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Multidimensional Assessment and Leverage Points in Integrated Aquaculture–agriculture Systems of Indonesian Wetlands

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ABSTRACT
Aquaculture–agriculture integration in wetland systems is widely promoted for food security and rural resilience. However, current land suitability classifications (S1) often mask real sustainability constraints. This study integrated land suitability assessment, multidimensional sustainability scaling, and leverage attribute analysis across shallow, middle, and deep wetland typologies in Indonesia. Despite being classified as highly suitable, ecological performance was weak due to feed inefficiency, nutrient accumulation, and excessive stocking densities. Economic outcomes varied: rice–fish systems showed higher stability, while monoculture ponds were highly sensitive to input prices and market volatility. Social conditions were comparatively strong, supported by community involvement and labor-sharing practices. Leverage analysis revealed a few critical attributes that disproportionately determined system sustainability: feed availability, pond productivity, market access, worker protection (health insurance), and conflict management. This study demonstrates that physical suitability alone is not enough. Sustainability depends on improving feed efficiency, diversifying markets, and strengthening social safeguards. By combining biophysical and socio-economic diagnostics, the framework offers practical guidance for policymakers to design more resilient and inclusive aquaculture interventions in wetland landscapes.

INTRODUCTION

Aquaculture has emerged as one of the fastest growing food production sectors globally, supplying over half of all fish consumed worldwide **(FAO, 2022)**. As capture fisheries approach ecological limits, aquaculture is increasingly recognized as essential to global food security, rural livelihoods, and economic development **(Naylor *et al.*, 2021)**. Integrated systems such as rice–fish farming and diversified aquaculture–agriculture practices have received particular attention in Asia for their ability to enhance productivity while delivering co-benefits such as pest control, nutrient cycling, and risk reduction **(Berg *et al.*, 2023)**. In regions characterized by fertile wetlands, these systems represent a promising pathway to achieve both economic resilience and ecological sustainability.

Despite this potential, aquaculture expansion often faces sustainability challenges. Studies highlight that while biophysical conditions may be favorable, ecological degradation can emerge from nutrient loading, poor feed management, and overstocking **(Liu *et al.*, 2019; Khan *et al.*, 2024)**. Economic vulnerabilities are similarly acute: smallholders face volatile input prices, limited access to quality feed and seed, and dependence on intermediaries for market access, which reduces profitability **(Byabasaija *et al.*, 2025; Zhou *et al.*, 2025)**. At the same time, social acceptance has become an increasingly critical dimension of sustainability, as aquaculture's legitimacy depends on labor welfare, community trust, and inclusive governance **(Garlock *et al.*, 2024; Pérez *et al.*, 2025)**. Together, these findings suggest that land suitability classifications alone are insufficient to ensure sustainability; multidimensional frameworks that integrate ecological, economic, and social perspectives are required.

The state of the art reflects growing use of multidimensional sustainability assessments in aquaculture. Methods such as Multidimensional Scaling (MDS) and Aquaculture Performance Indicators (APIs) have been developed to quantify ecological, economic, and social sustainability across systems and geographies **(Krause *et al.*, 2020; Garlock *et al.*, 2024)**. Research also increasingly identifies "leverage points," or critical attributes such as feed efficiency, market access, and labor protections, that can disproportionately influence sustainability outcomes **(Tran *et al.*, 2023; Rahman *et al.*, 2024)**. However, most existing studies focus on individual sustainability pillars or single intervention areas, leaving a gap in holistic approaches that integrate land suitability, multidimensional sustainability performance, and leverage attributes in a unified analytical framework.

Several gaps remain evident in the literature. First, few studies explicitly contrast land suitability classifications with realized sustainability outcomes. This limits understanding of why ecologically "highly suitable" sites may still perform poorly in practice. Second, research on leverage attributes is often fragmented, focusing either on technical issues such as feed innovation or institutional issues such as governance **(Partelow, 2023; Zhang *et al.*, 2025)**, but rarely integrating both. Third, there is limited empirical evidence from Southeast Asian wetlands despite the fact that this region hosts some of the most dynamic aquaculture–agriculture systems globally **(Samaddar *et al.*, 2025)**. Addressing these gaps is crucial for designing targeted, evidence-based strategies that align local practices with broader sustainability goals.

This study contributes novelty in three ways. First, it integrates land suitability assessments with multidimensional sustainability analysis, revealing where ecological, economic, and social dimensions align or diverge within aquaculture–agriculture systems. Second, it identifies high-leverage attributes across all three dimensions, from feed availability and pond productivity to worker health insurance and conflict management, providing concrete entry points for targeted interventions. Third, by applying this integrated approach to wetland systems in Indonesia, it advances empirical understanding in a region that has been underrepresented in comparative sustainability research, despite its strategic role in global aquaculture production.

The aims of this study were therefore fourfold: (i) to evaluate land suitability for aquaculture–agriculture integration across wetland typologies; (ii) to assess sustainability performance using multidimensional indices across ecological, economic, and social dimensions; (iii) to identify leverage attributes that exert disproportionate influence on system resilience; and (iv) to provide evidence-based recommendations for targeted interventions that enhance sustainability outcomes. By bridging technical, institutional, and social perspectives, this research seeks to inform both policy and practice, offering a framework that can be adapted to other regions facing similar sustainability challenges. Ultimately, the study highlights that achieving sustainable aquaculture requires more than land suitability; it requires integrated strategies that balance ecological integrity, economic viability, and social legitimacy.

MATERIALS AND METHODS

Study area and sampling design

The research was conducted in the Bonorowo wetlands of Lamongan Regency, East Java, Indonesia. Three hydrologically distinct stations were established: Station 1 (Shallow: Laren 6°59′0.312″S 112°16′58.519″E, Maduran 7°0′25.95881″S 112°16′51.41705″E, Sekaran Subdistricts 7°1′36″S 112°16′17″E), Station 2 (Middle: Karanggeneng 6°59′27″S 112°22′20″E, Kalitengah Subdistricts 7°0′52″S 112°24′0″E), and Station 3 (Deep: Turi 7°5′49.00175″S 112°22′26.29816″E, Karangbinangun 7°1′50″S 112°26′59″E, Glagah Subdistricts 7°3′0.34895″S 112°29′39.58476″E). Site selection was guided by satellite mapping and cluster sampling methodology, with 41 farmer groups (10% of 410 active aquaculture cohorts) randomly selected across stations to represent dominant cropping patterns: Fish-Fish-Fish, Rice-Fish-Rice, and Fish-Fish-Rice.

