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Key variables for sustainable mangrove ecosystem management based on *Scylla* spp. in Banten Bay, Indonesia

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Abstract. *Nihan ARK, Kusmana C, Krisanti M, Tiryana T, Ulumuddin YI. 2025. Key variables for sustainable mangrove ecosystem management based on* Scylla *spp. in Banten Bay, Indonesia. Biodiversitas 26: 2467-2484.* Mangrove forests are crucial ecosystems that significantly contribute to achieving several of the United Nations' Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). These ecosystems provide vital services, including carbon sequestration and coastal protection, and are home to species such as *Scylla* spp., critical for fisheries and local biodiversity. Mangroves contribute significantly to climate change mitigation by sequestering carbon at rates that exceed those of some terrestrial forests while also protecting coastal areas from erosion and severe weather phenomena. Mangrove habitats also support local economies through fisheries, wood products, and ecotourism, which align with SDGs 8 (Decent Work and Economic Growth) and 12 (Responsible Consumption and Production). However, concerns such as overexploitation and progressive habitat destruction endanger these ecosystems. This study examines the key variables that influence the sustainable management of *Scylla* spp. populations in a mangrove ecosystem in Banten Bay, Indonesia. This study employed the Matrix of Crossed Impact Multiplications Applied to a Classification (MICMAC) technique to analyze the ecological, economic, social, and institutional factors influencing the management of mangrove ecosystems. The results underscore the importance of collaboration, education, community engagement, and a strong regulatory framework in securing the long-term viability of mangrove ecosystems. The study highlights that *Scylla* spp. has both ecological and economic significance, and sustainable management of this species can incentivize local people to participate in conservation initiatives. Linking conservation efforts to the economic benefits of *Scylla* spp. allows for the reconciliation of ecological integrity with community well-being. The study highlights critical areas of intervention that can be addressed to enhance coastal communities' environmental sustainability and socio-economic well-being. The study provides practical recommendations for policymakers and environmentalists to manage mangrove ecosystems sustainably.

Keywords: Community involvement, conservation of *Scylla* spp., ecological sustainability, economic resilience, management of sustainable mangroves

INTRODUCTION

Mangrove forests are essential for the realization of numerous Sustainable Development Goals (SDGs), including SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). These ecosystems are crucial for the local fisheries and biodiversity, as they provide essential services such as carbon sequestration, coastal protection, and habitats for species such as *Scylla* spp. (Pricillia et al. 2021; Ewaldo et al. 2023). Mangroves are essential in climate change strategies because they can sequester carbon at levels surpassing terrestrial forests. (Pricillia et al. 2021; Fatonah et al. 2023). Additionally, they protect coastal areas from erosion and severe weather, supporting SDG 13 (Zulhalifah et al. 2021). Mangroves contribute to the local economy by providing fisheries, timber, and non-Timber Forest Products (NTFPs), such as medicinal plants, fruits, vegetables, fibers, and traditional materials, in addition to environmental benefits (Bao et al. 2022; Hatta et al. 2022). For instance, *Nypa fruticans* is extracted for its nectar, which is used to make local beverages, and its thatch, which is used in roofing (Swasta et al. 2023). Bioactive compounds are present in numerous mangrove species, contributing to the local community's health (Arbiastutie et al. 2021; Ramadhan et al. 2022). Mangroves also serve as nurseries for marine life, such as mud crabs, which are crucial for local fisheries (Ginantra et al. 2023; Swasta et al. 2023). Nevertheless, the sustainability of mangrove ecosystems is imperiled by pollution, coastal development, and overexploitation (Sahputra et al. 2021; Eddy et al. 2023). Unsustainable practices endanger their ecological equilibrium. Therefore, preserving these ecosystems necessitates sustainable management practices, including community engagement (Askar et al. 2021; Sahputra et al. 2021; Dharmawan et al. 2022). The ongoing ecological and economic advantages of mangroves are guaranteed by prioritizing conservation.

