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Ketahanan sosial ekonomi usaha budidaya rumput laut skala kecil di Kawasan Konservasi Perairan Minahasa Utara
[Socioeconomic resilience of small-scale seaweed aquaculture enterprises in the North Minahasa Marine Conservation Area]

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ABSTRACT | Small-scale seaweed aquaculture enterprises in marine conservation areas face intertwined ecological, market, institutional, and supply-chain pressures that weaken coastal livelihoods. This study assessed the socioeconomic resilience of small-scale seaweed aquaculture enterprises in the North Minahasa Marine Conservation Area, using West Likupang as an empirical case. An integrated House of Risk (HOR) and fuzzy Analytic Hierarchy Process (FAHP) approach was applied to identify vulnerabilities, prioritize risk agents, and formulate mitigation strategies using primary data from 30 key stakeholders. The HOR1 analysis revealed that market uncertainty and institutional constraints primarily threaten resilience, with unstable demand (ARP = 3,106.46) and reliance on local distributors (ARP = 3,081.03) emerging as top priority risks. Complementing these findings, the FAHP analysis highlighted profit enhancement and price stabilization as the primary criteria for socioeconomic resilience. To address these vulnerabilities, HOR2 results prioritized government-facilitated price agreements and subsidies (ETD = 68,809.34) alongside digital market-communication systems (ETD = 23,705.32) as the most effective mitigations, followed by a regional processing enterprise and seaweed hubs. The study demonstrates that enhancing the socioeconomic resilience of small-scale seaweed enterprises requires integrating marine conservation governance with interventions that improve market access, price transparency, transaction mechanisms, and institutional coordination.

Key words | Conservation area; North Minahasa; resilience; seaweed aquaculture; small-scale enterprise

ABSTRAK | Usaha budi daya rumput laut skala kecil di kawasan konservasi perairan menghadapi tekanan ekologis, pasar, kelembagaan, dan rantai pasok yang saling berkaitan serta melemahkan penghidupan masyarakat pesisir. Penelitian ini mengkaji resiliensi sosioekonomi usaha budi daya rumput laut skala kecil di Kawasan Konservasi Perairan Minahasa Utara, dengan Likupang Barat sebagai kasus empiris. Pendekatan terintegrasi *House of Risk* (HOR) dan *fuzzy Analytic Hierarchy Process* (FAHP) diterapkan untuk mengidentifikasi kerentanan, memprioritaskan agen risiko, dan merumuskan strategi mitigasi menggunakan data primer dari 30 pemangku kepentingan kunci. Analisis HOR1 mengungkapkan bahwa ketidakpastian pasar dan keterbatasan kelembagaan menjadi ancaman utama terhadap resiliensi, dengan permintaan yang tidak stabil (ARP = 3.106,46) serta ketergantungan pada distributor lokal (ARP = 3.081,03) sebagai risiko prioritas tertinggi. Melengkapi temuan tersebut, analisis FAHP menyoroti peningkatan keuntungan dan stabilisasi harga sebagai kriteria utama resiliensi sosioekonomi. Guna mengatasi kerentanan ini, hasil HOR2 memprioritaskan kesepakatan harga dan subsidi yang difasilitasi pemerintah (ETD = 68.809,34) serta sistem komunikasi pasar berbasis teknologi informasi (ETD = 23.705,32) sebagai mitigasi paling efektif, diikuti oleh BUMD pengolahan rumput laut dan sentra (*hubs*) rumput laut. Penelitian ini menunjukkan bahwa penguatan resiliensi sosioekonomi usaha rumput laut skala kecil memerlukan integrasi antara tata kelola konservasi laut dan intervensi yang meningkatkan akses pasar, transparansi harga, mekanisme transaksi, serta koordinasi kelembagaan.

Kata kunci | Kawasan konservasi; Minahasa Utara; ketahanan; budidaya rumput laut; usaha skala kecil

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INTRODUCTION

Small-scale seaweed aquaculture enterprises are an important component of coastal livelihood systems because they provide employment, household income, and opportunities for productive use of nearshore waters. In archipelagic regions, seaweed farming is often managed by coastal households with limited capital, simple technology, and strong dependence on local market networks. Seaweed has substantial economic value, can be cultivated using relatively accessible techniques, and contributes to livelihood diversification and community wellbeing in Indonesia (Rimmer *et al*., 2021).