Data collection and variables

Field observations were used to gather primary data, which included 28 granular attributes spanning the ecological, economic, and social dimensions of sustainability. The ecological dimension encompassed sediment substrate, disease incidence, feed availability, flooding frequency, and water quality parameters like temperature, pH, dissolved oxygen, nitrate, and phosphate levels. Productivity, market access, labor wages, subsidies, and capital institutions were evaluated in the economic dimension, whereas training access, regulatory compliance, land ownership, health insurance, and labor allocation were evaluated in the social dimension. Secondary data were also gathered from peer-reviewed literature, hydrological records, and government reports. While physicochemical parameters were measured *in situ* using calibrated instruments like spectrophotometers, pH/DO meters, and refractometers.

Land suitability assessment

A weighted scoring system (Table 1) was applied to nine biophysical parameters (e.g., temperature, salinity, soil pH). Suitability classes were derived using equal interval classification (Equation 1):

$$I = \frac{Nmax - Nmin}{K} \tag{1}$$

Where, I = interval width, K = 4 suitability classes (S1: Highly Suitable to N: Non-Suitable), and Nmax/Nmin = maximum/minimum parameter scores per site. Final classifications followed FAO guidelines (Table 1).

Table 1. Matrix of shrimp pond land characteristic parameters

Parameter	Score			
	1	2	3	4
Water temperature (°C)	< 12 or > 40	12 – 19 or 36 – 40	20 – 27 or 31 – 35	28 – 30
pH (water)	< 4.0 or > 11	4.0 – 5.9 or 9.6 – 11	6.0 – 7.4 or 8.6 – 9.5	7.5 – 8.5
Salinity (ppt)	> 50	< 10 or 31 – 50	10 – 14 or 21 – 30	15 – 20
Soil pH	< 4.0 or > 9.0	4.0 – 5.4 or 8.1 – 9.0	5.5 – 6.4 or 7.6 – 8.0	6.5 – 7.5
Dissolved oxygen (mg/L)	< 3.0 or > 10	3.1 – 4.0 or 8.1 – 10	4.1 – 5.0 or 7.1 – 8.0	5.1 – 7.0
Nitrate (mg/L)	< 0.01 or > 5	0.01 – 0.2 or 4.6 – 5.0	0.3 – 0.8 or 3.6 – 4.5	0.9 – 3.5
Phosphate (mg/L)	< 0.02	0.05 – 0.09	0.10 – 0.20	> 0.21
Sediment type	Mud, sand, gravel	Silty clay	Sandy clay	Clayey sandy loam
Annual rainfall (mm)	< 1,000 or > 3,500	1,000 – 1,999	2,000 – 2,499 or 3,001 – 3,500	2,500 – 3,000
Flooding duration (months)	> 6 months	~ 6 months	3 – 6 months	< 3 months

*Scoring system: 1 = not suitable; 2 = marginally suitable; 3 = moderately suitable; 4 = highly suitable.

Multidimensional sustainability analysis

Multi-Dimensional Scaling (MDS) was executed using Rap-Aquaculture Minapolitan software (modified from Rapfish). Twenty-eight attributes were scored (1–3 scale: poor–ideal) and transformed into sustainability indices (0–100 scale) categorized as: Unsustainable (0–50), Moderately sustainable (50.01–60), Sustainable (60.01–70), Highly sustainable (70.01–100) (Categorization adapted from KEPMEN KP 32/2010). Root Mean Square Change (RMSC) analysis identified high-leverage attributes driving index variance.

RESULTS

Land suitability classification

The data presented the land suitability for various cropping patterns in three distinct wetland typologies: shallow, middle, and deep (Table 3); the results of the data and scoring of land suitability parameters are shown in Table (2). The suitability of land across different districts has been assessed based on specific scores, with all areas categorized as "Highly Suitable" (S1). In the Shallow typology, districts such as Laren, Maduran, and Sekaran received scores of 32, 34, and 33, respectively. In the Middle typology, Kalitengah and Karanggeneng were evaluated with scores of 32 and 30, respectively. Lastly, in the Deep typology, districts including Turi, Glagah, and Karangbinangun were assigned scores of 32, 34, and 30, respectively. These scores indicate that all districts within the study area are highly suitable for the cropping patterns assessed, as all fall within the "Highly Suitable" classification.

Table 2. Assessment of land suitability in shallow basins across Bonorowo District

Parameter	Karang Gengeng	Kalitengah	Sekaran	Maduran	Laren	Karang Binangun	Glagah	Turi
Water temperature (°C)	26.8 – 28.8	28.3 – 33.0	25.5 – 26.7	26.0 – 33.0	23.4 – 28.7	25.9 – 39.7	25.8 – 33.0	27.4 – 28.0
pH (water)	6.7 – 7.8	7.2 – 7.6	7.3 – 7.7	7.3 – 8.3	7.0 – 7.4	7.4	7.9 – 8.1	7.4 – 8.4
Salinity (ppt)	0 – 2	0	0 – 1	0	0	0 – 1	0	0 – 5
Soil pH	6.4 – 6.8	6.9	6.4	6.6	6.5 – 6.8	6.4	6.8	6.8
Dissolved oxygen (mg/L)	6.6 – 7.2	3.8 – 5.6	2.8 – 7.6	3.6 – 5.6	3.0 – 5.6	2.2 – 6.4	6.0 – 6.1	4.6 – 6.4
Nitrate (mg/L)	0	0	0	0	0	0	0 – 10	0
Phosphate (mg/L)	0.25 – 1.0	2	1.0 – 2.0	1.0 – 2.0	~1.0	1.0 – 2.0	0.1 – 1.0	1.0 – 2.0
Soil texture	Clayey sandy loam	Clayey sandy loam	Clayey sandy loam	Clayey sandy loam	Clayey sandy loam	Clayey sandy loam	Clayey sandy loam	Clayey sandy loam
Annual rainfall (mm)	1,196	1,330	1,196	1,196	1,330	1,239	1,239	1,239
Flood duration (months)	3	3	1	1	1	5	5	5

Table 3. Recapitulation of land suitability distribution across Bonorowo stations

Cropping Pattern	Subistrict	Score	Description
Shallow	Laren	32	Highly Suitable (S1)
	Maduran	34	Highly Suitable (S1)
	Sekaran	33	Highly Suitable (S1)
Middle	Kalitengah	32	Highly Suitable (S1)
	Karanggeneng	30	Highly Suitable (S1)
Deep	Turi	32	Highly Suitable (S1)
	Glagah	34	Highly Suitable (S1)
	Karangbinangun	30	Highly Suitable (S1)

Multidimensional sustainability performance

The Multidimensional Scaling (MDS) analysis revealed substantial variability in sustainability indices across ecological, economic, and social dimensions under different depths and cropping patterns. The sustainability status ranged from bad to adequate, indicating that integrated management strategies are necessary to improve overall system resilience. In the ecological dimension, the shallow areas consistently exhibited low performance, particularly under the Fish–Rice (40.81) and Fish–Fish–Fish (44.32) patterns, both categorized as bad (Fig. 1A–C). Even though the middle and deep regions showed slight improvement, values remained within the bad to poor categories, such as the middle Fish–Fish–Fish (36.13) and deep Fish–Fish–Rice (40.08). This pattern suggests that ecological sustainability is the most constrained dimension across all systems, with limited carrying capacity and persistent environmental pressures.

