliance on expensive commercial feed **(Pouil *et al.*, 2024)**. Similarly, reproductive management of gourami remains constrained by limited physiological data, highlighting the need for routine monitoring of gonadal maturity to secure a reliable supply of superior seed **(Purnamasari *et al.*, 2025)**.

In Vietnam, parasitic infections from trematodes transmitted by snails pose serious risks to pond-based gourami culture. These findings emphasize the necessity of stronger biosecurity practices and better pond sanitation to prevent disease outbreaks and production losses **(Thien *et al.*, 2023)**. Comparable constraints are reported in Bangladesh and other smallholder-dominated systems, where climate variability and financial barriers exacerbate vulnerabilities—echoing the environmental and economic weaknesses also observed in Kemranjen.

At the global level, large-scale analyses reveal significant variation in sustainability performance across countries, driven by ecological conditions, institutional strength, and technological adoption. The Aquaculture Performance Indicators (API) framework demonstrates that benchmarking and cross-country learning are vital for narrowing these disparities **(Garlock *et al.*, 2024)**. Within Indonesia, governance challenges—including institutional complexity and stakeholder conflicts—are recurring barriers. Evidence suggests that participatory governance, which integrates farmer groups and local stakeholders into policy and management processes, can significantly improve outcomes **(Nagel *et al.*, 2024)**.

Priority strategies for Kemranjen gourami aquaculture

Building on the MDS and Monte Carlo analyses, four priority areas emerge for strengthening the sustainability of gourami aquaculture:

A. Enhancement of environmental management

Land conversion control and spatial planning represent critical issues for maintaining sustainable aquaculture. The expansion of non-aquaculture land uses, such as residential and industrial developments, exerts substantial pressure on the availability of productive aquaculture land. Therefore, the enforcement of spatial planning regulations and consistent application of the regional spatial plan (RTRW) are essential. This aligns with the findings of **Laapo *et al.* (2021)**, which emphasize that adaptive spatial planning can reduce land-use conflicts in coastal areas. Active monitoring by local government authorities is also required to prevent the degradation of aquaculture areas. GIS-based spatial approaches, as developed by **Nurhabib *et al.* (2025)**, have proven effective in assessing land suitability and minimizing conflicts in aquaculture zone development.

Strengthening environmental carrying capacity is another urgent priority. Periodic evaluation of water bodies to ensure they can accommodate aquaculture activities without exceeding ecosystem limits is necessary. Recommended strategies include the application of environmentally friendly technologies, calculation of aquatic carrying capacity, and regulation of stocking densities in accordance with environmental limits. This is consistent with **Weitzman and Filgueira (2020)**, who demonstrate that aquaculture sustainability is strongly influenced by maintained environmental carrying capacity. **Nurhabib *et al.* (2024)** further highlight the importance of AHP-based land suitability analyses to determine appropriate aquaculture zones, thereby minimizing pressure on aquatic carrying capacity.

Consistent implementation of biosecurity measures is also critical. Educating farmers on biosecurity procedures, improving sanitation, and monitoring fish health must be strengthened to reduce disease risk. According to **Subasinghe *et al.* (2023)**, successful biosecurity practices in tropical fish aquaculture are directly linked to production stability and reduced economic losses due to disease.

Moreover, adaptation to climate change poses a significant challenge to the sector. The impacts of extreme weather, temperature fluctuations, and unpredictable rainfall must be addressed through adaptive technologies and water monitoring systems. **Lebel *et al.* (2020)**, emphasize that farmer preparedness for extreme climate events is a key determinant of aquaculture sustainability in Southeast Asia. Proper land-use planning and adherence to infrastructure standards are also necessary to ensure that pond layouts, water channels, and production zones do not negatively impact the surrounding environment. **Shah and Wu (2019)**, note that compliant spatial planning and infrastructure enhance cultivation efficiency while reducing environmental pollution risks.

Although considered a medium priority, waste management and irrigation systems remain important. The application of wastewater treatment plants, adequate waste processing, and efficient water circulation systems can reduce pollution. **Li *et al.* (2018)**, demonstrate that biofilter-based wastewater treatment technology can improve water quality while lowering pollutant loads from intensive aquaculture.

Finally, external factors such as rainfall intensity and disease outbreaks cannot be overlooked. Weather monitoring, well-designed drainage systems, and increased farmer capacity in disease management should serve as supporting strategies. Consistent with this, **Hobday *et al.* (2018)** highlight that integrating early warning weather systems with fish health management can enhance aquaculture production resilience against external risks.