Scylla spp. play a crucial role in maintaining balance in mangrove ecosystems. From an ecological perspective, these crustaceans function as detritivores, thereby facilitating the circulation of nutrients in the soil and the aquatic environment and strengthening the structural integrity of mangrove vegetation (Gao et al. 2024). Moreover, concerning its ecological significance, *Scylla* spp. is an essential component of trophic dynamics for coastal predator species. Economically, *Scylla* spp. has considerable market value, serving as a key commodity in the fisheries sector and representing an important source of income for coastal populations. If correctly managed, realizing this economic potential can motivate communities to engage in mangrove habitat conservation. When individuals experience direct benefits from *Scylla* spp. through profitable harvests or other economic benefits, they will likely be more motivated to conserve the mangrove forests that serve as habitats for these crabs (Mhatre 2024). In essence, the sustainability of mangrove ecosystems is more likely to be assured when individuals recognize the economic incentives directly associated with such conservation efforts. However, a significant constraint is the over-harvesting of *Scylla* spp., which threatens the mangrove habitat and crab populations. Consequently, the implementation of sustainable *Scylla* spp. based on mangrove management practices, it is essential to balance mangrove conservation and the utilization of this natural resource (Budisusila et al. 2024).

Although many scientific studies have examined the principles of sustainable mangrove management, research emphasizes the integration of *Scylla* spp. within this paradigm, information is relatively scarce. Indeed, *Scylla* spp. has significant ecological, economic, and social values that can enhance sustainable mangrove management practices. Investigations into the key variables associated with mangrove management, based on *Scylla* spp., are critical to understanding the interactions between these variables, particularly in the context of Banten Bay. In addition to the critical role of *Scylla* spp. in maintaining the balance of the mangrove ecosystem, *Scylla* spp. serves as a commodity that provides economic benefits to coastal communities. It is hoped that directing mangrove ecosystem management strategies that focus on *Scylla* spp. conservation, more appropriate management approaches can be designed to sustain mangrove ecosystems and improve coastal communities' welfare (Annisa et al. 2024; Izzudin et al. 2024). This study aims to identify key variables affecting sustainable mangrove ecosystem management and examine their interactions. Thus, the results will yield tangible solutions for informed decision-making while ensuring the sustainability of *Scylla* spp. populations.

MATERIALS AND METHODS

Study area

This study was conducted over two months, specifically from December 2024 to January 2025, within the mangrove habitat of Banten Bay, Banten Province, Indonesia (Figure 1). The geographical focus of the study encompasses the mangrove forests along the Banten Bay coastline, specifically at the following locations: Bojonegara (coordinates ST1: 106°5'30.215" E, 5°59'12.522" S), Kramatwatu (coordinates ST2: 106°8'29.963" E, 6°1'22.582" S), Kasemen (coordinates ST3: 106°11'43.556" E, 6°1'11.617" S), Pontang (coordinates ST4: 106°15'2.631" E, 5°59'0.728" S), and Tirtayasa (coordinates ST5: 106°19'44.806" E, 5°59'10.141" S). The sampling sites comprised five stations, each representing a distinct sub-district: four from Serang District, Banten and one from Serang City, Banten.