Conversely, the economic dimension exhibited slightly better outcomes, with shallow Fish–Fish–Rice (64.78) and middle Fish–Fish–Rice (61.16) reaching the adequate category (Fig. 2C,E). However, most systems remained in the bad to poor categories, such as middle Fish–Fish–Fish (44.2) and deep Fish–Rice (42.64). This disparity implies that while diversified patterns integrating rice contributed positively to economic resilience, monoculture practices (Fish–Fish–Fish) performed poorly due to lower productivity stability and market vulnerability. The social dimension showed the most favorable results across all regions (Fig. 3). Nearly all systems scored within the adequate category, with values ranging from 61.88 to 69.58. The highest performance was recorded in the middle Fish–Fish–Fish system (69.58), while the lowest was found in deep Fish–Fish–Rice (62.23). These findings suggest that social acceptance and community participation are relatively strong, regardless of ecological or economic constraints. A consolidated summary of the sustainability indices is presented in Table (4), highlighting the multidimensional performance across regions and patterns. Notably, ecological indices remained consistently bad, economic indices fluctuated between bad and adequate, while social indices were more stable in the adequate category.

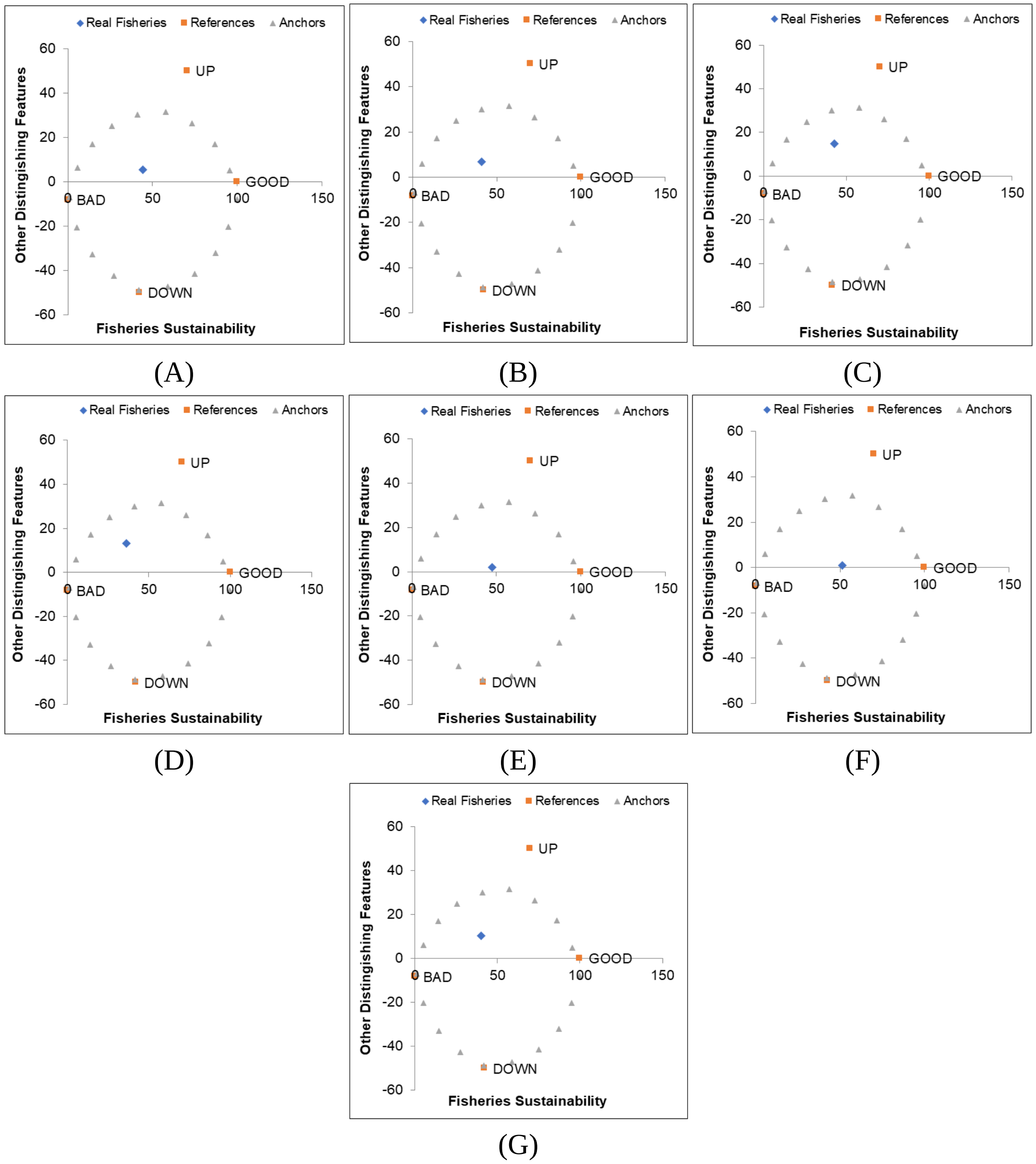

Fig. 1. MDS sustainability indices ecological dimensions. (A) Shallow with Fish- Fish-Fish pattern; (B) Shallow with Fish-Rice pattern; (C) Shallow with Fish-Fish-Rice pattern; (D) Middle with Fish-Fish-Fish pattern; (E) Middle with Fish-Fish-Rice; (F) Deep with Fish-Rice pattern; (G) Deep with Fish-Fish-Rice pattern