B. Strengthening the economic dimension

Ease of access to business capital is a key factor in enhancing the economic sustainability of gourami aquaculture. Availability of financing schemes through formal financial institutions, such as banks, cooperatives, and microfinance, serves as an essential support for farmers to maintain business continuity. Improving financial literacy and facilitating access to funding in the fisheries sector has been shown to expand business opportunities and reduce the risk of failure **(Pomeroy *et al.*, 2020)**.

In addition, the use of digital media as a marketing tool has become increasingly strategic. Digital transformation encourages farmers to utilize e-commerce platforms, social media, and online marketing applications to reach broader markets and increase profit margins **(Rowan *et al.*, 2022; Zhang & Fan, 2023)**. This underscores the need to continuously enhance digital literacy among farmers to enable them to adapt to modern market dynamics.

Long marketing chains remain a significant barrier in the distribution of gourami harvests. Shortening the distribution chain through the strengthening of cooperatives or joint business groups, as well as increasing direct access to consumers, has been shown to improve price efficiency at the farmer level. **Liu *et al.* (2019)** demonstrated that direct marketing models through cooperatives can increase farmers’ profit margins compared to conventional distribution channels. Therefore, strengthening marketing institutions is an integral part of economic sustainability strategies.

Feed represents the largest cost component in gourami aquaculture. Strategies to enhance productivity and reduce production costs include improving feed efficiency, monitoring quality, and developing alternative feeds based on local ingredients. Recent research by **Fahira *et al.* (2025)** shows that using locally sourced feed can reduce production costs without compromising fish growth rates. Furthermore, improving product quality standards, in terms of size, hygiene, and transport durability, is essential for competitiveness in both domestic and international markets **(Ababouch *et al.*, 2023)**.

From an economic institutional perspective, gourami aquaculture should be positioned as an attractive sector for investment. Promoting regional investment potential, implementing partnership schemes with private investors, and strengthening farmers’ economic institutions can broaden funding opportunities. **Arshad *et al.* (2018)** indicate that cooperative-based partnership schemes can attract investor interest, as they are perceived to ensure continuity in supply and product quality.

Finally, the economic contribution of aquaculture to household income remains an important indicator, even though it has relatively lower leverage. Family-based aquaculture empowerment programs play a tangible role in improving household welfare **(Nawaz & Rupa, 2025)**. Similarly, the utilization of information technology (IT) for marketing, while considered the attribute with the lowest leverage, remains crucial for promoting long-term digital transformation among farmers. Digital marketing innovations based on applications and online platforms have been shown to enhance the competitiveness of fisheries products in various regions **(Chan *et al.*, 2021)**.

C. Optimization of the social-institutional dimension

The role of farmer groups or fish farmer groups (Pokdakan) is a key factor in strengthening the social-institutional dimension of aquaculture. Farmer groups serve as strategic organizational platforms for farmers, facilitating access to government assistance, technical training, and capital. Strengthening these groups through management training, capacity building, and member empowerment has been shown to enhance the effectiveness of aquaculture programs. **Rahaman and Abdulai (2018)** demonstrate that farmer groups with strong management capacity can improve access to markets and financing, thereby positively impacting the socio-economic sustainability of farmers. This aligns with the findings of **Haryanto (2025)**, which highlight the significant role of community-based institutions in enhancing the resilience of the fisheries sector in Indonesia.

Collaboration culture among farmers also needs to be strengthened to promote production efficiency, knowledge exchange, and the consolidation of market networks. Well-established collaboration can enhance collective bargaining power within the supply chain and accelerate social innovation at the community level. Research by **Pedroza-Gutiérrez and Hernández (2017)** shows that, horizontal cooperation among farmers fosters more stable market networks and strengthens bargaining positions in the face of price fluctuations.

In addition, access to market and modern technological information is a critical determinant of aquaculture success. Limited access to information can reduce competitiveness, whereas digital information systems provide opportunities for more efficient production and distribution. Recent studies by **Ali *et al.* (2025)**, indicate that digital platforms can shorten distribution chains and increase farmers' profit margins. Similarly, **Obiero *et al.* (2019)** emphasize the importance of technology-based extension services in improving farmers' literacy regarding aquaculture innovations.

Equally important is the involvement of family members in aquaculture activities, which strengthens both social and economic stability at the household level. Family participation in daily operations not only ensures business continuity but also supports intergenerational knowledge transfer. **Ayeloja *et al.* (2021)** demonstrate that family involvement in aquaculture contributes to improved socio-economic resilience of farmers while reinforcing community foundations in facing external challenges.

