

Livelihood Changes and Socioeconomic Vulnerability of Seaweed Farmers in Nickel Mining-Affected Coastal Areas of Southeast Sulawesi, Indonesia

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Abstract

Seaweed farming has long been one of the most important coastal livelihood activities in Southeast Sulawesi, Indonesia, yet the rapid expansion of nickel mining in the province has raised serious concerns about the sustainability of this sector and the welfare of the households that depend on it. This study aimed to examine changes in seaweed farming conditions, identify livelihood transformation strategies, and analyze the socioeconomic vulnerability of seaweed farming households in nickel mining-affected coastal areas of Southeast Sulawesi. A mixed-methods design was employed in three coastal regencies Kolaka, Konawe Selatan, and Konawe Utara purposively selected as major seaweed-producing areas experiencing significant mining-related environmental change. Primary data were collected between June and September 2022 through household surveys, direct observation, in-depth interviews, and focus group discussions with active and former seaweed farmers, complemented by secondary statistical data on seaweed and nickel production trends. Quantitative data were analyzed descriptively, while qualitative data were analyzed using the interactive model of data condensation, display, and conclusion verification, guided by the Sustainable Livelihood Framework. The results show that provincial seaweed production declined by more than 63 percent between 2014 and 2019, with declines reaching 90.36 percent in Kolaka Regency and complete cessation of cultivation in Konawe Utara Regency, coinciding with a substantial increase in nickel production. Affected households adopted economic coping strategies, livelihood diversification into fishing and informal trading, and social coping mechanisms based on kinship and community support. Socioeconomic vulnerability emerged from the interaction of declining natural capital, limited livelihood alternatives, low educational attainment, and financial insecurity, although social capital partially mitigated these impacts. The findings underscore the need for integrated coastal management policies that balance mineral resource development with the sustainability of coastal livelihoods.

Keywords: coastal livelihoods; livelihood diversification; nickel mining; seaweed farming; socioeconomic vulnerability



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INTRODUCTION

Seaweed farming is one of the most important coastal economic activities in Indonesia, contributing significantly to employment generation, household income, export earnings, and rural development. Indonesia remains among the world's leading producers of tropical seaweed, supplying raw materials for food, pharmaceutical, cosmetic, and bio-industrial sectors, with the global state of exploitation, farming, and emerging research activity in this sector continuing to expand rapidly (Buschmann et al., 2017). The cultivation of *Kappaphycus alvarezii* and *Eucheuma denticulatum* has become a strategic livelihood activity for many coastal households because of its relatively low capital requirements, short production cycle, and broad market opportunities. In addition to its economic contribution, seaweed farming supports livelihood resilience by providing employment opportunities for household members, including women and youth, while strengthening local coastal economies; indeed, seaweed cultivation has been shown to contribute substantially to social and economic aspects of livelihoods and community wellbeing across Indonesia (Rimmer et al., 2021), and to generate measurable improvements in women's subjective wellbeing through income earned from farming activities (Larson et al., 2021).

Southeast Sulawesi Province has long been recognized as one of Indonesia's major seaweed-producing regions. Favorable coastal ecosystems and extensive marine areas have supported the rapid growth of seaweed cultivation over the past two decades. Seaweed farming has become a primary source of income in several coastal districts, including Konawe Selatan, Konawe Utara, and Kolaka. The sector has contributed substantially to poverty reduction and local economic development in coastal communities, consistent with broader evidence that industry policy supporting local value addition can meaningfully strengthen the economic position of seaweed-producing regions in eastern Indonesia (Langford et al., 2023). However, official statistics indicate a concerning decline in seaweed production during the last decade. Provincial seaweed production decreased from 949,141 tons in 2014 to only 346,886 tons in 2019, representing a decline of more than 63 percent. This decline has raised concerns regarding the sustainability of seaweed-based livelihoods and the future resilience of coastal communities that depend heavily on aquaculture activities.