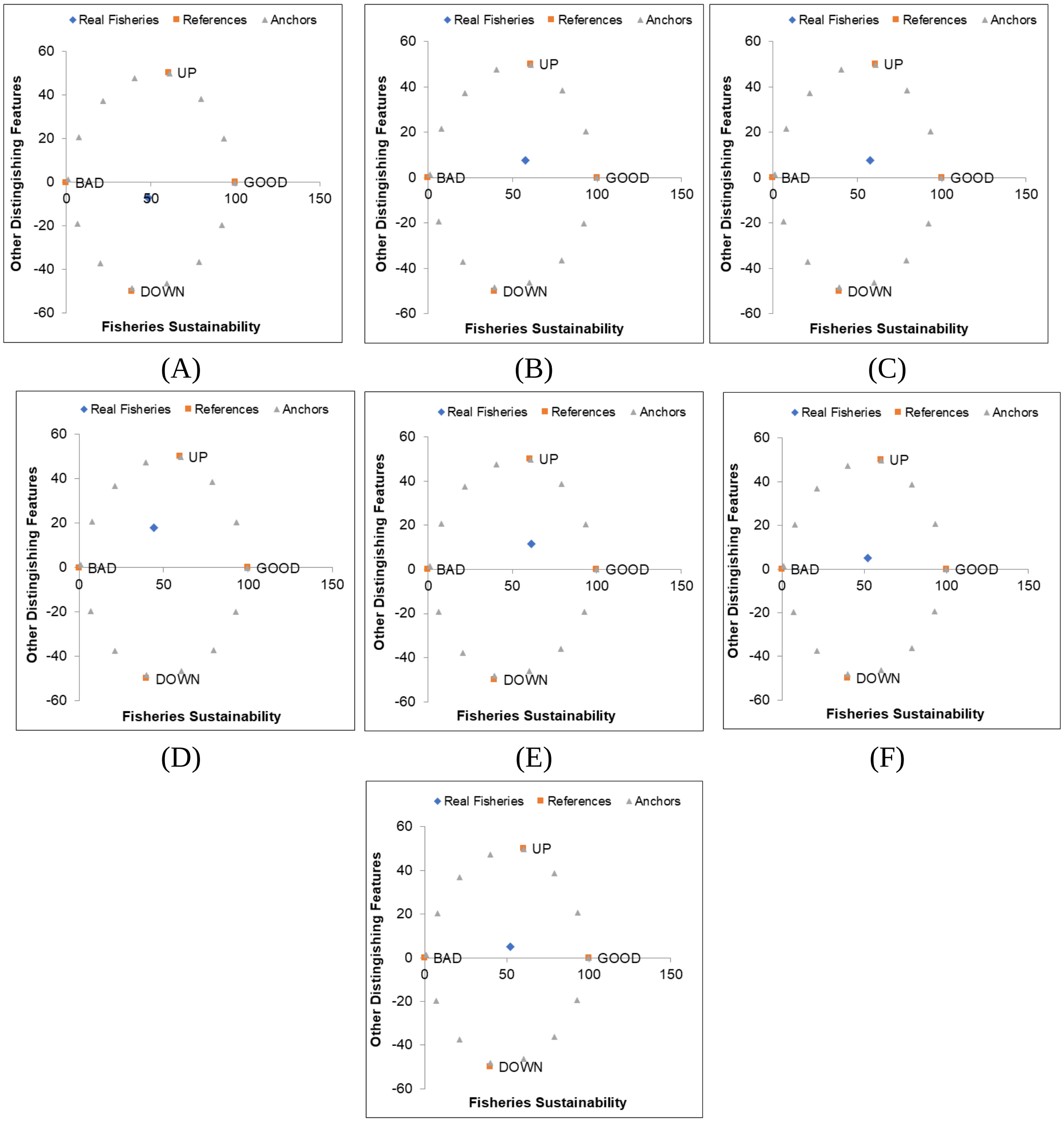

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Fig. 2. MDS sustainability indices economy dimensions. (A) Shallow with Fish-Fish-Fish pattern; (B) Shallow with Fish-Rice pattern; (C) Shallow with Fish-Fish-Rice pattern; (D) Middle with Fish-Fish-Fish pattern; (E) Middle with Fish-Fish-Rice; (F) Deep with Fish-Rice pattern; (G) Deep with Fish-Fish-Rice pattern

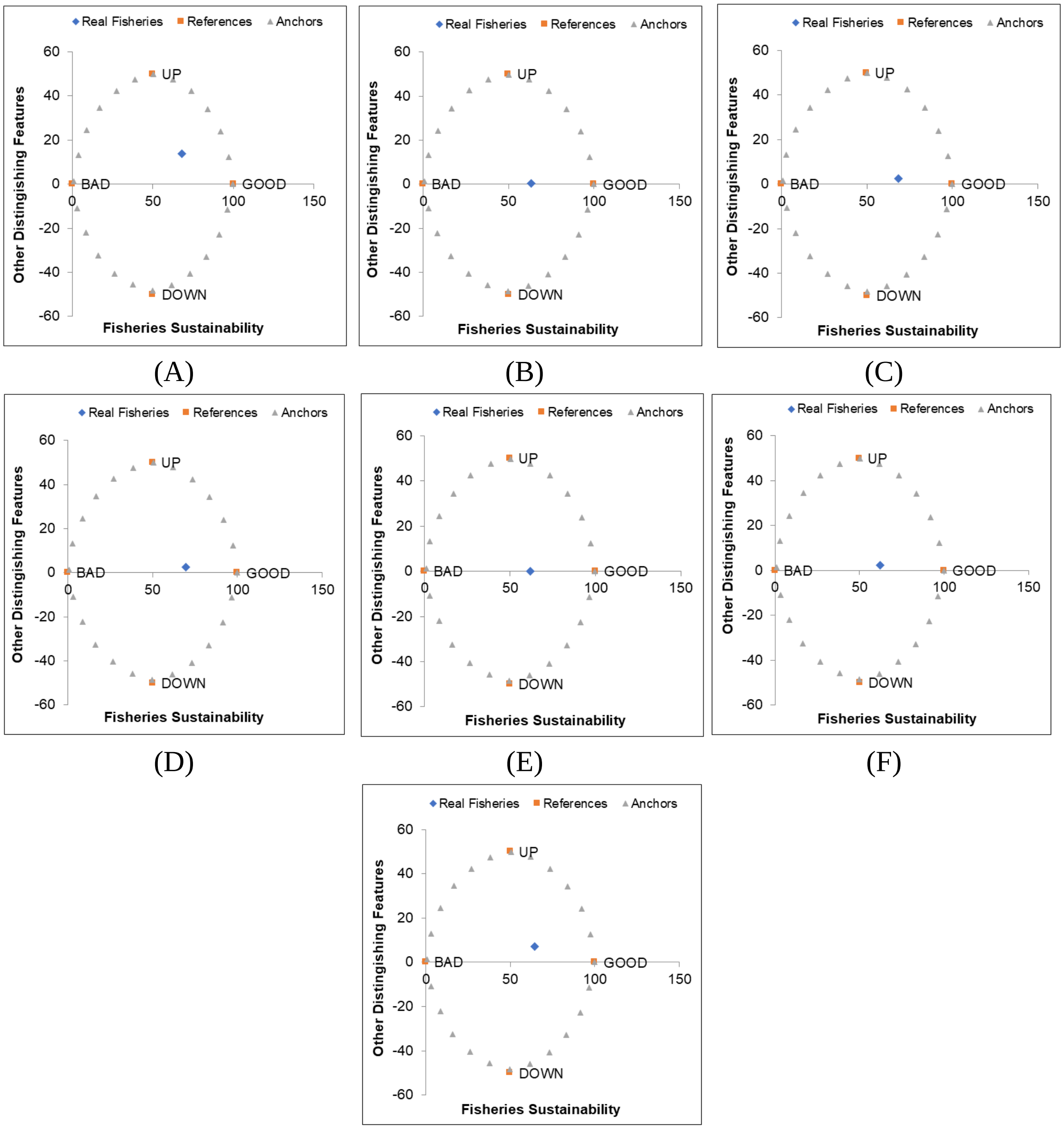


Fig. 3. MDS sustainability indices social dimensions. (A) Shallow with Fish-Fish-Fish pattern; (B) Shallow with Fish-Rice pattern; (C) Shallow with Fish-Fish-Rice pattern; (D) Middle with Fish-Fish-Fish pattern; (E) Middle with Fish-Fish-Rice; (F) Deep with Fish-Rice pattern; (G) Deep with Fish-Fish-Rice pattern

