

RESEARCH ARTICLE

Multicapital vulnerability and social resilience in coastal Bone Bolango Regency, Indonesia

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Abstract

Small coastal settlements rely heavily on marine ecosystems yet are highly exposed to climate variability, market shocks, and resource depletion. This study evaluates the social resilience and livelihood vulnerability of small-scale fishers in Kabila Bone subdistrict, Bone Bolango Regency, using the multi-aspect sustainability analysis framework. We surveyed 91 fisher households across nine villages through structured questionnaires and in-depth interviews, and constructed a composite sustainability index across five livelihood capitals. Results indicate that natural capital is the most sustainable (75.0%), followed by human (70.0%), social (60.0%), and physical (55.5%) capital, while financial capital scores the lowest (37.5%). These findings suggest that inclusive financial services, cold-chain and transport upgrades, and targeted capacity-building through local institutions are priorities to strengthen resilience and adaptive capacity.

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1. Introduction

At the global level, the urgency of building resilience in coastal communities aligns with international frameworks, such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 13 (climate action) and SDG 14 (life below water). The Food and Agriculture Organization (FAO) has also emphasized the Blue Transformation agenda, which encourages inclusive governance, sustainable fisheries, and resilience-based planning. These frameworks underscore the importance of integrating local livelihood considerations into coastal resilience planning. This is consistent with global fishing trends that show accelerating pressures on marine ecosystems due to shifting exploitation patterns (Hollingsworth *et al.*, 2021). Achieving sustainable fisheries requires balancing ecological, economic, and social objectives (Tracey, 2020).

According to FAO (2023), coastal communities significantly contribute to global biodiversity, food systems, and economic development by supplying approximately 10% of the world's fish and supporting over 200 million livelihoods. Within these dynamic systems, small-scale fisheries play a vital role, yet they face growing threats from climate change, environmental degradation, and economic vulnerability—conditions that

directly impede progress toward SDGs, including SDG 1 (no poverty), SDG 2 (zero hunger), and SDG 14 (life below water).

The contradiction in Indonesia's fisheries remains: although small-scale fisheries contribute 5.5% to the national gross domestic product, over 30% of the country's fish stocks are classified as overexploited (Ministry of Marine Affairs and Fisheries, 2023). Globally, similar trends indicate that overfishing has significant implications for food security and the sustainability of small-scale fisheries (Pauly *et al.*, 2023). These overlapping ecological and economic stressors are acutely visible in Bone Bolango Regency, located in northern Sulawesi, where the population's dependence on marine ecosystems renders livelihoods highly sensitive to external shocks. The coastal subdistrict of Kabila Bone, for example, consists of 994 small-scale fisher households spread across nine villages, most of whom have limited access to infrastructure, capital, and institutional support (BPS, 2024). The livelihood vulnerability observed in Bone Bolango aligns with broader patterns among small-scale fishers in Indonesia, where limited assets, fluctuating income sources, and exposure to multiple stressors compel households to adopt diverse coping and adaptation strategies. Similar findings from Tanjung Kait, Banten, show that livelihood choices are strongly shaped by poverty conditions and constrained access to key resources, reinforcing the multidimensional nature of vulnerability among artisanal fishers (Fitriani *et al.*, 2023).

Bone Bolango Regency is a strategically located yet socioeconomically vulnerable region, with a high proportion of low-income, low-education households relying solely on artisanal fishing. This reflects global patterns seen in marginalized coastal zones, such as the Amazon and East Africa, where excessive resource extraction and ecosystem degradation destabilize food security (Mikkola, 2024). Beyond climatic and environmental stress, rapid coastal development driven by aquaculture, tourism, and land reclamation continues to marginalize traditional fishing zones, limiting access and escalating spatial conflicts (Fabinyi *et al.*, 2022). Therefore, effective resilience strategies must integrate institutional empowerment, nature-based adaptation, and inclusive governance (Jouffray *et al.*, 2021; Lin, 2019; Sieber *et al.*, 2024).