North Minahasa Regency is characterized by small-island waters that support fisheries, marine tourism, conservation, and seaweed-based coastal economies. The marine conservation area in the waters of

North Minahasa has been formally designated through Ministerial Decree of the Ministry of Marine Affairs and Fisheries Number 128 of 2023. This designation reinforces the need to maintain ecological functions, but conservation governance also needs to safeguard the socioeconomic resilience of seaweed-farming households and other coastal actors whose livelihoods depend on sustainable marine-resource use.

In the context of small-scale seaweed aquaculture enterprises, socioeconomic resilience refers to the capacity of farmers, enterprise groups, and coastal households to maintain, adapt, and recover livelihood functions when exposed to environmental disturbances, market volatility, institutional constraints, and supply-chain shocks. Studies on small-scale fisheries and coastal livelihoods show that vulnerability is shaped not only by resource conditions but also by market access, price information, collective organization, adaptive capacity, and institutional support (Amadu *et al*., 2021; Bassett *et al*., 2022).

The main challenges faced by small-scale seaweed aquaculture enterprises in archipelagic areas include limited information access, dependence on intermediaries, price fluctuations, high logistics costs, inconsistent dried-seaweed quality, and limited post-harvest technology. In seaweed production centres in North Minahasa, production decline and crop diseases such as ice-ice have intensified socioeconomic risks by reducing product quality, farm-gate prices, and incentives to continue farming. These conditions show that conservation-area strengthening should be linked to seaweed value-chain development, farmer institutions, and locally appropriate livelihood-support mechanisms.

Previous studies on socioeconomic resilience in small-scale fisheries and coastal livelihoods have largely emphasized adaptive capacity and the availability of livelihood assets, including financial, human, social, physical, and natural capital. These perspectives have provided important insights into how households and fishing communities respond to environmental change, market disturbances, and institutional pressures. However, resilience is not determined solely by the assets available to individual households or communities. For small-scale seaweed enterprises, the continuity of livelihoods is also strongly influenced by the performance and vulnerability of the supply chain through which inputs, production activities, post-harvest handling, transportation, market information, and sales are connected.

Compared with the extensive attention given to adaptive capacity and livelihood assets, the supply-chain risk dimension of socioeconomic resilience has received relatively limited attention in studies of small-scale seaweed enterprises, particularly in marine conservation areas. Supply-chain disruptions can affect farmers even when their productive and livelihood assets remain available. Limited access to quality seed, unstable demand, dependence on local distributors, non-competitive selling prices, transportation constraints, and weak institutional coordination can reduce the capacity of enterprises to maintain production and generate stable income. These risks may interact and accumulate across different stages of the supply chain, suggesting that socioeconomic resilience should also be examined as the capacity of an enterprise system to identify, absorb, and mitigate interconnected supply-chain risks.

This gap is particularly relevant in small-island and archipelagic settings, where geographical isolation, limited market connectivity, and dependence on a small number of buyers can intensify supply-chain vulnerabilities. A supply-chain risk perspective can therefore complement the conventional livelihood-assets and adaptive-capacity approaches by identifying specific risk sources and prioritizing interventions that can strengthen the resilience of small-scale enterprises. In this context, integrating supply-chain risk identification with multi-criteria prioritization provides an opportunity to move beyond a general assessment of resilience toward a more operational framework for identifying and addressing the mechanisms that constrain socioeconomic resilience. Hafinuddin *et al*. (2024) reported that the Kuala Tadu Fish Landing Base plays an important role in the local fishing economy, although its function needs to be strengthened through improved facilities, better fisher knowledge, more effective auction mechanisms, and cold-chain infrastructure. From a socio-ecological perspective, Najmi *et al*. (2024) emphasized that community perceptions and participation influence the success of sustainable mangrove-ecosystem management. Nur and Irfannur (2024) further showed that production and supply-chain analysis of fishery commodities is important for understanding consumer demand, regional economic bases, and product-distribution performance. These findings support the argument that seaweed-enterprise resilience should be approached through conservation management, logistics support, community participation, and market transparency.

The House of Risk (HOR) and fuzzy Analytic Hierarchy Process (FAHP) approaches can be used to identify risk sources, assess mitigation priorities, and formulate systematic strategies for strengthening small-scale seaweed aquaculture enterprises. HOR supports the mapping of risk events and risk agents across supply-chain processes, whereas FAHP accommodates expert judgement when decision-making involves multiple criteria and uncertainty (Ayağ & Özdemir, 2006; Pujawan & Geraldin, 2009).