Table 4. Recapitulation of MDS sustainability indices station

Region	Cropping Pattern	Ecology	Economy	Social
Shallow	Fish-Fish-Fish	44.32 (Bad)	48.38 (Bad)	68.24 (Adequate)
	Fish-Rice	40.81 (Bad)	57.49 (Poor)	63.44 (Adequate)
	Fish-Fish-Rice	42.68 (Bad)	64.78 (Adequate)*	68.45 (Adequate)

Middle	Fish-Fish-Fish	36.13 (Bad)**	44.2 (Bad)	69.58 (Adequate)*
	Fish-Fish-Rice	47.55 (Bad)	61.16 (Adequate)	61.88 (Adequate)**
Deep	Fish-Rice	51.32 (Poor)*	42.64 (Bad)**	64.56 (Adequate)
	Fish-Fish-Rice	40.08 (Bad)	52.12 (Poor)	62.23 (Adequate)

High-leverage sustainability attributes

The leverage analysis identified several key attributes that strongly influenced the sustainability performance of aquaculture systems across ecological, economic, and social dimensions. The results demonstrated that specific factors act as leverage points, meaning that targeted improvements in these attributes could significantly enhance overall sustainability. In the ecological dimension, the highest leverage attributes included feed availability, crop management, electricity availability, and stocking density (Fig. 4A–G). Among these, feed availability exerted the most dominant effect, especially in shallow and middle zones, highlighting its pivotal role in maintaining ecological balance. High dependence on external feed sources and fluctuating costs increase environmental pressures, while poor crop management and inappropriate stocking densities exacerbate ecological risks. Electricity availability also emerged as a critical attribute, particularly in deep-water systems, where intensive operations rely heavily on pumping and aeration technologies.

For the economic dimension, leverage attributes were primarily related to market and productivity drivers. Pond productivity and shrimp sales represented the strongest attributes influencing economic sustainability (Fig. 5). Additionally, sales market access and sales system proved essential for ensuring consistent revenue streams. Limited diversification of sales channels and dependency on middlemen constrain profitability, while fluctuations in shrimp prices directly affect farmers’ financial resilience. In deep-water systems, land ownership also appeared as a contextual driver of economic leverage, underscoring the importance of tenure security for long-term investments.

The social dimension displayed a unique pattern, with attributes linked to labor welfare and community stability (Fig. 6). Worker health insurance and time allocation emerged as the most critical leverage points, reflecting the growing recognition of social protection in aquaculture livelihoods. In addition, conflict occurrences and working hours duration were key factors shaping social sustainability. The presence of cultivation regulations further influenced social acceptance and compliance, particularly in middle and deep systems. Together, these findings indicate that strengthening labor welfare and reducing conflict risks can substantially improve social resilience. A consolidated overview of the identified leverage attributes is summarized in Table (5). The presented data highlight the most influential ecological, economic, and social attributes, providing guidance for policymakers and practitioners to design targeted interventions.

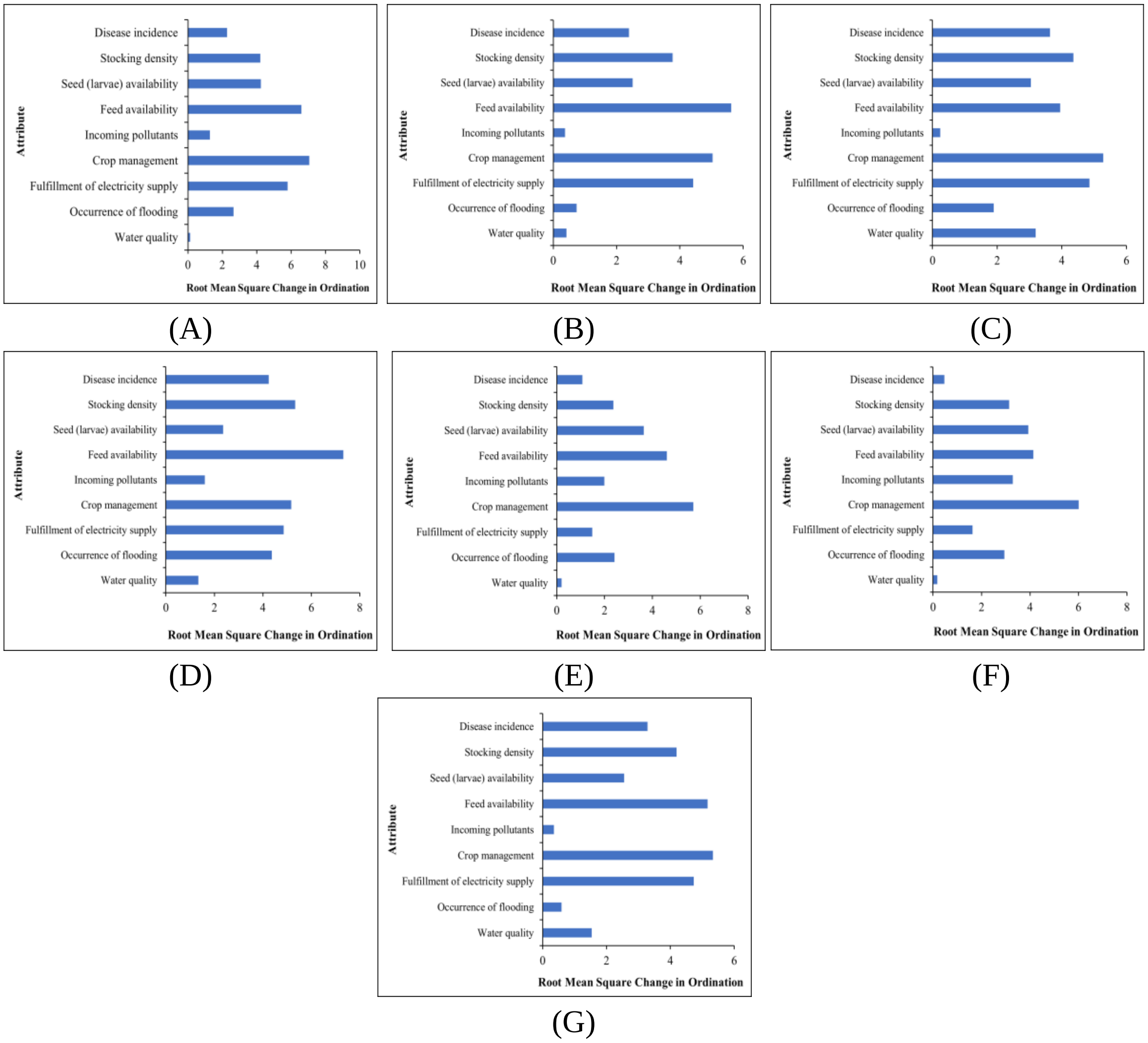
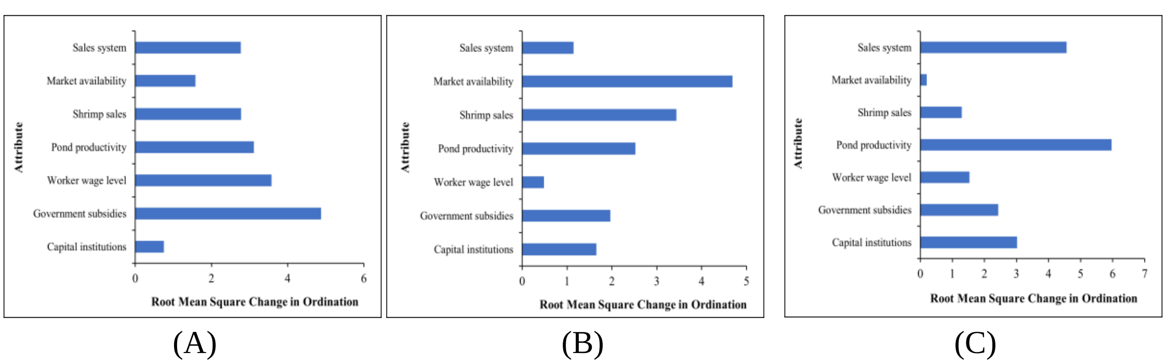