The capacity to adapt is closely linked to how communities access knowledge, services, and productive assets. Localized assessments show that communities frequently exposed to climate variability tend to cultivate stronger adaptive mechanisms (Ilosvay *et al.*, 2022; Lamichhane *et al.*, 2022). This is evident in traditional

communities, such as the Inuit in Canada and the Coastal-Vedda in Sri Lanka, whose livelihood systems adapt through diversification, co-management, and reinforcement of indigenous ecological knowledge (Galappaththi *et al.*, 2021).

To guide the analysis, we applied the multi-aspect sustainability analysis (MSA) framework because it quantifies interdependencies among livelihood capitals, enables sustainability scoring with a sensitivity classification, and supports the derivation of actionable policy recommendations—particularly for financial inclusion, infrastructure improvement, and adaptive resource governance. Unlike the sustainable livelihood framework (SLF), the MSA framework allows for integrated evaluation through sustainability analysis, which quantifies the relative impact of each capital under stress scenarios (Barth *et al.*, 2021; Firmansyah, 2022; Rizieq *et al.*, 2023). Although studies on small-scale fisheries and livelihood vulnerabilities exist (Ayilu *et al.*, 2022; Silvano & Kurien, 2023; Fontenele *et al.*, 2024), few have operationalized multicapital assessments in high-risk coastal settings using sensitivity tools. Moreover, Bone Bolango Regency remains underexamined despite its high dependency on marine resources, growing environmental uncertainty, and infrastructure constraints. Index-based assessments have also been used to quantify climate-related livelihood vulnerability in coastal regions (Saha *et al.*, 2024).

Small-scale fishers in Bone Bolango Regency are trapped in a cycle of structural vulnerability: overexploited fisheries, rising climatic disruptions, and limited access to financial and institutional support (BPS, 2024; FAO, 2023). Around 73% rely solely on fishing, and only 40% have access to credit. These conditions are further aggravated by poverty, weak infrastructure, and limited resilience investment, diminishing their adaptive capacity (Lynch *et al.*, 2020; Olmos *et al.*, 2018).

This study investigates the resilience of the five livelihood capitals to climate, ecological, and economic pressures. It identifies which capitals are most vulnerable and the factors driving their weakness. It then evaluates strategies to strengthen sustainability and adaptive capacity in the study area.

2. Data and methods

2.1. Research design

This study applied a descriptive and exploratory research design to examine the sustainability of small-scale fishers' livelihoods in Bone Bolango Regency. The descriptive component captured the existing conditions of five key livelihood capitals—natural, human, financial, social, and physical—while the exploratory component examined how

these assets interact with external shocks, such as climate variability, economic stress, and gaps in institutional support.

We employed the MSA framework for its ability to quantify interdependencies among livelihood capitals, generate sustainability scores with sensitivity classifications, and inform actionable policy recommendations, particularly in financial inclusion, infrastructure improvement, and adaptive resource governance.

2.2. Population and sample

The study area comprises 994 small-scale fisher households across nine villages. Using probability-proportional-to-size sampling, 91 households were selected, preserving village shares: Huangobotu accounts for 24.7% of the population and 24.2% of the sample; Olele 15.6% and 15.4%; Biluango 13.5% and 13.2%. The smallest share is Molotabu (3.7% of the population, 3.3% of the sample), while the remaining villages contribute 5.4–11.8% of the population and 5.5–12.1% of the sample, indicating good proportionality.

2.3. Data collection methods

This study used both quantitative and qualitative methods to enrich data quality. Survey questionnaires were administered to assess perceptions of the condition of each livelihood capital on a 5-point Likert scale, supported by in-depth interviews to gather contextual information. Secondary data were obtained from Statistics Indonesia and local government records to cross-verify the primary results.

Data focused on five key dimensions of sustainability:

- i. Natural capital was measured using three indicators: the trend in catch per unit effort over the past 12 months, proximate habitat/water quality (perceived clarity and waste incidence; 1–5 Likert scale), and peak-season species availability relative to 5 years ago (1–5 Likert scale).
- ii. Human capital comprised three indicators: years of schooling of the household head, upskilling (number of fisheries/business trainings in the past 12 months), and health (number of days unable to work in the past 30 days, reverse-coded).
- iii. Financial capital included access to finance (availability of formal/informal loans in the past year), liquid savings relative to monthly expenditure, and income stability (variance of monthly income over the past 6 months, reverse-coded).
- iv. Social capital captured network embeddedness (group membership and participation frequency), institutional trust (confidence in cooperatives and government services; 1–5 Likert scale), and mutual aid (frequency of receiving/providing help during recent shocks).