At the same time, Southeast Sulawesi has become one of Indonesia's major nickel-producing regions. Driven by the government's downstream industrialization policy and increasing global demand for electric vehicle batteries, nickel mining activities have expanded rapidly throughout the province. Provincial nickel production increased dramatically from 1.54 million tons in 2016 to 23.97 million tons in 2019. While the mining sector contributes significantly to regional economic growth, investment, and employment creation, its expansion has generated growing concerns regarding environmental degradation and conflicts over coastal resource utilization, a pattern consistent with cross-national evidence that extractive industries frequently generate income loss and disproportionate harm to vulnerable community members even as they contribute to macroeconomic growth (Kitula, 2006; Nguyen, Boruff, & Tonts, 2018). Previous studies have shown that mining activities can negatively affect coastal ecosystems through land clearing, sediment runoff, increased turbidity, coastal pollution, and habitat degradation. Empirical assessments in Southeast Asian nickel-mining regions confirm that laterite mining substantially increases siltation loads and degrades coastal water quality (Apodaca, Domingo, David, & David, 2018), while sediment sampling in Sulawesi's own nickel-affected coastal waters has documented elevated heavy-metal contamination directly attributable to mining activity (Ya'la et al., 2025). These environmental disturbances are particularly important for seaweed farming because seaweed growth is highly dependent on water quality, transparency, nutrient availability, and stable ecological conditions. Excessive sedimentation and declining water quality may reduce growth rates, increase disease outbreaks, and ultimately cause cultivation failure. Consequently, mining-induced environmental changes may directly threaten the sustainability of seaweed farming systems and the livelihoods of coastal households.

Evidence from mining-affected districts in Southeast Sulawesi illustrates the severity of this challenge. In Kolaka Regency, seaweed production declined from 283,245.78 tons in 2014 to only 27,302 tons in 2020, representing a decrease of approximately 90.36 percent. In Konawe Selatan Regency, production declined by approximately 66.69 percent during the same period. The most severe

condition occurred in Konawe Utara Regency, where seaweed production completely disappeared in 2019 and 2020 after previously reaching more than 26,000 tons. These patterns indicate that environmental and economic pressures associated with mining expansion may have fundamentally altered the viability of seaweed farming in several coastal areas.

The decline of seaweed farming productivity extends beyond environmental concerns and directly affects household welfare. Coastal households that depend primarily on seaweed cultivation are particularly vulnerable because their livelihoods are strongly linked to natural resource conditions, a pattern consistent with broader evidence that small-scale fishing and aquaculture-dependent households are especially exposed to economic vulnerability when resource productivity declines (Béné, 2009). According to the Sustainable Livelihood Framework, vulnerability emerges when households are exposed to shocks while possessing limited adaptive capacity and restricted access to livelihood assets, with livelihoods perspectives emphasizing that the sustainability of a livelihood depends on the interaction between household assets, the vulnerability context, and the strategies households are able to pursue (Scoones, 2009). In such situations, households may respond by diversifying income sources, seeking alternative employment, utilizing savings, selling productive assets, or relying on social networks and informal financial arrangements; evidence from Indonesia itself shows that households without access to formal financial services are particularly likely to resort to liquidating productive assets when confronted with income shocks (DeLoach & Smith-Lin, 2018).

Research on mining impacts has predominantly focused on environmental degradation, ecological conflicts, and broad socioeconomic changes within local communities, with systematic evidence confirming that mining-affected communities routinely experience disproportionate income and welfare losses relative to non-mining communities (Nguyen, Boruff, & Tonts, 2018; Kitula, 2006). Other studies have examined the social and economic consequences of extractive industries, including employment transitions and resource governance issues. However, empirical studies specifically investigating livelihood changes and socioeconomic vulnerability among seaweed farming households affected by nickel mining remain limited, particularly in Indonesia. Existing studies rarely examine how coastal households adapt to the collapse or decline of seaweed cultivation and how these adaptive responses shape their vulnerability and resilience, even though comparative research on small-scale fisheries elsewhere shows that livelihood diversification does not uniformly improve welfare outcomes and can, in some contexts, produce mixed or even negative results for affected households (Roscher et al., 2022; Salayo, Perez, Garces, & Pido, 2012).