Fig. 4. Leverages of attributes indices ecological dimensions. (A) Shallow with Fish-Fish-Fish pattern; (B) Shallow with Fish-Rice pattern; (C) Shallow with Fish-Fish-Rice pattern; (D) Middle with Fish-Fish-Fish pattern; (E) Middle with Fish-Fish-Rice; (F) Deep with Fish-Rice pattern; (G) Deep with Fish-Fish-Rice pattern



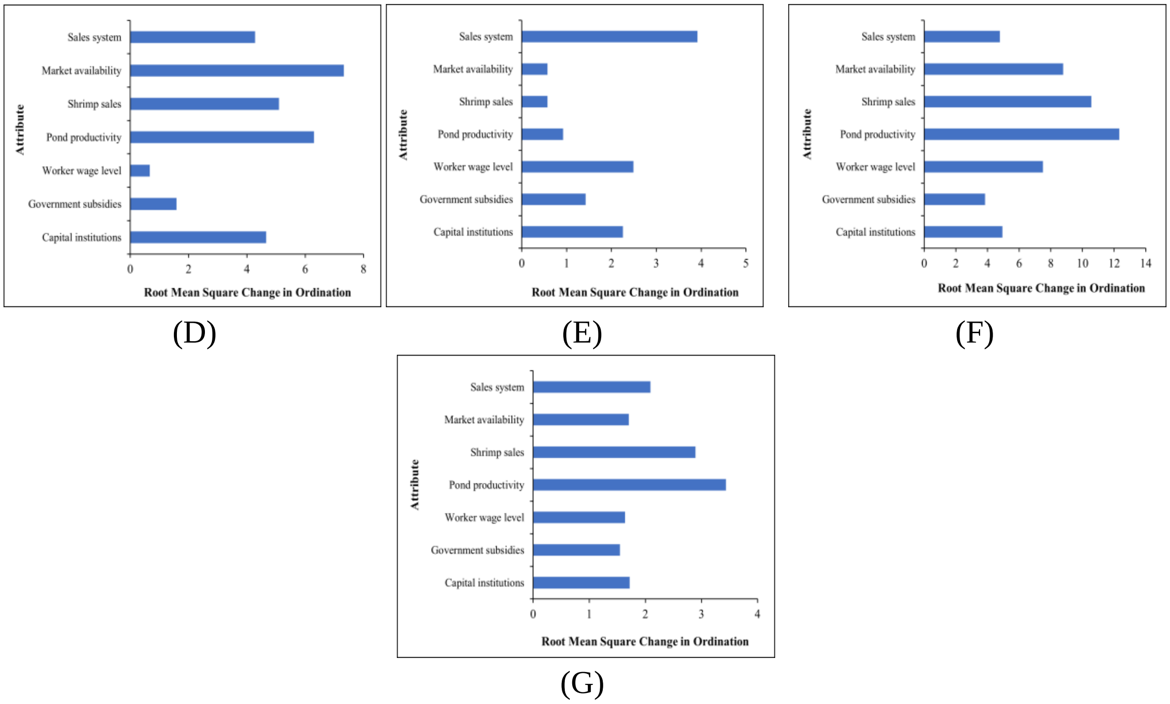
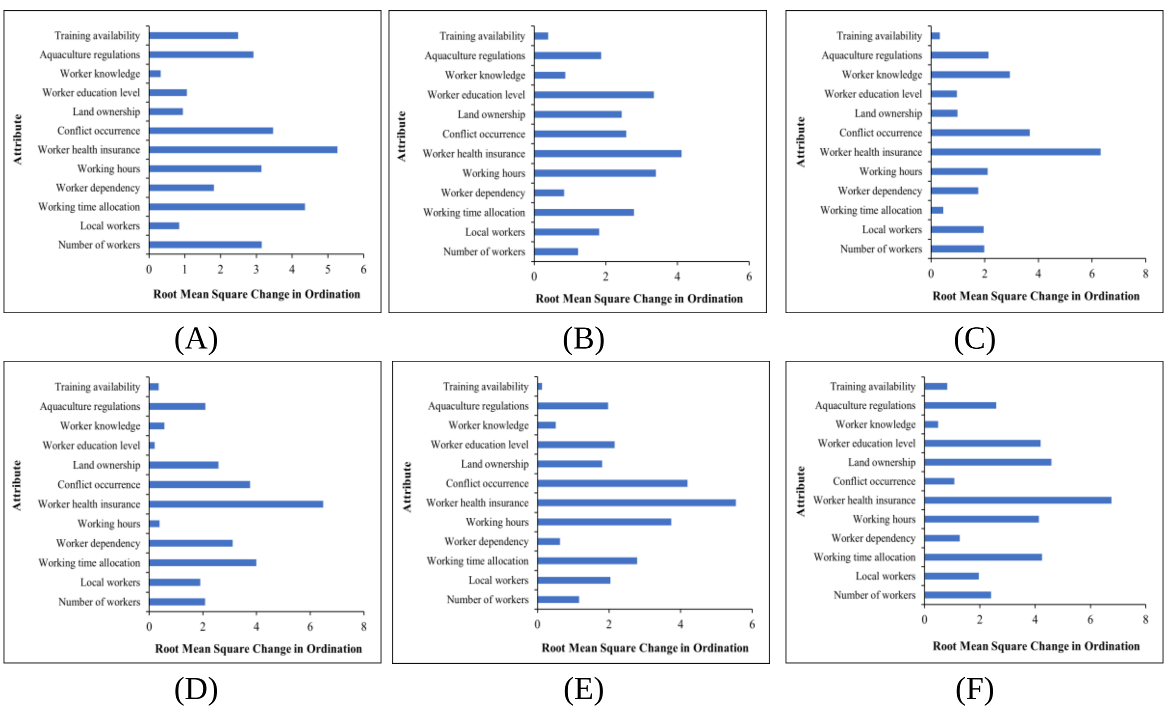