- v. Physical capital reflected fishing asset condition (boat/engine age and frequency of unplanned breakdowns, reverse-coded), gear adequacy (equipment condition relative to target species; 1–5 Likert scale), and infrastructure access (travel time to landing site, cold storage facilities, and main roads, reverse-coded).

2.4. Procedure and data analysis methods

The research workflow included sampling, survey design, pilot testing, data collection, scoring, sensitivity analysis, and policy inference. Data were analyzed using the MSA framework implemented in the specialized ExsimPro software (ExsimPro, Indonesia), a web-based analysis platform.

2.5. Analytical approach

The choice of the MSA framework over conventional models, such as SLF, was grounded in its ability to quantify leverage points through multidimensional sensitivity analysis. While SLF effectively maps asset relationships, MSA enables researchers to identify which capitals exert the greatest influence on overall resilience, a feature critical for prioritizing policy and funding interventions.

Data analysis was performed using a combination of MS Excel (version 2021, Microsoft Corporation, United States) for score normalization and visualization, and Statistical Package for Social Sciences (SPSS version 25, IBM, United States) for cross-tabulation and trend identification. The scoring used a weighted average system adjusted for capital-specific indicators, ensuring balanced comparisons. Sensitivity values were derived from the standard deviation and adjusted impact scores across capital dimensions. In addition, qualitative findings were triangulated through thematic coding of interview data using NVivo software (version 14, QSR International, Australia) to validate the consistency between perceived vulnerability and statistical patterns.

This mixed-method strategy enhances both the explanatory power and policy relevance of the study by capturing not only structural vulnerability patterns but also lived experiences and adaptation strategies. Daw *et al.* (2022) provide a comprehensive analysis of vulnerability and adaptation strategies, emphasizing the need for resilient management practices in the face of climate risks. The integrated approach ensures that policy recommendations are grounded in data-driven insight while being sensitive to local socio-cultural realities. To answer the research questions, a sustainability index was constructed (Equation [1]) (Firmansyah, 2022).

$$\text{Sustainability index} = \frac{1}{N} \sum_{i=1}^N \frac{A_i}{M_i} \quad (1)$$

and the sensitivity model was applied to identify which capital has the greatest impact on resilience (Equation [2]) (Riziq *et al.*, 2023).

$$S_i = \frac{\Delta R}{\Delta A_i} \quad (2)$$

3. Results

3.1. Descriptive results

The analysis of small-scale fishers' livelihoods in Kabila Bone subdistrict revealed varying sustainability across different asset capitals. Specifically, most fishers are between 18 and 27 years old, and 97.8% have only an elementary education or less. This low educational attainment restricts their employment flexibility and access to advanced fishing technologies, confirming the strong correlation between higher education levels, reduced unemployment, and improved economic resilience (Béné *et al.*, 2019; Datzberger, 2022).

The average monthly household income is Indonesian Rupiah (IDR) 5,036,813—mainly from fishing (IDR 3,632,418), with secondary work adding IDR 1,404,396. The average monthly operating costs for fishing are IDR 6,004,209, exceeding both consumption (IDR 979,780) and non-consumption expenditures (IDR 2,146,154), which constrains savings and productive investment. The income and expenditure ranges are wide (main-job income: IDR 0.8–15.0 million; side-job income: IDR 0–30.0 million; fishing operating costs: IDR 0.337–49.0 million), underscoring financial volatility.

The MSA indicates an overall average sustainability score of 59.5%, categorized as moderately sustainable. This suggests that while fishermen possess moderate resilience to external shocks—such as ecosystem degradation, market volatility, and climate anomalies—critical vulnerabilities remain, especially within financial and physical capitals.

3.2. Analysis by livelihood capitals

Multi-aspect sustainability analysis yielded the following capital scores: natural 75.0% (highest), human 70.0%, social 60.0%, physical 55.5%, and financial 37.5% (lowest). The composite sustainability index is 59.5%, indicating a “moderately sustainable” status overall.