This study addresses this gap by examining livelihood changes and socioeconomic vulnerability among seaweed farmers in nickel mining-affected coastal areas of Southeast Sulawesi. Unlike previous studies that primarily focus on environmental impacts or general community conditions, this study emphasizes household-level livelihood transformations and vulnerability dynamics following the decline of seaweed farming activities. Particular attention is given to the role of social capital and community networks in shaping household resilience, since social ties and reciprocal relationships have been repeatedly shown to function as a critical resource enabling communities to withstand and recover from external shocks (Aldrich & Meyer, 2015; Coleman, 1988), a dynamic also documented among fishing communities whose engagement in collective institutions has been found to strengthen resilience amid environmental and regulatory pressure (Bakker, de Koning, & van Tatenhove, 2019), and among small firms more broadly, where networks of trust and reciprocity have been shown to enhance business performance where formal competitive resources are limited (Cooke & Wills, 1999; Eloire, 2018). The findings are expected to contribute to the growing literature on coastal livelihood vulnerability and provide evidence-based recommendations for policymakers seeking to balance mining development with the sustainability of coastal livelihoods. Specifically, this study aims to: (1) examine changes in seaweed farming conditions in mining-affected coastal areas; (2) identify livelihood transformation strategies adopted by seaweed farming households; and (3) analyze the socioeconomic vulnerability experienced by seaweed farmers following the decline of seaweed cultivation activities. The results are expected to support the formulation of more inclusive and sustainable coastal development policies in Indonesia.

RESEARCH METHOD

Research Location and Design

This study was conducted in three coastal regencies of Southeast Sulawesi Province, Indonesia, namely Kolaka Regency, Konawe Selatan Regency, and Konawe Utara Regency. These locations were purposively selected because they represent major seaweed-producing areas that have experienced significant environmental and socioeconomic changes associated with the expansion of nickel mining activities. The selected districts also exhibit different levels of seaweed farming decline, ranging from reduced productivity to the complete cessation of cultivation activities. Therefore, these locations provide an appropriate setting for examining livelihood changes and socioeconomic vulnerability among seaweed farming households affected by mining-related environmental pressures. The study employed a mixed-methods approach by integrating quantitative and qualitative data collection and analysis procedures. The mixed-methods approach allows researchers to obtain a comprehensive understanding of social phenomena by combining numerical information with contextual explanations derived from respondents' experiences and perceptions, an integrative rationale that has been widely documented as strengthening the validity and depth of applied social research (Doyle, Brady, & Byrne, 2009). This approach was considered appropriate because the study sought not only to describe socioeconomic conditions quantitatively but also to explore the processes of livelihood transformation and adaptation among seaweed farming households.

Data Collection

Primary data were collected from June to September 2022 through field surveys, direct observations, in-depth interviews, and focus group discussions (FGDs). Respondents consisted of active and former seaweed farmers residing in mining-affected coastal communities. Informants were selected purposively based on their experience in seaweed cultivation and their understanding of local socioeconomic conditions. Additional information was obtained from village leaders, fisheries extension officers, community representatives, and relevant government officials involved in fisheries and coastal resource management. The survey instrument was designed to collect information on household socioeconomic characteristics, including age, educational attainment, farming experience, livelihood sources, household income, and adaptation strategies adopted following the decline of seaweed farming activities. Qualitative interviews focused on community perceptions regarding environmental changes, the impacts of nickel mining on seaweed cultivation, livelihood transitions, and household coping mechanisms. Secondary data were obtained from the Central Bureau of Statistics (BPS), provincial and district fisheries agencies, government reports, and relevant scientific publications, and were primarily used to analyze trends in seaweed production and mining development within the study areas.

Data Analysis

Quantitative data were analyzed using descriptive statistical techniques, including frequencies, percentages, averages, and tabulations. These analyses were employed to describe respondent characteristics and identify general patterns of livelihood changes among seaweed farming households. Production trends and changes in seaweed farming activities were examined using time-series data obtained from government statistics and related reports. Qualitative data were analyzed using an interactive analysis model consisting of three interconnected stages: data condensation, data display, and conclusion drawing and verification. Data condensation involved selecting, simplifying, organizing, and categorizing information collected through interviews, observations, and focus group discussions. The organized data were subsequently displayed in narrative, tabular, and graphical forms to facilitate interpretation. Finally, conclusions were drawn through continuous verification and triangulation among multiple data sources to ensure the credibility and consistency of the findings. To understand the dynamics of livelihood transformation and vulnerability, this study adopted the Sustainable Livelihood Framework (SLF) as an analytical lens (Scoones, 2009). The framework emphasizes the interaction between livelihood assets, vulnerability contexts, and livelihood strategies. In this study, socioeconomic vulnerability was examined through changes in household income sources, loss of productive activities, reduced access to livelihood resources, and the capacity of households to adapt to environmental and economic pressures. Particular attention was given to the role of livelihood diversification, social

networks, and alternative economic activities in supporting household resilience following the decline of seaweed farming.