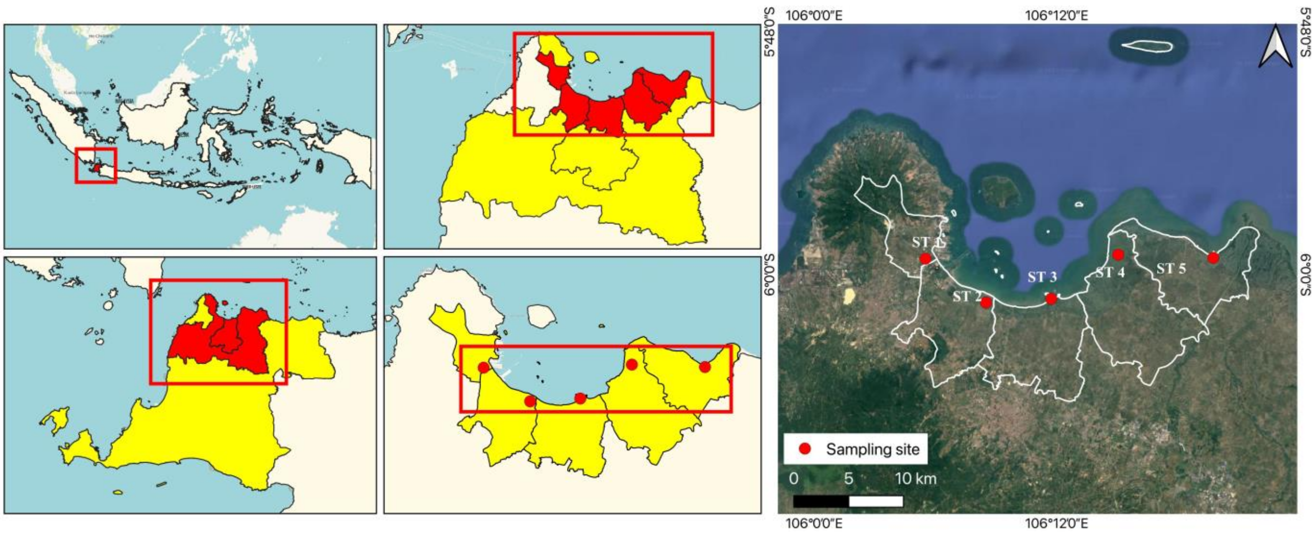

Figure 1. Map of Banten Bay study area, Banten Province, Indonesia

Scylla spp., which include *Scylla serrata*, *Scylla paramamosain*, and *Scylla olivacea*, are the dominant mud crab species in Banten Bay and make significant contributions to ecology (Aulia et al. 2024; Fatryani et al. 2022). These species exhibit extraordinary flexibility, thriving in estuarine and mangrove ecosystems where they play crucial ecological roles. *Scylla* spp. generally inhabit areas with muddy substrates that facilitate burrowing behavior, providing essential resources such as shelter, food, and breeding grounds (Sugiarti and Novianti 2022). Although the habitats of these species often overlap, each species shows distinct salinity preferences: *Scylla serrata* favors high salinity levels, *Scylla paramamosain* prefers low salinity, and *Scylla olivacea* typically thrives in areas with moderate salinity (Muhtadi et al. 2022; Swasta et al. 2023). Despite these variations, the shared habitats in mangrove and estuarine ecosystems highlight the importance of these areas as nursery grounds, where young crabs can develop in relative safety from predators (Md et al. 2025). These environments significantly enhance local biodiversity by providing shelter from predation and promoting nutrient cycling (Fazhan et al. 2021; Waiho et al. 2021). Anthropogenic drivers, such as urbanization and mangrove loss, jeopardize the availability of these habitats, leading to declines in *Scylla* populations in certain areas (Madduppa et al. 2022; Swasta et al. 2023). Due to the similar ecological characteristics and habitat requirements of these species, *Scylla* spp. can be viewed as an integrated functional group in the expansive mangrove and estuary ecosystems of Banten Bay, making species-level identification unnecessary for ecosystem management purposes (Fazhan et al. 2021; Md et al. 2025). Sustainable ecosystem management is vital to maintain the health of *Scylla* populations and the overall biodiversity of Banten Bay.

Procedures

This section outlines the procedural technique employed to perform the Matrix of Crossed Impact Multiplications Applied to a Classification (MICMAC) analysis. The analysis aims to clarify the interactions among the various factors affecting mangrove conservation, explicitly focusing on the population dynamics of *Scylla* spp. (Figure 2).