D. Enhancement of technical production aspects

Within the technical dimension, ease of access to production facilities remains the attribute with the highest leverage and is therefore a primary priority in strengthening aquaculture sustainability. The availability of essential inputs—such as feed, harvesting equipment, medicines, and supporting infrastructure—directly determines operational efficiency. Recent studies confirm that access to these facilities substantially improves productivity and profitability in small-scale aquaculture systems. For example, evidence from Kenya's Nile tilapia sector shows that membership in Common Interest Groups increased fish sales income by approximately 32.3% **(Gichuki *et al.*, 2025)**. On the other hand, in China, cooperative participation boosted net profit by about 15.6% and productivity by 11.5% **(Cai *et al.*, 2022)**. Similar findings were reported in Indonesia, where fisheries cooperative membership significantly enhanced household incomes **(Taniu *et al.*, 2024)**. Moreover, cross-sectoral analyses highlight that cooperatives often outperform investor-owned firms in efficiency and profitability due to their governance structures **(Meliá-Martí *et al.*, 2024)**. At a broader scale, survey data from more than 700 small-scale aquaculture farms underline the strong relationship between infrastructure access, input availability, and farm efficiency **(Munthali *et al.*, 2024)**. Strategic interventions such as strengthening fishery cooperatives, revitalizing input kiosks, and reforming distribution systems are therefore essential to lower operational costs while simultaneously increasing productivity.

In addition, the availability of high-quality feed and certified seed is another key factor influencing aquaculture productivity. Quality control of feed and improved access for farmers to official seed from certified hatcheries are essential to ensure optimal production outcomes. **Munguti *et al.* (2024)** demonstrate that the use of high-quality locally sourced feed can reduce production costs without compromising fish growth performance. Meanwhile, **Kumari *et al.* (2018)** emphasize the importance of transparent and affordable seed distribution in improving survival rates and ensuring production consistency.

Other critical technical aspects include the availability of fish medicines and the improvement of seed survival rates. High mortality rates during early cultivation phases can be mitigated through fish health services, disease management training, and improved water quality. **Opiyo *et al.* (2018)** indicate that the application of integrated fish health management significantly reduces mortality rates in intensive aquaculture.

Furthermore, the implementation of appropriate technologies and the availability of adequate infrastructure play a major role in enhancing technical performance. Technology extension, construction of water channels, electricity supply, and access roads are important prerequisites for improving operational efficiency. **Rowan (2023)** found that integrating appropriate technology with infrastructure improvements can increase freshwater aquaculture productivity by up to 25%.

Although their leverage is lower, Good Aquaculture Practices (CBIB) certification, the alignment of cultivation sites with spatial planning regulations, and professional farm management remain important for ensuring long-term technical sustainability. CBIB certification not only improves product quality but also strengthens market access and farmer competitiveness. This is supported by **Muliawan *et al.* (2021)**, who demonstrate that CBIB certification enhances consumer confidence and creates export opportunities for aquaculture products.

CONCLUSION

This study shows that gourami aquaculture in Kemranjen, Banyumas (Central Java) is moderately sustainable overall, based on an integrated Multidimensional Scaling–Analytical Hierarchy Process (MDS–AHP) assessment across technical, economic, social-institutional, and environmental dimensions. Technically, systems are sound but uneven, with the greatest leverage found in securing reliable access to production inputs, high-quality feed, and certified seed. Economically, performance lags due to capital constraints, long marketing chains, and limited digital adoption—suggesting that improved financing, cooperative marketing, and e-commerce use could lift returns. Social-institutional capacity is comparatively stronger and can be a catalyst for change, especially by reinforcing farmer groups, collaboration norms, information/extension access, and family participation. Environmentally, the weakest area, priority risks include land conversion, suboptimal waste and water management, uneven biosecurity, and climate stress; stronger spatial planning, carrying-capacity management, biosecurity practices, and climate adaptation are therefore essential. Methodologically robust (low Stress, high R^2), the analysis identifies concrete leverage points that align with global lessons from Asia and Europe: targeted, incremental technology upgrades; participatory governance; and benchmarking against best practices. Taken together, the pathway to “highly sustainable” status hinges on coordinated policy and investment to control land use, expand affordable capital and inputs, shorten and digitize market channels, and empower farmer organizations to accelerate adoption of good aquaculture practices.

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