The analysis of livelihood changes focused on identifying shifts in occupational structures and income-generating activities among coastal households. Adaptation strategies were categorized into three main dimensions: economic strategies, livelihood diversification strategies, and social coping strategies. Economic strategies included the utilization of savings, borrowing from informal financial institutions, and the sale of productive assets. Livelihood diversification strategies referred to transitions into fishing, small-scale trading, wage labor, and other income-generating activities. Social coping strategies included reliance on kinship networks, community support systems, and social relationships that enabled households to withstand economic shocks. The study adhered to ethical principles throughout the research process. Prior to data collection, all respondents were informed about the objectives of the study and their voluntary participation. Informed consent was obtained from all participants before interviews and discussions were conducted. Personal information was anonymized to ensure confidentiality and privacy. Participation was entirely voluntary, and respondents were free to withdraw from the study at any stage without consequence.

RESULTS AND DISCUSSION

Characteristics of Respondents

The socioeconomic characteristics of respondents provide important insights into the adaptive capacity of seaweed farming households facing livelihood disruptions. Household vulnerability is often influenced by demographic characteristics, educational attainment, and farming experience, which collectively shape decision-making processes and the ability to respond to environmental and economic changes.

Table 1. Socioeconomic Characteristics of Respondents

Characteristics	Category	Percentage (%)
Age Group	21–30 years	25.00
	31–40 years	44.44
	41–50 years	16.67
	51–60 years	11.11
	61–70 years	2.78
Education Level	Primary School	66.67
	Junior High School	16.67
	Senior High School	16.67
Farming Experience	6–10 years	22.22
	>10 years	77.78

Source: Primary Data Processed, 2022.

The results indicate that the majority of respondents were within the productive age category, particularly between 31 and 40 years old (44.44%). This finding suggests that most respondents possess sufficient physical capacity to engage in productive economic activities and livelihood adaptation processes. Productive-age households generally have greater flexibility in seeking alternative employment opportunities compared to elderly households, thereby reducing vulnerability to economic shocks, a pattern consistent with evidence that age structure significantly shapes household adaptive capacity in communities dependent on natural resources exposed to environmental disturbance (Das, Das, Momin, & Pandey, 2020). Educational attainment among respondents was relatively low, with

approximately 66.67% having only completed primary school education. Limited educational achievement may constrain access to information, technology adoption, and alternative employment opportunities outside the fisheries sector. Lower educational levels often increase livelihood vulnerability because households face difficulties in diversifying economic activities and accessing formal employment opportunities.

Despite limited formal education, respondents possessed extensive experience in seaweed farming. More than three-quarters (77.78%) had over ten years of farming experience. Long-term involvement in seaweed cultivation reflects the historical importance of seaweed farming as a primary livelihood source in coastal communities. However, extensive experience alone does not guarantee livelihood security when environmental changes significantly reduce production potential, consistent with broader evidence that environmental degradation can undermine the value of accumulated farming knowledge and experience within community-based seaweed production systems (Rimmer et al., 2021). The combination of productive age, low educational attainment, and long farming experience suggests a paradoxical situation. While households possess substantial practical knowledge of seaweed farming, their limited educational background may restrict their ability to transition into alternative economic sectors. Consequently, livelihood adaptation tends to rely heavily on informal employment, fisheries-related activities, and social support networks. These conditions contribute to the emergence of socioeconomic vulnerability when seaweed farming activities become increasingly unproductive.

Trends in Seaweed Production Decline in Mining-Affected Areas

Seaweed farming has historically served as one of the most important economic activities in coastal areas of Southeast Sulawesi. However, statistical evidence indicates a substantial decline in seaweed production across several mining-affected districts during the last decade. This decline coincides with the rapid expansion of nickel mining activities throughout the province. At the provincial level, seaweed production declined from approximately 949,141 tons in 2014 to 346,886 tons in 2019, representing a reduction of more than 63%. Simultaneously, nickel production increased dramatically from 1.54 million tons in 2016 to 23.97 million tons in 2019. These contrasting trends suggest increasing pressure on coastal ecosystems and livelihood systems that depend heavily on environmental quality.