Fig. 5. Leverages of attributes indices economy dimensions. (A) Shallow with Fish-Fish-Fish pattern; (B) Shallow with Fish-Rice pattern; (C) Shallow with Fish-Fish-Rice pattern; (D) Middle with Fish-Fish-Fish pattern; (E) Middle with Fish-Fish-Rice; (F) Deep with Fish-Rice pattern; (G) Deep with Fish-Fish-Rice pattern



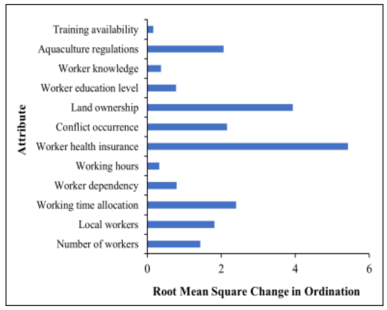


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Fig. 6. Leverages of attributes indices social dimensions. (A) Shallow with Fish-Fish-Fish pattern; (B) Shallow with Fish-Rice pattern; (C) Shallow with Fish-Fish-Rice pattern; (D) Middle with Fish-Fish-Fish pattern; (E) Middle with Fish-Fish-Rice; (F) Deep with Fish-Rice pattern; (G) Deep with Fish-Fish-Rice pattern

Table 5. List of important attributes in each dimension

No	Ecology	Economy	Social
1	Feed availability	Pond productivity	Worker health insurance
2	Crop management	Shrimp sales	Worker time allocation
3	Electricity availability	Sales market	Conflict occurrences
4	Stocking density	Sales system	Working hours duration
		Cultivation regulations	Land ownership

DISCUSSION

Ecological constraints amid high land suitability

Although land suitability assessments often classify wetland areas as highly suitable (S1) for aquaculture-agriculture integration, practical ecological constraints frequently undermine sustainability. First, feed input inefficiencies are a primary concern. Excess feed or feed that is nutritionally imbalanced leads to elevated nitrogen and phosphorus loading in pond waters. This eutrophication depletes dissolved oxygen and can trigger harmful algal blooms, which in turn reduce fish survival and ecological quality **(Liu *et al*.. 2019; Perwira *et al*., 2020; Hasan *et al*., 2023)**. For instance, the study by **Liu *et al*. (2019)** shows that reactive N and P from aquaculture feed significantly accelerate eutrophication in freshwater systems, degrading water quality and biodiversity. FAO's work on feed quality aligns, illustrating that poor feed formulation worsens trophic imbalances. In sum, despite optimal land for cultivation, these feed-related inefficiencies place a severe ecological burden.

Second, stocking density and pond management practices exacerbate ecological strain even where land is technically ideal. High stocking densities increase metabolic waste, ammonia excretion, and organic matter deposition; poorly managed ponds have reduced capacity for natural self-purification **(Henriksson *et al*., 2021; Liu *et al*., 2021; Fujita, 2023; Kurniawan *et al*., 2024a)**. In pond aquaculture, for example, the inability of water to cycle or filter effectively can lead to accumulation of pollutants in sediment and water, which diminishes benthic organisms and alters microbial community structure **(Liu *et al*., 2021)**. Fujita's synthesis on ecological risks in marine and inland aquaculture highlights that system overload via overstocking or inadequate flushing consistently emerges as a risk factor for ecosystem collapse. **Henriksson *et al*. (2021)** emphasize that improving feed conversion ratios (FCR) and reducing stocking stress are essential management levers to prevent ecological degradation at sites otherwise classified as suitable.

Third, broader ecosystem-level processes such as nutrient cycling, hydrological connectivity, and habitat integrity are often overlooked in land suitability models, yet they are critical for maintaining ecological resilience. Even areas classified as highly suitable may experience ecological stress due to watershed inputs (e.g., fertilizer runoff), limited water exchange, or the loss of buffer vegetation that regulates sediment and nutrient flows **(Fujita *et al*., 2023; Salamah *et al*., 2024; Anggayasti *et al*., 2025)**. For instance, **Dong *et al* (2022)** and **Al Zamzami *et al* (2025)** highlight that eutrophication is not merely a local pond issue but often originates from landscape-scale nutrient inputs, making "ideal" sites vulnerable if upstream land use is poorly managed. Similarly, recent studies emphasize that site hydrology particularly circulation and water exchange mediates the ecological impacts of feed waste and nutrient loading. Moreover, **Gao *et al* (2025)** demonstrate that risks are amplified in deep or enclosed water systems, where stagnation and waste accumulation reduce resilience to environmental perturbations despite favorable soil or slope conditions.

Economic vulnerabilities and the role of diversification

The sustainability gaps in the economic dimension underscore how strongly aquaculture livelihoods are shaped by vulnerability to external shocks. Smallholders operating in monoculture systems remain particularly exposed to fluctuations in input prices, market dependence on a single commodity, and weak bargaining positions in value chains. Recent evidence suggests that reliance on limited sales outlets and middlemen reduces farmers' ability to capture fair value, while high transaction costs further erode net incomes **(Belton & Bush, 2014; Kumar *et al*., 2022; Ababouch *et al*. 2023)**. These conditions create a cycle where profitability is inconsistent, discouraging reinvestment in technology and management improvements that could otherwise enhance sustainability.

Diversification strategies offer a promising counterbalance to these vulnerabilities by spreading risks across multiple products and production cycles. Integrated rice–fish systems, for example, provide complementary benefits: rice paddies enhance fish nutrition through natural feed availability, while fish contribute to pest control and nutrient recycling in rice fields. Studies across South and Southeast Asia demonstrate that such diversification improves household income stability, even under volatile market conditions, while also supporting ecosystem services **(Halwart & Gupta, 2004; Berg *et al*., 2023; Kurniawan *et al*., 2024b; Samaddar *et al*., 2025)**. Importantly, diversification is not only a production strategy but also a financial buffer, reducing dependency on single-product markets that are prone to seasonal or global price shocks.