3.2.1. Human capital (70% sustainability)

Within the human capital dimension, educational attainment and vocational skills emerged as the most sensitive factors (sensitivity value: 0.5) (Figure 1). Limited formal education curtails opportunities for strategic resource management and technological adaptation, corroborating findings by Cinner *et al.* (2018) and

Datzberger (2022). Vocational training, scholarships, and lifelong learning initiatives are necessary to enhance adaptive capacities and livelihood diversification.

3.2.2. Natural capital (75% sustainability)

Within the natural capital dimension of the MSA, coral reefs, fish stocks, and marine ecosystems remain relatively intact, serving as the foundation of resilience (Blanchard *et al.*, 2019; Reid *et al.*, 2016). For the sensitivity analysis, all variables were equally sensitive and are close to the threshold value, necessitating immediate interventions in conservation, sustainable fisheries management, and community-led marine protection initiatives (Figure 2) (Abraham *et al.*, 2022; Jacquemont *et al.*, 2022).

3.2.3. Social capital (60% sustainability)

In the social capital dimension, social networks facilitate resource sharing (Figure 3); however, the lack of consistent external support (sensitivity value: 0.75) significantly weakens resilience (Chetty *et al.*, 2022; Linke, 2021). It is crucial to enhance technical training, institutional support, cooperative strengthening, and participatory governance frameworks. Begossi

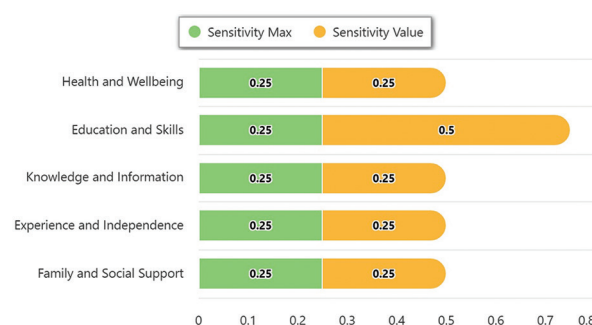


Figure 1. Sensitivity analysis of human capital factors affecting livelihood resilience

Source: Processed data of multi-aspect sustainability analysis, 2024.

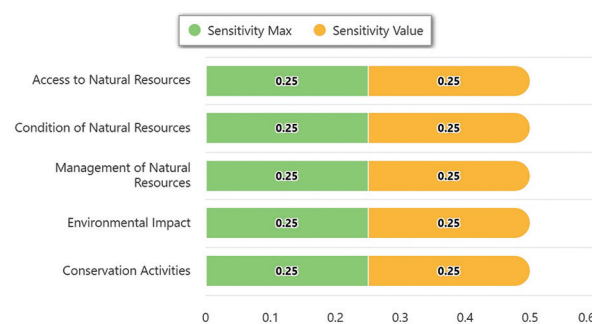


Figure 2. Sensitivity analysis of natural capital in fishermen's livelihood sustainability

Source: Processed data of multi-aspect sustainability analysis, 2024.

et al. (2019) and Purcell *et al.* (2021b) emphasize the importance of community-based management and collaborative decision-making in enhancing both social and ecological resilience.

3.2.4. Financial capital (37.5% sustainability)

In the financial capital dimension, the MSA results indicate that limited investment and savings render small-scale fishers highly vulnerable to external shocks (Figure 4) (Islam & Ahmed, 2023; Muktadir, 2022). The expansion of microfinance schemes, financial literacy programs, and the integration of digital financial platforms should be prioritized (Chakraborty & Dhawan, 2025).

3.2.5. Physical capital (55.5% sustainability)

For physical capital, the MSA results showed that infrastructure deficits (limited cold storage and transportation networks) and outdated fishing technologies constrain productivity (Khalid, 2022; Mukherjee & Ray, 2019). Technological innovation and access to market information exceeded sensitivity thresholds, indicating strategic investment areas (Figure 5).



Figure 3. Sensitivity analysis of social capital and its influence on livelihood resilience

Source: Processed data of multi-aspect sustainability analysis, 2024.