Table 2. Seaweed Production Decline in Mining-Affected Study Districts

Location	Production Before (tons)	Production After (tons)	Decline (%)
Southeast Sulawesi (Province)	949,141 (2014)	346,886 (2019)	63.4
Kolaka Regency	283,245.78 (2014)	27,302 (2020)	90.36
Konawe Selatan Regency	— (2014)	— (2020)	66.69
Konawe Utara Regency	>26,000 (peak)	0 (2019–2020)	100

Source: Adapted from research data and provincial statistics.

These findings indicate that the sustainability of seaweed farming has become increasingly threatened in mining-affected coastal areas. Similar patterns have been observed in other coastal regions affected by laterite nickel mining, where increased siltation loads and heavy-metal contamination of coastal sediments have been directly linked to mining and mineral-transport operations (Apodaca et al., 2018; Ya'la et al., 2025). From a livelihood perspective, declining production directly reduces household income and increases economic uncertainty. Households that depend heavily on a single economic activity are particularly vulnerable because income shocks cannot easily be absorbed through existing livelihood assets. According to the Sustainable Livelihood Framework, vulnerability increases when environmental disturbances simultaneously affect natural capital and financial capital, thereby reducing the capacity of households to maintain livelihood security (Scoones, 2009). Furthermore, the complete cessation of seaweed farming observed in several villages of Konawe Utara and parts of Kolaka illustrates a more profound transformation of local livelihood systems. The disappearance of

cultivation activities not only affects income generation but also disrupts social and economic networks that have historically supported coastal community development. Consequently, households are compelled to seek alternative livelihood strategies, often under conditions of limited resources and increasing uncertainty.

Impacts of Nickel Mining on Seaweed Farming Activities

The findings revealed that nickel mining activities have substantially affected seaweed farming operations in the study areas. Respondents consistently reported declining production, increased cultivation risks, and, in some locations, the complete cessation of seaweed farming activities. Although the magnitude of impacts varied among districts, all study sites experienced negative consequences associated with environmental changes occurring after the expansion of nickel mining operations. In Konawe Selatan Regency, respondents reported that mining activities located in upstream areas contributed to increased sediment loads entering coastal waters, particularly during periods of heavy rainfall. Sediment runoff transported through rivers eventually reached seaweed farming areas, reducing water transparency and affecting seaweed growth. Farmers also indicated that shipping activities associated with nickel transportation contributed to water turbidity due to the discharge of residual sediments from cargo vessels. As a consequence, seaweed productivity declined considerably, with respondents estimating production reductions ranging from 20% to 40% compared with conditions prior to mining expansion.

The impacts were more severe in Kolaka Regency, particularly in Muara Lapao-Pao Village, which was previously recognized as one of the major seaweed-producing areas in the region. During field observations, no active seaweed farming activities were found in the village. According to respondents, repeated cultivation failures had occurred since mining operations expanded in surrounding areas. Several farmers attempted to restart cultivation activities; however, production failures continued to occur, discouraging further investment in seaweed farming. Consequently, many households abandoned seaweed cultivation entirely and shifted to alternative livelihood activities. A similar situation was observed in Konawe Utara Regency. Villages such as Lemobajo, Kampung Cina, Barasanga, and Tanjung Bunga were previously known as important seaweed-producing communities. However, at the time of the study, no households were actively engaged in seaweed farming. Respondents associated this condition with declining water quality and increasing disturbances resulting from mining-related shipping activities. The movement of large vessels transporting nickel ore was perceived to contribute to changes in coastal environmental conditions, ultimately reducing the suitability of farming areas for seaweed cultivation.