Against this background, this study assessed the socioeconomic resilience of small-scale seaweed aquaculture enterprises in the North Minahasa Marine Conservation Area by examining the risks embedded in their supply-chain system. The study specifically aimed to (1) identify and prioritize supply-chain risk events and risk sources affecting small-scale seaweed enterprises, (2) assess the relative importance of socioeconomic resilience drivers, and (3) prioritize feasible mitigation strategies using an integrated House of Risk (HOR) and fuzzy Analytic Hierarchy Process (FAHP) approach. By integrating supply-chain risk management with a socioeconomic resilience perspective, the study seeks to provide an operational basis for strengthening small-scale seaweed livelihoods while maintaining compatibility with marine conservation objectives.

MATERIALS AND METHODS

Study site and period

Data collection was carried out from August to November 2024 in the coastal and small-island areas of West Likupang District, North Minahasa Regency, North Sulawesi Province, Indonesia. The study focused empirically on small-scale seaweed aquaculture enterprises operating within and around the North Minahasa Marine Conservation Area.

Research design and approach

This study employed a qualitative case study approach, supported by expert-based decision analysis using the House of Risk (HOR) and Fuzzy Analytic Hierarchy Process (FAHP). The case study focused on small-scale seaweed aquaculture enterprises operating within and around the North Minahasa Marine Conservation Area, with particular attention to the supply-chain processes linking production, input procurement, post-harvest handling, transportation, and marketing.

The qualitative case study approach was used to obtain an in-depth understanding of the production, market, institutional, and supply-chain conditions affecting the socioeconomic resilience of small-scale seaweed enterprises. Primary information was collected through key informant interviews, focus group discussions (FGDs), and field observations. These qualitative data were used to identify supply-chain processes, risk events, risk sources, institutional constraints, and feasible mitigation alternatives.

The HOR and FAHP methods were subsequently used to structure and prioritize the information obtained from the field. HOR was applied to identify and prioritize the major sources of supply-chain risk by examining the relationships between risk events and their underlying risk agents. FAHP was then used to assess the relative importance of socioeconomic resilience drivers and prioritize feasible mitigation alternatives based on expert judgement. Thus, the qualitative case study provided the empirical basis for identifying and interpreting the risks, while HOR and FAHP provided a systematic decision-analysis framework for risk prioritization and mitigation planning.

Data collection and informants

Primary data were collected through field surveys, focus group discussions, and structured assessments of supply-chain risks. The qualitative and risk-assessment component involved 30 participants, comprising 20 seaweed farmers, five local distributors, and three local government representatives. In addition, two experts were involved in the expert-based assessment of the decision hierarchy and mitigation priorities. Participants were selected purposively based on their direct involvement in seaweed cultivation, distribution, local government support, or technical and institutional knowledge relevant to seaweed supply-chain management and coastal governance in North Minahasa.

The two experts were selected based on their professional experience, technical knowledge, institutional involvement, and familiarity with seaweed supply-chain management and coastal governance in the study area. The collected information covered risk-event severity, risk-agent occurrence, relationships between risk agents and risk events, and the feasibility and effectiveness of potential mitigation actions.

Risk identification using House of Risk

The first stage of the House of Risk (HOR1) mapped risk events (Ei) and risk agents (Aj) across the seaweed supply-chain processes. Each risk event was assessed according to its severity (Si), while each risk agent was assessed according to its occurrence (Oj). The relationship between each risk agent and risk event (Rij) was subsequently assessed using the adopted HOR relationship scale. Respondent assessments were aggregated using the arithmetic mean to obtain the values used in HOR1.

The Aggregate Risk Potential (ARP) for each risk agent was calculated as:ARP_j=O_j\sum_{i=1}^{n}(S_i\times R_{ij})where ARPj represents the aggregate risk potential of risk agent j, Oj is the occurrence score of risk agent j, Si is the severity score of risk event i, and Rij represents the strength of the relationship between risk agent j and risk event i. Risk agents were ranked according to their ARP values, and the cumulative contribution of the ranked ARP values was used to identify the principal risk sources.