Figure 4. Sensitivity analysis of financial capital showing economic vulnerability among fishermen households

Source: Processed data of multi-aspect sustainability analysis, 2024.

3.3. Inferential results

The sensitivity analysis identified four critical determinants shaping the resilience and vulnerability of small-scale coastal livelihoods in Bone Bolango Regency. Education and skills development emerged as a primary factor influencing adaptive capacity. Fishermen with high levels of education and diversified vocational skills tend to demonstrate strong resilience when facing environmental and economic disruptions.

Another determinant is external support systems, where access to institutional assistance and strong networks within the fishing community play crucial roles in mitigating vulnerability. Communities endowed with robust social capital are generally capable of mobilizing resources and recovering from adverse events.

In addition, sensitivity analysis of financial capital highlighted that limited access to investment and savings exacerbates economic fragility. Conversely, households possessing better financial literacy and diversified income sources tend to achieve higher sustainability scores.

Finally, fishing equipment, infrastructure, technology, and finance collectively represent a decisive factor in shaping livelihood sustainability. Inadequate infrastructure, outdated fishing technologies, and weak market linkages collectively constrain productivity. Therefore, technological modernization and improved logistical infrastructure are essential for enhancing both productivity and resilience in coastal communities.

4. Discussion

This study emphasizes that small-scale fishers in Kabila Bone subdistrict are highly dependent on marine resources for their livelihoods, rendering them acutely vulnerable to external shocks, such as environmental degradation, climate variability, and economic instability.

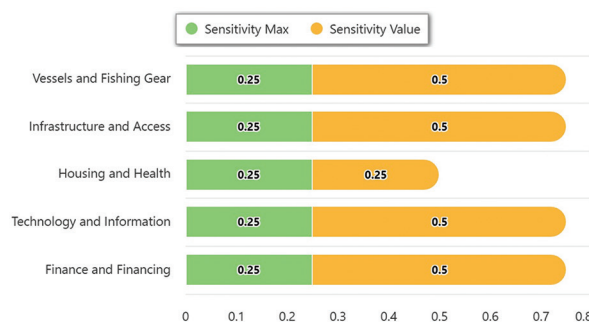


Figure 5. Sensitivity analysis of physical capital highlighting infrastructure and technological constraints

Source: Processed data of multi-aspect sustainability analysis, 2024.

Overfishing can exacerbate livelihood fragility by reducing catch rates and increasing uncertainty (Teh *et al.*, 2023). These vulnerabilities are further intensified by climate-related pressures that threaten the long-term viability of small-scale fisheries (Purcell & Pomeroy, 2021a). Global evidence also shows that effective fisheries management plays a decisive role in improving fish stock status and strengthening long-term ecosystem resilience (Hilborn *et al.*, 2020). This dependence further exposes them to ecological and financial risks, consistent with previous findings (Saleh *et al.*, 2016). Environmental pressures such as habitat degradation, declining fish stocks, and increasing climate-related disturbances continue to intensify vulnerability in coastal communities. These ecosystem changes not only reduce resource availability but also weaken the ecological foundation that supports small-scale fisheries (Burke & Reytar, 2020). Declining fish availability not only reduces income opportunities but also diminishes the nutritional contributions that coastal households derive from reef-based fisheries. Recent evidence shows that increased capture of small fish does not necessarily enhance food or nutrition security, as such practices can undermine ecosystem productivity and long-term resource sustainability (Galligan & McClanahan, 2024). Hicks *et al.* (2021) emphasize the importance of integrating financial literacy and community savings initiatives to enhance the resilience and sustainability of small-scale fisheries.

Using the MSA framework integrated with sensitivity analysis, the study provides a comprehensive understanding of livelihood sustainability by evaluating five capitals—natural, human, social, financial, and physical—simultaneously. As a foundational concept, social capital—built on trust, reciprocity, and shared norms—shapes collective resilience in coastal communities (Putnam, 2001). Findings demonstrate that while natural and human capitals are relatively strong, financial and physical capitals remain critically weak, reflecting significant structural gaps in resilience.