The preliminary phase of the inquiry entailed a comprehensive analysis of the factors affecting mangrove ecosystem management. This was derived from the research of Walters et al. (2018), who executed a Delphi study that amalgamated expert viewpoints to discern significant elements via an online survey platform. The discovered parameters were subsequently utilized in MICMAC modeling Forum Group Discussions (FGD), which served as the primary tool for analyzing the intricate relationships among these variables. In the focus group discussions, a consortium of experts was assembled to evaluate the pairwise interactions of the identified factors, therefore assessing their impact on the dynamics and evolution of the mangrove ecosystem in Banten Bay. During the focus group discussions, experts assessed the direct and indirect effects of the factors. The interactions were methodically analyzed and represented using MICMAC, resulting in a matrix illustrating the impacts and dependencies among significant factors. The outcomes of this analysis delineate the principal factors that had the most significant effects, as well as those that demonstrated the greatest reliance on other variables. This allows for identifying leverage areas that can be selectively targeted for short-term and long-term policy and management practice adjustments. The outcomes of the MICMAC FGD generated a series of definitive practical measures for managing mangrove ecosystems centered on protecting *Scylla* spp. The action stages were carefully classified into short-term and long-term plans, including the implications of present and future policy decisions. The FGD highlighted the importance of incorporating environmental and socio-economic perspectives into developing sustainable management strategies for mangrove ecosystems. This study aimed to identify and evaluate the essential sustainability attributes inherent in management methodologies related to mangrove forests, specifically those involving *Scylla* spp. populations. The investigation was conducted from December 2024 to January 2025, using the FGD methodology to collect data on key variables.

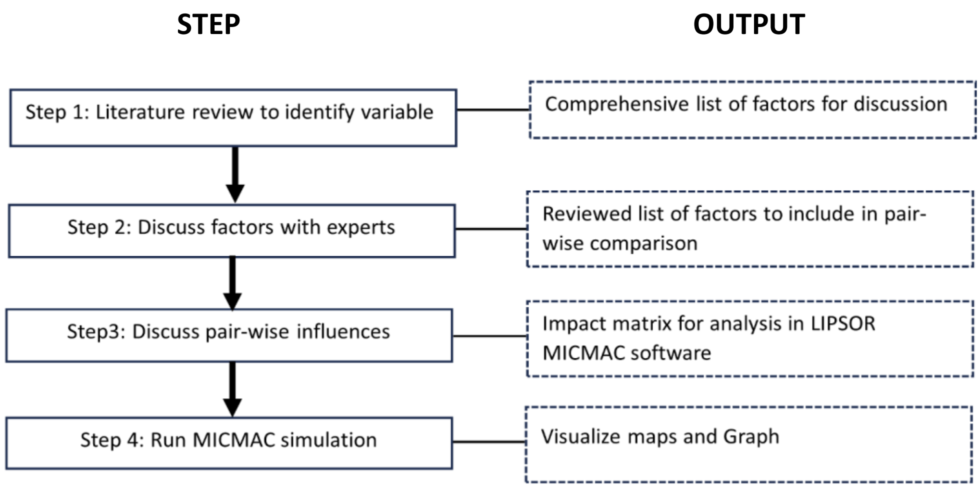

Figure 2. Research steps and output

Nine experts were purposively selected, considering the relevance of their expertise to the subject of the study, comprising academics specializing in Indonesian mangrove ecosystems, representatives from the Department of Marine Affairs and Fisheries (*Diskanlut*), officials from the Department of Environment and Forestry (*DLHK*), local community members, business people involved in *Scylla* spp. production, personnel from Non-Governmental Organizations (NGOs), influential public figures (Tokmas), and representatives from the River Basin Management Agency (BPDAS) and the Natural Resources Conservation Agency (BKSDA). Within the FGD framework, these experts systematically identified and classified critical variables into four categories: Ecological, Economic, Social, and Institutional. Next, to explain the interconnections among these variables, this study utilized the MICMAC methodology, as formulated by Godet et al. (1999) and further refined by Godet et al. (2006), which has demonstrated success in the field of sustainability assessment (Ahmed et al. 2009; Arozamena et al. 2012; Fauzi 2019). The analytical process was conducted in three phases: initially, identifying key variables during the FGD; next, examining the linkages between variables by assessing the strength of influence exerted by each variable; and finally, using the MICMAC software developed by LIPSOR to perform impact matrix multiplication and identify key variables. The results obtained from this MICMAC analysis will provide a comprehensive map of impacts and interdependencies among variables, offering significant insights into the leverage points necessary for the sustainable management of mangrove ecosystems centered around *Scylla* spp. activities.