Table 1. Risk events of small-scale seaweed aquaculture enterprises by supply-chain process

Process	Sub-process	Risk event	Code	Si
Plan	Production planning	Information on superior seed from suppliers is unavailable	E1	3
Plan	Production planning	Information on suitable farming sites is limited	E2	2
Plan	Demand forecasting	Annual price forecasts are inaccurate	E3	9
Plan	Demand forecasting	Forecasts of local and external market demand are inaccurate	E4	9
Source	Input procurement	Seeds purchased do not meet quality or quantity standards	E5	6
Make	Production	Seaweed is affected by pests or disease	E6	9
Make	Production	The ratio between dried and wet seaweed is inconsistent	E7	7
Make	Production	Harvesting is conducted too early due to household or market pressure	E8	8
Deliver	Distribution	Products are damaged by freshwater exposure during transportation	E9	9
Deliver	Distribution	Delivery to distributors is delayed	E10	4
Deliver	Distribution	Transportation costs are relatively high	E11	4
Return	Seed return	Returning seeds to suppliers is delayed	E12	4

Note: Si = risk-event severity score.

Table 2. Risk agents and occurrence probabilities

Risk agent	Oj	Code
Unstable seaweed demand	9	A1
Government assistance is not well targeted	7	A2
Availability of high-quality seed remains limited	5	A3
Climate variability	3	A4
Rapid technological change	4	A5
Dependence on local distributors	8	A6
Conflicts among business actors	3	A7
Non-competitive selling price	8	A8
Limited involvement of NGOs, universities, and research institutions	8	A9
Geographical distance from urban centres	5	A10

Note: Oj = occurrence probability of the risk agent.

Table 3. Mitigation alternatives evaluated in the study

Code	Mitigation alternative
PA1	Establishment of a regional government-owned enterprise for seaweed processing
PA2	Formation of seaweed farmer communities or cooperatives
PA3	Development of an information centre through collaboration among government, NGOs, universities, and research institutions
PA4	Use of information technology for market communication and coordination
PA5	Government-facilitated agreements with suppliers and distributors on selling prices, including subsidies
PA6	Establishment of seaweed hubs on major islands through multi-stakeholder collaboration

Mitigation prioritization using fuzzy AHP

Mitigation alternatives obtained from HOR were evaluated using FAHP. The hierarchy consisted of the goal, criteria, sub-criteria, actors, and alternative actions. Expert assessments were converted into triangular fuzzy numbers through fuzzification and transformed into crisp scores through defuzzification. Expert consensus was calculated using the geometric mean, and the consistency of judgements was tested using the Consistency Ratio with an acceptance threshold of CR < 0.10.

Data analysis

HOR data were analysed by calculating severity, occurrence probability, risk-agent-to-risk-event correlations, and Aggregate Risk Potential. The ARP score was used to determine priority risks as the basis for formulating mitigation measures. FAHP data were analysed through pairwise comparison matrices, priority-weight calculation, defuzzification, and consistency testing. The final results were interpreted to explain the linkages among supply-chain risks, socioeconomic resilience, and marine conservation-area management.

RESULTS

Priority risk sources for small-scale seaweed aquaculture enterprises

The HOR1 analysis revealed considerable variation in the priority of risk agents affecting the socioeconomic resilience of small-scale seaweed aquaculture enterprises. Unstable seaweed demand (A1) emerged as the highest-priority risk agent, with an occurrence score of 8.47 and an Aggregate Risk Potential (ARP) of 3,106.46. Dependence on local distributors (A6) ranked second, with an ARP of 3,081.03, followed by limited involvement of NGOs, universities, and research institutions (A9), with an ARP of 2,996.00. Non-competitive selling prices (A8) and poorly targeted government assistance (A2) ranked fourth and fifth, with ARP values of 2,762.21 and 2,726.17, respectively (Table 4).

The five highest-ranked risk agents accounted for 65.83% of the total ARP, indicating that market, institutional, and transactional factors constitute major sources of vulnerability for small-scale seaweed enterprises in the study area. The prominence of unstable seaweed demand suggests that socioeconomic resilience is influenced not only by production capacity but also by farmers' ability to anticipate market conditions and secure reliable outlets for their products. Meanwhile, dependence on local distributors remains a substantial risk because farmers may have limited access to alternative buyers, market information, and direct market channels.

The results further indicate that limited institutional involvement, non-competitive prices, and poorly targeted government assistance are interconnected with market vulnerability. These findings suggest that resilience-building interventions should extend beyond production-oriented support and address market access, price mechanisms, institutional coordination, and the effectiveness of public-sector interventions. Strengthening these dimensions may reduce farmers' exposure to multiple risk sources simultaneously.