These observations align with previous studies (Béné *et al.*, 2019; Sullivan & Hickel, 2023) that identify financial insecurity as a core vulnerability for small-scale fisheries. However, this study advances prior research by quantifying the relative sensitivity of each capital, revealing that interventions targeting education, financial inclusion, and infrastructure improvement yield the greatest sensitivity in enhancing resilience outcomes. Livelihood adaptation is shaped by interactions between environmental exposure and household asset capacity (Shah & Subramanian, 2020). This is consistent with findings showing that livelihood resilience in ecologically sensitive environments depends on adaptive household strategies (Kuipers & de Jong, 2023).

Consistent with Reid *et al.* (2016), the importance of biodiversity (natural capital) for stabilizing community resilience is reaffirmed. Climate-driven ecosystem degradation further accelerates losses in marine biodiversity, compounding local vulnerability (Trégarot *et al.*, 2024). Long-term ocean warming has altered ecosystem structure and reduced productivity across tropical coasts (Venegas *et al.*, 2023). Moreover, cascading vulnerabilities across capital dimensions highlight the systemic nature of livelihood sustainability, in which weaknesses in financial or physical capital constrain the potential development of human and social capital.

Building on these findings, several strategic implications and policy directions emerge for strengthening the adaptive capacity of coastal livelihoods in Bone Bolango Regency. Improving education and vocational training is fundamental to enhancing human capital. Expanding access to formal education and providing technical training in sustainable fishing practices and entrepreneurship can stimulate livelihood diversification and strengthen adaptive behavior among fishermen. Adapting fisheries governance to climate stressors is crucial for sustaining coastal livelihoods (Purcell & Pomeroy, 2021b).

Equally important is the reinforcement of community-based social services. Interventions such as microcredit schemes, social protection programs, and institutional support should be integrated within broader empowerment frameworks. Embedding educational outreach and participatory governance within these programs can amplify social cohesion and reduce household vulnerability to income shock.

Financial inclusion also constitutes a crucial pathway toward resilience. Expanding affordable access to credit, savings mechanisms, and insurance products tailored to the realities of small-scale fishing communities can alleviate economic fragility and foster more sustainable investment behavior. Complementary to this, investment in infrastructure and technological innovation—such as cold storage facilities, transportation networks, digital marketplaces, and modern fishing tools—is essential to improve productivity, market access, and post-harvest efficiency.

Environmental stewardship and marine conservation must also be embedded in local governance strategies. Institutions fundamentally mediate resource access and influence coastal governance outcomes (Smith & Basurto, 2019). Community-driven initiatives focusing on marine biodiversity protection, habitat restoration, and bottom-up fisheries management are vital for safeguarding natural capital and ensuring long-term ecological sustainability. Community engagement has also been

shown to significantly enhance conservation outcomes in marine settings (Reed *et al.*, 2021). At the institutional level, promoting collaborative governance that connects fishers, government agencies, and non-governmental organizations can strengthen collective action, enhance trust, and improve policy responsiveness. Environmental pressures such as habitat degradation and declining fish stocks continue to intensify vulnerability among small-scale fishing communities. These ecological pressures are closely linked to the cumulative impacts of fishing activities, which reduce marine ecosystem productivity and undermine the long-term sustainability of coastal livelihoods (Cheung & Froese, 2020).

By integrating social service approaches with sustainability-oriented strategies, these interventions provide a coherent roadmap for empowering vulnerable coastal communities and advancing global SDGs, particularly SDG 1 (no poverty), SDG 2 (zero hunger), and SDG 14 (life below water).

These findings highlight the need for targeted policy interventions to strengthen the institutional and economic foundations of coastal livelihoods. Such strategies are aligned with broader regional frameworks promoting sustainable fisheries governance and blue economy integration in Southeast Asia, which emphasize resilience, innovation, and ecosystem-based management approaches (Cabral *et al.*, 2022). Studies from the Philippines, Bangladesh, and Mozambique have shown that weak financial systems and insufficient institutional support remain persistent challenges to livelihood resilience (Islam & Ahmed, 2023; Muhala *et al.*, 2021). Parallel studies in Bangladesh similarly show that climate-induced vulnerabilities are deeply embedded within livelihood systems (Rahman *et al.*, 2024). Fish also contributes substantially to micronutrient intake in coastal households, reinforcing its role in local food security (Kawarazuka *et al.*, 2023). Small-scale fisheries likewise supply essential nutrients that support the well-being of coastal communities (Kjelleveid *et al.*, 2022). Nutrient supply from small-scale fisheries, therefore, remains a critical determinant of food security in coastal regions (Viana *et al.*, 2023). Conversely, adaptive practices in Pacific Island communities demonstrate that strong local governance, traditional ecological knowledge, and inclusive participation play critical roles in sustaining marine-based livelihoods (Eriksson *et al.*, 2019). Recent frameworks explicitly link climate exposure to food-security risks in small-scale fisheries (Sekadende *et al.*, 2024). These global comparisons underscore that the most effective resilience strategies are multisectoral—combining education, financial inclusion, technological modernization, and environmental conservation.