Data analysis

The investigation focuses on the administration of the mangrove environment in Banten Bay, situated in Banten Province, Indonesia. This prospective evaluation utilizes primary data from diverse stakeholders participating in, managing, or comprehending mangrove ecosystems in a specific region. The participants in this focus group discussion are categorized as stakeholders. Most of the data acquired comprises the viewpoints, views, and evaluations of various stakeholders gathered through several empirical field data collection initiatives. The data collection employs thorough, in-depth interviews and FGD. The FGD technique is ideal for gathering data on opinions, perceptions, and evaluations from multiple viewpoints, enhancing analysis through a participatory, transparent, and responsible framework. This study employed MICMAC analysis, utilizing FGD to identify and establish contextual variable strategies relevant to mangrove ecosystem conservation in Banten Bay, Banten Province, Indonesia. The selected framework for the FGD is the World Cafe model, which effectively promotes an atmosphere favorable to information exchange and the transfer of expertise and experience among participants. This study emphasizes certain parts of the variable approach, particularly within the ecological, economic, social, and institutional dimensions. The number of participants in the FGD is restricted to nine persons. Moreover, alongside FGD, significant data and information are obtained from diverse study papers, activity documents, and other pertinent sources.

Structural analysis employing the MICMAC methodology encompasses three primary functions (Fauzi 2019): (i) Identification of critical variables, comprising influencing and dependent variables; (ii) Delineation of the relationships between variables within the axes of influence (Y) and dependence (X), alongside an assessment of their significance within the overarching system; (iii) Elucidation of the causal dynamics inherent in the system. The MICMAC technique for mapping variables in a system involves four primary stages: (i) Defining the problem; (ii) Identifying internal and external variables; (iii) Determining connections among variables; and (iv) Mapping and rating the variables concurrently. The primary and secondary stages utilized FGD, whereas the tertiary and quaternary phases employed MICMAC software. The degree of correlation among variables was evaluated using the following scale: 0: no relationship; 1: weak association; 2: moderate association; 3: strong association; P: prospective effect (uncertain). The connection evaluation results will classify the relationship between variables into three distinct influence categories: direct influence, indirect influence, and prospective influence. Direct influence transpires when one variable impacts another variable without the mediation of an intermediary variable. Conversely, indirect influence occurs when one variable affects a second variable, which, in turn, impacts a third variable. The potential influence is assessed by comparing the impact of one variable against another. In this instance, one variable does not directly influence another, resulting in no effect (Lin et al. 2024).

The use of the MICMAC technique in this study involved a multifaceted approach. Initially, it was necessary to investigate the scale and complexity of mangrove management in Banten Bay, Banten Province, Indonesia, and to identify measures to mitigate these issues. This initial phase involved stakeholders, including policymakers, policy implementers, subject matter experts, entrepreneurs, and community members, within the framework of FGD as previously outlined. The data from the FGD were systematically entered into a matrix using MICMAC software to identify significant factors. The results from this MICMAC study will inform the upcoming step of the FGD. The two stages together yielded the MICMAC results, specifically pinpointing crucial factors to thoroughly address the mangrove management issue in Banten Bay, Banten Province, Indonesia.