Table 4. Risk agents prioritized based on Aggregate Risk Potential

Rank	Code	Risk agent	Oj	ARP	Contribution (%)	Cumulative (%)
1	A1	Unstable seaweed demand	8,47	3.106,46	13,94	13,94
2	A6	Dependence on local distributors	8,37	3.081,03	13,82	27,76
3	A9	Limited involvement of NGOs. universities. and research institutions	8,13	2.996,00	13,44	41,20
4	A8	Non.competitive selling price	7,63	2.762,21	12,39	53,59
5	A2	Government assistance is not well targeted	7,57	2.726,17	12,23	65,83
6	A10	Geographical distance from urban centres	5,00	1.815,73	8,15	73,97
7	A3	Availability of high.quality seed remains limited	5,00	1.723,90	7,73	81,71
8	A5	Rapid technological change	4,27	1.569,02	7,04	88,75
9	A7	Conflicts among business actors	3,73	1.357,22	6,09	94,84
10	A4	Climate variability	3,03	1.151,22	5,16	100,00

Table 5. Priority of mitigation actions based on HOR2

Rank	Code	Mitigation action	TE	Difficulty	ETD
1	PA5	Government, facilitated price agreements/subsidies	100,920.36	1.47	68,809.34
2	PA4	Information technology	118,526.60	5.00	23,705.32
3	PA1	Regional government, owned enterprise for seaweed processing	63,053.85	3.27	19,302.20
4	PA6	Seaweed hubs	57,535.84	3.00	19,178.61
5	PA2	Seaweed farmer communities/cooperatives	59,890.70	4.93	12,140.01
6	PA3	Information centre	33,254.98	4.73	7,025.70

Note: TE = Total Effectiveness; ETD = Effectiveness to Difficulty ratio.

Table 6. FAHP criteria for assessing socioeconomic resilience

Criterion	Operational definition	Key assessment indicators	FAHP weight	Rank
Profit enhancement	The capacity of seaweed enterprises to generate sufficient economic returns to sustain production and support household needs and reinvestment	Household income, production sustainability, capacity to purchase seed and inputs, post-harvest investment, and transportation capacity	0.41	1
Price stabilization	The degree to which farmers can access predictable and transparent selling-price conditions	Price transparency, reduced price uncertainty, access to market information, and bargaining capacity	0.35	2
Trust-building among supply-chain actors	The quality and reliability of relationships among farmers, distributors, government institutions, and supporting organizations	Information transparency, reliability, commitment, coordination, and compliance with agreements	0.23	3

Note: FAHP weights were derived from aggregated pairwise comparisons provided by the selected experts. The consistency ratio (CR) of the aggregated comparison matrix was 0.046, which is below the recommended threshold of 0.10.

Table 7. Relationship scores between priority risk agents and mitigation actions in HOR2

Constraint	Effect on enterprise performance	Score
Limited access to superior seed	Inconsistent harvest quality and reduced product competitiveness	8.50
Limited farming knowledge	Premature harvesting and sub-optimal production	7.20
Inadequate post-harvest technology	Products fail to meet market standards and therefore receive lower prices	7.80

Note: Relationship scores were assigned based on expert judgement using the HOR scale: 0 = no relationship, 1 = low relationship, 3 = moderate relationship, and 9 = strong relationship. The scores represent the assessed effectiveness of each mitigation action in addressing the corresponding priority risk agent. Scores were aggregated across the expert assessments and subsequently combined with the ARP values from HOR1 to calculate the total effectiveness (TE) of each mitigation action.

Table 8. Actor roles in strengthening socioeconomic resilience

Actor	Role focus	FAHP weight
Local government	Subsidies, extension services, infrastructure, and conservation-area coordination	0.34
Universities/research institutions	Applied research, training, seaweed cultivation technology, and post-harvest technology	0.26
Seaweed farmer organizations/cooperatives	Collective bargaining, logistics, and quality control	0.22
Private sector	Market access, price setting, and product procurement	0.12
NGOs/development partners	Facilitation, mentoring, and capacity building	0.06

Table 9. Priority alternatives for strengthening the socioeconomic resilience of small-scale seaweed aquaculture enterprises

Rank	Alternative	FAHP weight	Cumulative (%)
1	Seaweed Cultivation Information Centre	309	30.90
2	Producer clusters based on location or production patterns	271	58.00
3	Formation of seaweed farmer communities or cooperatives	245	82.50
4	ICT-based market and logistics coordination platform	176	100.00

Priority Mitigation Actions Based on HOR2

Based on the five highest-priority risk agents identified through HOR1, the second stage of the House of Risk (HOR2) evaluated alternative mitigation actions according to their effectiveness and implementation difficulty. Government-facilitated agreements on selling prices and subsidies (PA5) obtained the highest Effectiveness to Difficulty (ETD) ratio, with a value of 68,809.34. Information technology for market communication and coordination (PA4) ranked

second, with an ETD value of 23,705.32. The establishment of a regional government-owned enterprise for seaweed processing (PA1) ranked third (ETD = 19,302.20), followed by the establishment of seaweed hubs on major islands (PA6; ETD = 19,178.61).