Yet the capacity of diversification to strengthen resilience is mediated by structural and institutional conditions. Farmers require secure land tenure, reliable water governance, and equitable access to credit and markets to realize the full benefits of diversified systems. Without supportive policy and infrastructure, diversification risks becoming superficial, providing only marginal improvements while leaving systemic vulnerabilities unaddressed. Recent analyses highlight that inclusive value-chain interventions, investment in rural infrastructure, and farmer cooperatives are essential to convert diversification into sustained economic resilience **(Genschick *et al*., 2018; Krause *et al*., 2020; FAO, 2022; Sukoso *et al*., 2025)**. In this sense, diversification should be understood as part of a broader resilience-building strategy that integrates ecological efficiency, institutional support, and socio-economic equity.

Social acceptance as a stabilizing dimension

Social acceptance emerges as a pivotal stabilizer in aquaculture-agriculture systems where ecological or economic weaknesses might otherwise lead to instability. Recent work shows that public perceptions and social license to operate (SLO) are closely tied to how transparent operations are, how well environmental and social risks are communicated, and whether local communities are included early in planning processes **(Budhathoki *et al*., 2024; Olsen *et al*., 2024; Pérez *et al*., 2025)**. For example, in “Social license to operate for aquaculture – A cross-country comparison,” **Olsen *et al*. (2024)** found that countries with stronger engagement practices and public communication enjoy higher trust from communities and greater tolerance for aquaculture expansion. Similarly, **Budhathoki *et al*. (2024)** note that ambiguity around environmental impacts (e.g. water quality, waste discharge) erodes acceptance, whereas clarity and evidence of mitigations bolster support. Thus, systems that embed stakeholder communication and enforce accountability mechanisms tend to sustain better social stability.

Labor welfare, fairness in benefit sharing, and conflict prevention are additional components of social acceptance that play out in practical ways. Studies suggest that when aquaculture operations provide fair employment terms, health or safety protections, and visible sharing of gains (e.g. local hire, community benefits), local resistance is reduced and community cooperation improves **(Wood *et al*., 2022; Garlock *et al*., 2024; Pérez *et al*., 2025)**. In “Environmental, Economic, and Social Sustainability in Aquaculture: The Aquaculture Performance Indicators,” **Garlock *et al*. (2024)** found positive correlations between social outcome metrics and the presence of welfare practices. **Pérez *et al*. (2025)** highlight that regulation which mandates benefit sharing and fair labor conditions increases legitimacy of aquaculture in the eyes of affected communities. **Wood *et al*. (2022),** working on bivalve aquaculture, show that perceived fairness, not just economic gain, matters a great deal for whether communities accept or reject aquaculture projects. In effect, social stability is often more durable when local well-being is visibly prioritized rather than treated as an afterthought.

Governance frameworks and participatory decision-making determine how social acceptance is institutionalized and maintained. The newly developed Aquaculture Governance Indicators (AGI) framework **(Toonen *et al*. 2025)** underscores that legitimacy, coordination, and governance capability are essential dimensions of sustainable governance which directly influence public trust and acceptance. **Partelow (2023)** argues that multi-stakeholder forums, co-management schemes, and mandated public feedback loops are necessary to reduce conflict and ensure regulations reflect community needs. In addition, in "Strengthening policy action to tackle social acceptability" **(Pérez *et al*., 2025)**, it is shown that regulatory regimes which are perceived as inclusive, enforceable, and responsive tend to yield higher social license and compliance. Therefore, stable social acceptance depends not only on delivering benefits but on building and sustaining governance institutions that are trusted, fair, and adaptive.

Leverage points for targeted interventions

One of the most effective levers lies in feed efficiency and alternative feed sources. Improving feed efficiency reduces costs, lowers environmental load, and improves profitability simultaneously. Recent reviews show that fermented feed ingredients, plant-based proteins, insect meals, and fishery by-products can replace portions of traditional fishmeal/fish oil without compromising growth or health in many species. For example, insect-based diets and aquaculture by-product inclusion are identified as scalable alternatives **(Tran *et al*., 2023; Mas'ud *et al*., 2025)**. Similarly, fermented feeds improve digestibility and reduce waste output **(Zhang *et al*., 2025)**. Nanotechnology applications in aquaculture feeds further enhance nutrient absorption and reduce feed conversion ratio (FCR), amplifying gains from feed interventions **(Khan *et al*., 2024; Ismail *et al*., 2025)**. Thus, targeted investment in alternative feed research, local feed production, and farmer training in feed management emerges as a high-leverage strategy.

Secondly, market access, value chain strengthening, and supply chain resilience represent critical intervention points. Producers with diversified market channels (direct, local, regional) are more resilient to demand shocks **(Zhou *et al*. 2025)**. Similarly, improving input supply chains such as ensuring reliable hatcheries and quality fingerlings supports profitability and reduces vulnerability **(Byabasaija *et al*. 2025)**. Interventions piloted in Kenya also demonstrate that investments in cold storage, improved seed strains, and stronger producer–market linkages effectively reduce post-harvest losses **(WorldFish, 2024)**. These findings suggest that policy and investment focus on infrastructure, supply chain transparency, and facilitate direct farmer buyer relationships with leverage to attain large gains in economic stability.

Third, labor welfare, governance, and institutional support serve as stabilizing levers to maintain resilience and social license. Without good labor conditions, fair regulation, and participatory governance, even technically strong systems may falter. Certification schemes, safety standards, and worker welfare measures have been shown to reduce attrition, build trust, and increase productivity **(Lloyd's Register Foundation, 2025)**. Governance support through climate-resilient and regenerative aquaculture initiatives also highlights the importance of institutional clarity and community engagement **(Rahman *et al*., 2024; Kurniawan *et al*., 2025)**. Moreover, integrating aquatic organism health into management decisions provides direct economic benefits while maintaining community trust and social acceptance **(Chen *et al*., 2025)**. These examples suggest that interventions should not just focus on technical improvements but embed them within institutional frameworks through policy, certification, training, and stakeholder participation.

CONCLUSION

This study demonstrates that while wetland systems may be classified as highly suitable for aquaculture–agriculture integration, ecological, economic, and social performance often diverge from biophysical potential. By applying a multidimensional sustainability framework and identifying high-leverage attributes, the research highlights that ecological constraints such as feed inefficiency and stocking practices, economic vulnerabilities tied to market dependence, and social dimensions shaped by labor welfare and governance must all be addressed simultaneously. The novelty lies in integrating land suitability with sustainability indices and leverage analysis, offering a more holistic approach to understanding system resilience. The findings underscore that sustainable aquaculture development cannot rely solely on land potential but requires targeted interventions improving feed systems, diversifying markets, and strengthening social protections to build ecological integrity, economic viability, and community legitimacy in tandem.

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