The findings demonstrate a strong relationship between environmental degradation and declining aquaculture productivity. Seaweed farming is highly dependent on ecological conditions, particularly water transparency, salinity, nutrient availability, and current circulation. Increased sedimentation and turbidity can reduce photosynthetic efficiency and inhibit seaweed growth, thereby increasing production risks and lowering yields, consistent with sediment-yield assessments elsewhere in the region that directly link nickel-mining siltation with degraded coastal water quality and ecosystem health (Apodaca et al., 2018). Beyond environmental impacts, mining expansion has also altered the socioeconomic foundations of coastal communities. The decline of seaweed farming has reduced household income opportunities and weakened the economic role traditionally played by aquaculture in supporting local livelihoods. This condition is particularly significant because seaweed farming previously represented the dominant economic activity for many coastal households. The loss of productive farming activities has therefore created new forms of vulnerability, increasing dependence on alternative and often less stable livelihood sources, a pattern broadly consistent with cross-country evidence that mining expansion frequently generates disproportionate income losses among community members who had previously relied on non-mining, natural-resource-based livelihoods (Kitula, 2006; Nguyen, Boruff, & Tonts, 2018). These findings support the argument that coastal development policies should consider cumulative impacts across sectors rather than focusing exclusively on economic growth generated by extractive industries. Sustainable coastal management requires balancing the benefits of mining investments with the protection of environmentally sensitive livelihood sectors, including

fisheries and aquaculture. Failure to achieve such balance may result in long-term socioeconomic consequences for coastal communities that rely heavily on natural resource-based livelihoods.

Livelihood Changes and Adaptation Strategies

The decline of seaweed farming activities has triggered substantial livelihood transformations among coastal households in the study areas. As seaweed cultivation became increasingly unprofitable or impossible to continue, households were compelled to adopt various adaptation strategies to maintain their economic well-being and household survival. These strategies reflected both the vulnerability of affected communities and their capacity to respond to changing environmental and economic conditions. The study identified three major categories of adaptation strategies: economic coping strategies, livelihood diversification strategies, and social adaptation strategies. These strategies were often implemented simultaneously, indicating that households relied on multiple mechanisms to reduce the impacts of declining seaweed production. One of the most immediate responses to declining seaweed production involved the utilization of financial resources available within the household. Respondents reported using personal savings, selling productive assets, and borrowing money from informal financial institutions to meet daily household needs. Informal credit sources, including local money lenders, relatives, and community members, played an important role in supporting household consumption during periods of income reduction. The use of savings and asset liquidation represents a common short-term coping strategy among resource-dependent households experiencing livelihood shocks; however, these mechanisms often provide only temporary relief and may increase long-term vulnerability when household assets become depleted, particularly among households lacking access to formal savings or credit institutions, who are consistently more likely to resort to liquidating productive assets when confronted with income shocks (DeLoach & Smith-Lin, 2018). Several respondents indicated that prolonged cultivation failures had exhausted their financial reserves, forcing them to rely increasingly on debt and informal borrowing arrangements.

Livelihood diversification emerged as the most important adaptation strategy adopted by affected households. Former seaweed farmers increasingly shifted toward capture fisheries, small-scale trading activities, wage labor, transportation services, and other informal economic activities. In several villages, fishing became the primary alternative livelihood because it required relatively limited additional investment and remained closely connected to existing coastal knowledge and skills. The transition from seaweed farming to alternative occupations illustrates the dynamic nature of livelihood systems in coastal communities. According to the Sustainable Livelihood Framework, diversification is often employed to reduce dependence on a single source of income and enhance household resilience against environmental and economic disturbances (Scoones, 2009). Nevertheless, diversification does not always guarantee improved welfare because alternative occupations may generate lower and more unstable incomes than seaweed farming, a finding that mirrors broader evidence from small-scale fisheries showing that diversification outcomes are frequently mixed rather than uniformly positive, and can in some cases fail to improve, or even worsen, household livelihood conditions (Roscher et al., 2022; Salayo, Perez, Garces, & Pido, 2012). Field observations revealed that many households considered seaweed farming to be more profitable and predictable than their new livelihood activities. Consequently, although diversification enabled households to survive economically, it did not fully compensate for the loss of income previously generated through seaweed cultivation.