Seaweed farmer communities or cooperatives (PA2) ranked fifth, with an ETD value of 12,140.01, whereas the establishment of a seaweed cultivation and market information centre (PA3) obtained the lowest ETD value of 7,025.70. The results indicate that interventions directly addressing market transactions, price mechanisms, and communication channels have relatively greater effectiveness compared with interventions requiring more complex institutional or infrastructural arrangements.

The high ETD value of PA5 is particularly relevant to the risk profile identified in HOR1 because unstable demand, dependence on distributors, and non-competitive selling prices were among the most important risk agents. Government-facilitated price agreements and appropriate subsidy mechanisms may therefore provide a direct institutional mechanism for reducing transaction uncertainty and improving farmers' economic security. However, such mechanisms should be designed transparently and periodically reviewed to avoid creating excessive dependence on government intervention or distorting market incentives.

The high ranking of PA4 further indicates the importance of accessible digital communication for improving market coordination. Information technology can facilitate the dissemination of market prices, demand information, buyer contacts, production conditions, and logistics information. In the context of small-island and archipelagic communities, however, implementation should consider connectivity constraints, digital literacy, and the capacity of farmers and local institutions to maintain and use digital platforms effectively.

Drivers of socioeconomic resilience

The FAHP analysis identified three major drivers of socioeconomic resilience among small-scale seaweed aquaculture enterprises: profit enhancement, price stabilization, and trust-building, with priority weights of 0.41, 0.35, and 0.23, respectively (Tabel 6). Profit enhancement ranked highest, reflecting its importance in improving household economic returns through better market access, stronger bargaining power, transparent buyer selection, reduced transaction inefficiencies, and reinvestment in production and post-harvest activities. Adequate returns enable farmers to maintain production, purchase quality seed, manage harvesting and drying, and meet operational costs. Price stabilization ranked second, highlighting the need to reduce uncertainty caused by limited access to reliable market information. Transparent price and demand information can reduce information asymmetry and support better harvest and selling decisions. Trust-building, although ranked third, remains essential for strengthening relationships and information exchange among farmers, suppliers, distributors, government agencies, universities, and other institutions. Overall, socioeconomic resilience depends not only on income growth but also on price certainty and institutional relationships. Strengthening these dimensions simultaneously can help small-scale seaweed enterprises absorb market shocks, sustain production, and adapt business practices within marine conservation areas.

Constraints affecting product quality and business profitability

The technical constraints that most strongly affected seaweed quality and business profitability were limited access to superior seed, insufficient cultivation knowledge, and inadequate post-harvest technology. These constraints led to inconsistent harvest quality, premature harvesting, low dried-seaweed standards, and weak selling prices. In conservation areas, such technical issues must be addressed while maintaining ecosystem carrying capacity and sustainable-use principles.

Priority actors and interventions

The FAHP results showed that local government had the highest institutional weight because of its role in subsidies, extension, infrastructure, and conservation-area coordination. Universities and research institutions contributed through technology development, training, and market information for seaweed farming. Seaweed farmer organizations or cooperatives served as mechanisms for strengthening bargaining power, quality control, and logistics coordination.

The mitigation alternative with the highest weight was the establishment of a seaweed cultivation information centre. This alternative would consolidate information on prices, seed quality, ice-ice disease incidence, weather, harvest schedules, drying standards, and market opportunities. The next priorities were seaweed producer clusters, farmer community or cooperative formation, and ICT-based market-coordination platforms.

DISCUSSION

The identification of unstable seaweed demand (A1) as the highest-ranked risk agent indicates that market uncertainty is a central constraint on the socioeconomic resilience of small-scale seaweed aquaculture enterprises in North Minahasa. An occurrence score of 8.47 and an ARP of 3,106.46 indicate that uncertainty in demand has a substantial combined effect when both its frequency and its relationships with the identified risk events are considered. Demand uncertainty can influence production planning, harvesting decisions, sales timing, and farmers' expectations regarding household income.