Despite the strength of this analysis, the study has several limitations. The cross-sectional design restricts the ability to capture changes in resilience dynamics over time. Future longitudinal research examining how targeted interventions influence adaptive behavior and livelihood outcomes would help address this limitation. Decision-making processes also shape how communities adopt or resist sustainability practices (Weinrich *et al.*, 2023). The COVID-19 pandemic further disrupted local economies and indirectly affected livelihood adaptation pathways (Willies, 2023). In addition, incorporating digital innovation pathways—such as mobile financial tools or e-market access platforms—could further enhance sustainability and reduce environmental pressures, including those associated with marine debris. Climate-related disturbances, including rising sea temperatures, shifts in species composition, and increased frequency of extreme weather events, further exacerbate the fragility of marine ecosystems. These climatic threats reduce biodiversity resilience and diminish ecosystem services that coastal communities depend on, thereby heightening livelihood vulnerability (Dube, 2024).

Although the MSA and sensitivity frameworks offer robust analytical power, they also have inherent constraints. Sensitivity indices are relative measures and may not fully capture inter-capital dependencies, potentially oversimplifying complex livelihood interactions. Future studies integrating longitudinal datasets, participatory modeling, and multilevel governance analysis could provide an in-depth understanding and improve the precision of resilience-based policy design in vulnerable coastal regions. This finding highlights how multiple livelihood stressors interact to shape vulnerability among small-scale fishing communities. Similar patterns of climate-induced livelihood and food-security risks have also been documented in other coastal contexts, where limited adaptive capacity and resource constraints amplify exposure to environmental and socio-economic pressures (Brodie *et al.*, 2024).

5. Conclusions

This study assessed the sustainability of small-scale fishers' livelihoods in Bone Bolango Regency through the MSA framework integrated with sensitivity analysis. Results show that natural (75%) and human (70%) capitals demonstrate relatively strong resilience, while social capital (60%) remains moderate. In contrast, physical (55.5%) and financial (37.5%) capitals are critically weak, resulting in an overall sustainability score of 59.5%, categorized as moderately sustainable.

The sensitivity analysis highlights education, financial access, institutional support, and infrastructure as key

leverage points for enhancing resilience. Strengthening these domains through vocational training, inclusive financial programs, technological modernization, and community-based conservation efforts is crucial to reducing vulnerability and promoting sustainable livelihoods.

Future research should adopt longitudinal approaches to capture changes in adaptive strategies and explore the roles of gender, youth participation, and local governance in shaping resilience trajectories.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors

Formal analysis: Sri Endang Saleh, Ismail Djakaria

Investigation: All authors

Methodology: Sri Endang Saleh, Ismail Djakaria

Writing—original draft: Sri Endang Saleh, Ismail Djakaria

Writing—review & editing: All authors

Ethics approval and consent to participate

This study was reviewed and approved by the Research Ethics Committee of Universitas Negeri Gorontalo (Approval ID: No. 824/UN47.D1/PT.01.03/2024). Informed consent was obtained from all individual participants (91 Fisher households) before conducting the structured questionnaires and interviews. Participants were informed of the study's objective.

Consent for publication

All participants provided informed consent for the publication of the findings derived from this study. Where applicable, participants gave explicit permission for the publication of any data, images, or information that could

potentially reveal their identity. The authors affirm that all relevant consent forms have been obtained and are available upon request.

Availability of data

Data underlying this study are available upon reasonable request from the corresponding author.

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