Social networks constituted another important mechanism supporting household adaptation. Respondents frequently relied on kinship relationships, neighbors, friends, and community support systems during periods of economic hardship. Assistance often took the form of food sharing, informal loans, labor exchange, and temporary employment opportunities provided through social connections. The importance of social capital in supporting household resilience has been widely documented in the livelihood literature: social relationships facilitate access to resources, information, and support systems that help households cope with uncertainty and economic stress (Coleman, 1988), and networks of trust, cooperation, and reciprocal obligation have been consistently shown to enhance the capacity of small enterprises and community groups to sustain themselves under adverse economic conditions (Cooke & Wills, 1999; Eloire, 2018). In the present study, social capital functioned as an informal safety net that partially compensated for limited access to formal financial and institutional support, echoing evidence

from disaster-affected communities showing that social capital, more than physical infrastructure, is often the decisive factor enabling communities to recover from external shocks (Aldrich & Meyer, 2015), and evidence from fishing communities showing that strong engagement in collective social structures enhances resilience amid environmental and regulatory pressure (Bakker, de Koning, & van Tatenhove, 2019). The findings suggest that livelihood adaptation among seaweed farming households extends beyond purely economic considerations. Adaptation processes involve a combination of financial resources, occupational transitions, and social support mechanisms. While these strategies have enabled households to survive under difficult circumstances, they also reveal the growing socioeconomic vulnerability associated with the decline of seaweed farming in mining-affected coastal areas. From a policy perspective, the results highlight the need for integrated interventions that strengthen livelihood diversification opportunities, improve access to financial services, and enhance community-based support systems. Such interventions are essential for reducing vulnerability and promoting sustainable livelihood transitions among coastal households facing environmental and economic change.

Socioeconomic Vulnerability of Seaweed Farming Households

The findings indicate that the decline of seaweed farming has increased the socioeconomic vulnerability of coastal households across the study areas. Socioeconomic vulnerability in this context refers to the reduced capacity of households to maintain stable livelihoods, income security, and social well-being when faced with environmental and economic disturbances. The results demonstrate that vulnerability emerged through the interaction of declining natural resource productivity, reduced income opportunities, limited livelihood alternatives, and dependence on informal support mechanisms. Within the Sustainable Livelihood Framework, vulnerability is influenced by changes in livelihood assets, including natural, financial, human, physical, and social capital (Scoones, 2009). The expansion of nickel mining activities has primarily affected natural capital through the deterioration of coastal environmental quality, thereby reducing the productivity of seaweed farming systems. As seaweed cultivation became less productive or ceased entirely, households simultaneously experienced a decline in financial capital due to reduced income and increased production uncertainty.

The results revealed that many households remained highly dependent on seaweed farming prior to the decline in production. Consequently, the loss of this primary livelihood source created substantial economic pressure. Households with limited income diversification opportunities were particularly vulnerable because alternative employment options were often characterized by lower returns, seasonal fluctuations, and unstable earnings, consistent with evidence that households with greater dependence on natural-resource-based livelihoods tend to experience higher vulnerability when environmental disturbances affect production systems (Das, Das, Momin, & Pandey, 2020). Educational attainment also contributed to vulnerability levels. The majority of respondents possessed only primary-level education, which limited their ability to access formal employment opportunities outside the fisheries sector. Lower educational levels often reduce adaptive capacity because households face greater difficulties in acquiring new skills, adopting innovative livelihood strategies, and responding effectively to economic change. Consequently, many respondents remained concentrated in low-income and informal occupations after abandoning seaweed farming. Another important aspect of vulnerability relates to financial insecurity. The findings showed that many households relied on savings depletion, asset sales, and informal borrowing to sustain household consumption. Although these mechanisms provide short-term solutions, they may increase long-term vulnerability by weakening household asset bases and increasing indebtedness, a pattern well documented among households without access to formal credit institutions, who are forced to rely disproportionately on asset liquidation and informal borrowing when confronted with income shocks (DeLoach & Smith-Lin, 2018). Persistent dependence on informal credit can further expose households to financial instability, particularly when alternative income sources remain uncertain.

Despite these challenges, social capital emerged as a critical factor reducing vulnerability among affected households. Kinship networks, community solidarity, and reciprocal social relationships enabled households to access informal financial assistance, labor support, and livelihood information. Social capital therefore functioned as an important buffer against economic shocks. This finding

supports previous studies suggesting that strong social networks play a significant role in enhancing community resilience and reducing vulnerability in coastal communities facing environmental change (Aldrich & Meyer, 2015; Bakker, de Koning, & van Tatenhove, 2019). Overall, the study suggests that socioeconomic vulnerability among seaweed farming households is multidimensional. Vulnerability is not solely determined by declining income but also by the interaction between environmental degradation, limited livelihood alternatives, low educational attainment, and financial insecurity. While social capital partially mitigates these impacts, long-term vulnerability remains significant unless sustainable livelihood opportunities are strengthened through targeted policy interventions.