Dependence on local distributors (A6) remained the second-highest risk agent, with an ARP of 3,081.03. This finding indicates that intermediary dependence remains important even though it was not the highest-ranked risk in the present dataset. Limited access to market information and alternative buyers may reduce farmers' bargaining power and increase their vulnerability to unfavourable transaction conditions. Similarly, limited institutional involvement (A9), non-competitive selling prices (A8), and poorly targeted government assistance (A2) occupied the third to fifth positions, indicating that market, institutional, and policy factors jointly influence socioeconomic resilience.

The cumulative contribution of the five highest-ranked risk agents was 65.83%, suggesting that resilience-building interventions should address several interconnected dimensions rather than concentrating on a single supply-chain constraint. In particular, improving market-demand information, strengthening producer organizations, expanding institutional support, improving price transparency, and

increasing the effectiveness of government assistance may reduce multiple sources of vulnerability simultaneously.

The findings indicate that the socioeconomic resilience of small-scale seaweed aquaculture enterprises in a marine conservation area cannot be separated from market structure and supply-chain institutions. Dependence on local distributors reflects information asymmetry between seaweed farmers and market actors who have stronger access to price information, quality standards, and demand. Under such conditions, farmers risk becoming price takers rather than strategic decision-makers in the seaweed value chain.

This result is consistent with the small-scale fisheries and aquaculture literature, which identifies supply chains as a critical factor in livelihood resilience. Bassett *et al*. (2022) showed that the vulnerability of small-scale fishery supply chains increases when distribution channels are narrow, information access is limited, and business actors have few market options. In the context of seaweed aquaculture, market-channel diversification and stronger communication among actors are therefore important prerequisites for strengthening adaptive capacity.

From a conservation-area perspective, marine management cannot be limited to spatial boundaries and rules of resource use. Ecological protection must be accompanied by mechanisms that safeguard community income from seaweed farming and other coastal livelihoods. If seaweed farmers do not obtain fair market access, conservation benefits may be difficult to accept as part of livelihood strategies. Therefore, conservation-area management in North Minahasa needs to integrate ecosystem protection, local economic strengthening, and participatory governance.

Thus, socioeconomic resilience strategies in conservation areas should be understood as a combination of resource protection, production-support services, and market institutions. Evidence from the Kuala Tadu Fish Landing Base shows that basic facilities, auction functions, ice plants, and fisher capacity-building are important for improving the economic function of fisheries (Hafinuddin *et al*., 2024). Similarly, coastal-ecosystem management requires social acceptance and community participation so that conservation efforts are not separated from local livelihood interests (Najmi *et al*., 2024). This linkage is also consistent with supply-chain studies of Pacific white shrimp, which position production, distribution, and regional base-sector information as foundations for fishery commodity development planning (Nur & Irfannur, 2024). For seaweed enterprises, these insights imply that conservation governance should be accompanied by practical support for market information, quality management, and producer coordination.

The seaweed cultivation and market information centre emerged as the highest-priority intervention because it addresses the information and market-access constraints underlying price instability. In this study, price stabilization was operationally interpreted through three related indicators: transparency and accessibility of current seaweed price information, reduction of information asymmetry between farmers and buyers, and improvement of farmers' bargaining capacity. The relevance of these indicators is supported by the HOR results, in which dependence on local distributors was the highest-priority risk source (25%), followed by non-competitive selling prices (15%). These findings indicate that farmers' price-setting capacity is constrained by limited access to market information and strong dependence on local buyers.

The FAHP analysis further identified price stabilization as the second-ranked criterion of socioeconomic resilience, with a priority weight of 0.363, after profit enhancement (0.408), while trust-building among supply-chain actors received a weight of 0.229. The consistency ratio (CR) of the aggregated criteria comparison was approximately 0.046, indicating an acceptable level of consistency in the expert judgements.

Based on these findings, the seaweed cultivation and market information centre is not interpreted as a mechanism for directly regulating or fixing market prices. Rather, it is proposed as a supporting mechanism for improving access to transparent and timely information on prevailing prices, market demand, buyer conditions, and product-quality requirements. Such information may enable farmers to compare buyers, assess market conditions, determine more appropriate selling times, and negotiate from a stronger information position. Information concerning seed quality, ice-ice disease, weather conditions, drying requirements, and post-harvest standards may also reduce uncertainty in production and marketing decisions.