The process of mapping variables inside the MICMAC framework yields four distinct quadrants, each elucidating the status, function, and implications of the variables included within that quadrant, as illustrated in Figure 3 and detailed in Table 1, which outlines the status of each variable's position, illustrates the differential role assigned to each variable within the overall system.

Table 1. Types, functions, and consequences of variables in the MICMAC system

Variable types (Quadrant)	Status and role of variables	Consequences
Influence variables (Quadrant I)	Very practical with little dependency	It is an essential component of a critical system, but it does not incorporate the impact of other variables on this variable.
Relay variables (Quadrant II)	Influential but highly dependent, depicting an unstable variable	Describes the instability of a system. Any modification to this variable significantly impacts the system's other variables.
Dependence variables (Quadrant III)	It has little influence but is highly dependent	This variable is highly responsive to fluctuations in the influence and relay variables
Autonomous variables (Quadrant IV)	Small influence, small dependency	Possessing a minimal capacity to effect change. This variable is also known as "excluded" because it does not obstruct the system from functioning or utilizing it.
Regulator variable	It has a moderate influence and dependence	Acting as a lever

Source: Delgado-Serrano et al. (2015) and Fauzi (2019)

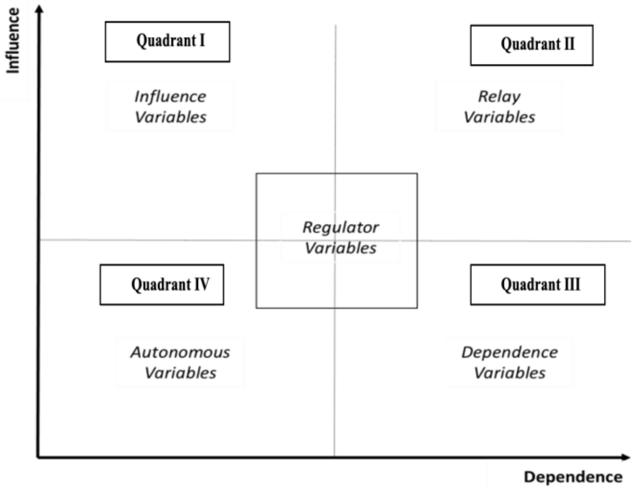

Figure 3. Categorization of variables based on their influence and dependency (Delgado-Serrano et al. 2015)

There are four main classifications for variables. (i) Quadrant I contain influential variables, which are also referred to as determinant variables; (ii) Quadrant II contains relay variables; (iii) Quadrant III contains dependent or output variables; (iv) Quadrant IV contains autonomous or excluded variables (Fauzi 2019). Conversely, as discussed by Delgado-Serrano et al. (2015), Variable regulators are characterized by moderate influence and system dependency, serving as a crucial lever.

RESULTS AND DISCUSSION

Identification of variables in sustainable mangrove management based on *Scylla* spp.

This study identified 16 essential factors related to sustainable mangrove management in Banten Bay, focusing on the sustainability of *Scylla* spp. populations. The sixteen variables cover four dimensions: ecological, economic, social, and institutional (Table 2). The matrix illustrated in Table 3 shows the direct linkages between variables in Sustainable Mangrove Management based on *Scylla* spp.

In this context, acknowledging the economic advantages of mangrove ecosystems, primarily through the sustainable management of high-value species such as *Scylla* spp., is vital for including local populations in conservation initiatives. To minimize the overexploitation of *Scylla* spp., it is imperative to establish solutions that harmonize resource extraction with sustainable practices. A key management strategy is transitioning from excessive dependence on wild harvesting to hatchery and nursery-based culture systems, which have demonstrated efficacy in offering controlled conditions for juvenile crabs, alleviating pressure on natural populations (Ut et al. 2007). Innovations include constructing artificial shelters replicating natural mangrove microhabitats, which might enhance juvenile survival rates, facilitating population rebound, and sustainable harvesting (Watchorn et al. 2023).