Policy Implications for Sustainable Coastal Livelihoods

The findings of this study provide several important policy implications for promoting sustainable coastal livelihoods in mining-affected regions. The substantial decline in seaweed farming productivity observed in the study areas indicates that environmental and economic policies should not be implemented independently. Instead, integrated coastal management approaches are needed to balance the objectives of mineral resource development and the sustainability of coastal livelihood systems.

First, environmental monitoring and regulation should be strengthened in areas where mining activities coexist with fisheries and aquaculture sectors. Effective management of sediment runoff, coastal water quality, and mining-related transportation activities is essential for protecting the ecological conditions required for seaweed cultivation, particularly given documented evidence that laterite mining and associated shipping activity are directly linked to elevated sediment and heavy-metal loads in nearby coastal waters (Apodaca et al., 2018; Ya'la et al., 2025). Environmental impact assessments should incorporate livelihood considerations to ensure that economic benefits from mining development do not disproportionately burden coastal communities.

Second, livelihood diversification programs should be expanded to reduce household dependence on a single economic activity. Government agencies and development organizations can support alternative livelihood development through vocational training, entrepreneurship programs, value-added fisheries processing, and small-scale coastal enterprises. Diversification initiatives should be designed according to local resource potentials and community capacities to ensure long-term sustainability, informed by evidence that diversification outcomes vary considerably and require careful design to avoid generating lower and more unstable incomes than the livelihoods they replace (Roscher et al., 2022).

Third, improving access to financial services is crucial for reducing household vulnerability. The findings demonstrate that many households rely heavily on informal credit sources during periods of economic stress. Expanding access to microfinance institutions, community-based savings groups, and productive credit schemes could help households invest in alternative livelihoods without increasing dependence on high-risk informal borrowing arrangements.

Fourth, strengthening social and institutional capital should become an integral component of coastal development strategies. Community organizations, farmer groups, cooperatives, and local associations can facilitate information exchange, collective action, and resource mobilization. Strong institutions can enhance community resilience by improving access to markets, financial support, and government assistance programs, consistent with evidence that collective engagement and institutional trust materially strengthen the resilience of resource-dependent communities (Bakker, de Koning, & van Tatenhove, 2019).

Finally, policy interventions should adopt a livelihood-centered approach to coastal development. Rather than focusing exclusively on economic growth indicators, development planning should consider household welfare, livelihood security, and community resilience. Such an approach would support more equitable and sustainable development outcomes, particularly in regions where multiple economic sectors compete for access to coastal resources.

The findings of this study highlight the importance of integrating environmental protection, livelihood diversification, financial inclusion, and community empowerment into coastal development

policies. By addressing these interconnected dimensions, policymakers can reduce socioeconomic vulnerability and strengthen the resilience of coastal communities facing environmental and economic change.

CONCLUSION

This study demonstrates that nickel mining expansion has contributed to significant changes in seaweed farming systems and coastal livelihoods in Southeast Sulawesi. Declining environmental quality and reduced seaweed productivity have affected household income, increased economic uncertainty, and forced many seaweed farmers to abandon or reduce cultivation activities. Provincial production declined by more than 63 percent between 2014 and 2019, with the decline reaching approximately 90 percent in Kolaka Regency and complete cessation of cultivation in Konawe Utara Regency. Affected households adopted various adaptation strategies, including the utilization of savings, informal borrowing, asset sales, livelihood diversification, and reliance on social support networks. These strategies enabled households to cope with immediate economic pressures; however, they were often insufficient to fully compensate for the loss of income generated by seaweed farming. The study further reveals that socioeconomic vulnerability among seaweed farming households is shaped by the interaction of environmental degradation, limited livelihood alternatives, financial insecurity, and low educational attainment. Social capital played an important role in reducing vulnerability by providing informal support mechanisms and strengthening community resilience. The findings suggest that sustainable coastal development in mining-affected areas requires integrated policy interventions that simultaneously address environmental protection, livelihood diversification, financial inclusion, and institutional strengthening. Such efforts are essential for reducing vulnerability and enhancing the long-term resilience of coastal communities dependent on natural resource-based livelihoods.

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AUTHOR CONTRIBUTIONS

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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