In the archipelagic context of North Minahasa, such information services could be implemented through a hybrid mechanism combining physical information points in villages or major islands with simple digital services accessible through low-bandwidth devices. However, the revised HOR2 results indicate that the information centre itself was not the highest-priority mitigation action. Government-facilitated price agreements and subsidies (PA5) ranked first, information technology for market communication and coordination (PA4) ranked second, whereas the information centre (PA3) ranked sixth based on the ETD ratio. Therefore, the information centre is interpreted as a complementary mechanism that can support broader market and institutional interventions rather than as the primary mitigation action.

Seaweed producer clusters and cooperatives have complementary functions in strengthening trust and coordination among supply-chain actors. In this study, trust-building was operationally defined through four interrelated dimensions: transparency in sharing production and market information, reliability in fulfilling agreed responsibilities and transactions, commitment to maintaining longer-term cooperation, and compliance with agreed arrangements concerning product quality, harvesting schedules, delivery, purchasing, and other business practices. These dimensions were considered relevant because small-scale seaweed enterprises often operate through repeated transactions and relationships among farmers, local distributors, government institutions, and other supporting actors. Evidence from farmer and fisher institutions also indicates that collective organizations can improve access to services, transaction efficiency, and negotiating capacity when supported by transparent governance (Bijman *et al*., 2012).

The relevance of trust-building is further supported by the HOR findings. Dependence on local distributors was identified as one of the most important risk agents, with an ARP of 3,081.03. This result indicates that strong dependence on particular buyers may increase farmers' exposure to information asymmetry and constrain their ability to coordinate transactions and negotiate market conditions.

The finding also highlights the importance of institutional and collective mechanisms that can provide alternative channels for information exchange, coordination, and market access.

In the FAHP assessment, trust-building received a priority weight of 0.229, compared with 0.408 for profit enhancement and 0.363 for price stabilization. The weight represents the experts' relative assessment of the importance of trust-building as a criterion of socioeconomic resilience; it should not be interpreted as a direct quantitative measure of the absolute level of trust among supply-chain actors. The assessment was based on the expected contribution of trust-building to reducing information asymmetry, improving coordination, and strengthening reliable cooperation among farmers, distributors, government agencies, research institutions, and other relevant actors.

Producer clusters and cooperatives can translate these trust-building functions into practical arrangements through routine information exchange, transparent records of prices and product quality, agreed production and delivery schedules, documented responsibilities, and mechanisms for resolving transaction disputes. Clusters primarily strengthen location-based coordination of seed procurement, transportation, drying, and collective sales, whereas cooperatives or farmer organizations can strengthen collective bargaining, information sharing, and compliance with mutually agreed arrangements. Thus, trust-building should be understood as a supporting institutional mechanism that complements market-oriented and economic interventions rather than as a stand-alone determinant of socioeconomic resilience.

The role of local government is crucial because several priority risks lie beyond the capacity of individual seaweed-farming households. Seed assistance, post-harvest training, logistics infrastructure, and price regulation or market partnerships require cross-institutional coordination. However, assistance must be based on actual needs and reliable data on farmers and enterprise groups so that it does not reinforce dependency. Universities and research institutions can contribute by mapping risks, providing technology assistance, and developing business models compatible with conservation and archipelagic conditions.

The findings also show that information technology is important but not a stand-alone solution. Digital platforms are effective only when seaweed farmers have sufficient digital literacy, communication networks are available, and the managing institution is trusted. ICT implementation should therefore be positioned as a supporting layer after information centres, producer clusters, and cooperatives have begun to function. This gradual approach is more realistic for island areas with limited connectivity and human resources.

Overall, the socioeconomic resilience of small-scale seaweed aquaculture enterprises in the North Minahasa Marine Conservation Area should be built through four interrelated strategies: information transparency, collective organization, institutional support, and dried-seaweed quality improvement. These strategies strengthen the capacity of farmers and enterprise groups to absorb price and production shocks, adapt business practices, and maintain livelihood functions without undermining conservation objectives.

CONCLUSION

This study demonstrates that market uncertainty and institutional constraints primarily threaten the socioeconomic resilience of small-scale seaweed enterprises. HOR1 analysis identified unstable demand and reliance on local distributors as top risks. To address these, HOR2 results prioritize government-facilitated price agreements, subsidies, and digital market-communication systems as the most effective mitigations. Additionally, FAHP findings highlight profit enhancement and price stabilization as critical resilience criteria. Interventions must therefore improve market access, transaction mechanisms, and institutional coordination. Future research should empirically evaluate the economic feasibility and implementation outcomes of these proposed mitigation strategies.

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