Establishing appropriate governance and regulatory frameworks poses considerable difficulty in coastal regions, such as Banten Bay, potentially impeding the overall viability of sustainable mangrove management initiatives. Mangrove habitats, especially those that sustain commercially significant species such as *Scylla* spp., need robust regulatory frameworks for enduring conservation. However, institutional fragmentation, conflicting interests, and the intricate, evolving characteristics of coastal ecosystems may hinder the comprehensive enforcement of these restrictions (Doelle and Puthucherril 2023; Divsalar et al. 2024). The challenge of reconciling policy with practical execution is a primary issue, as current conservation policies frequently neglect the complex requirements of local communities, governmental entities, and the environment due to inadequate enforcement and coordination (Friess et al. 2016; Chamberland-Fontaine et al. 2022).

Scylla spp. is environmentally reliant on robust mangrove forests and holds economic importance for coastal populations. By emphasizing the economic potential of these fisheries, conservation programs may be presented as financially beneficial, encouraging local populations to engage in and endorse mangrove protection efforts. *Scylla* spp. provide a direct connection between mangrove health and community livelihoods, creating a feedback loop that guarantees ecological conservation and economic advantage (Mirera et al. 2014; Oktamalia et al.

2019; Fithor 2023). Communities are more inclined to engage in conservation efforts when they see concrete advantages from sustainable crab harvesting, thereby alleviating the difficulties arising from conflicting stakeholder interests.

Research endeavors seek to clarify the principal factors influencing the sustainability of mangrove ecosystems and their corresponding *Scylla* spp. populations, which are fundamental for formulating conservation policies and strategies. The primary focus was on analyzing ecological factors, including habitat quality, biodiversity, and mangrove forest protection, directly impact the economy by promoting sustainable income and market diversification. Pollution control significantly affects environmental integrity and economic viability, underscoring the complex interdependencies between ecological and economic factors. Institutional policies and infrastructure influence community engagement, awareness, and educational endeavors.

Long-term ecological impacts of habitat destruction on *Scylla* spp. populations and mangrove ecosystems

The enduring biological consequences of habitat degradation on *Scylla* spp. populations and the general well-being of mangrove ecosystems are significant and complex. Mangrove ecosystems offer vital functions, serving as crucial habitats, nurseries, and feeding grounds for several species, including mud crabs such as *Scylla* spp. (Karniati et al. 2021; Swasta et al. 2023). The deterioration of these ecosystems caused by coastal reclamation, pollution, and sedimentation can result in substantial ecological disturbances. These activities impact both the physical environment and the animals that are dependent on mangroves for their existence. Comprehending these long-term effects is essential for managing mangrove ecosystems and surviving species such as *Scylla* spp. The obliteration of mangrove ecosystems diminishes habitat complexity, which is essential for the survival of *Scylla* spp. Research indicates that reclamation activities and pollution modify mangrove ecosystems' physical and chemical characteristics, encompassing water quality and sediment conditions. This immediately affects the species dependent on these habitats for sustenance and refuge (Islam et al. 2022). Moreover, the depletion of appropriate substrates and vegetation is vital for the reproduction and growth of *Scylla* spp. intensifies the reduction in their populations (Swasta et al. 2023).

Table 2. Critical variables for sustainable mangrove management in Banten Bay, Indonesia, concentrating on *Scylla* spp.

Dimensions	Variables	Short labels
Ecology	Habitat condition	Habitat
	Biodiversity	Biowaiver
	Pollution control	Pollution
	Mangrove conservation	Conservat
Economy	Sustainable income	Income
	Infrastructure and technology	Infratec
	Markets and prices	Market
	Product diversification	Diversific
Social	Community participation	Partisipat
	Education and awareness	Education
	Social welfare	Welfare
	Conflict management	Conflict
Institutional	Regulation and policy	Policy
	Inter-agency collaboration	Collaborat
	Funding and technical support	Funding
	Monitoring and evaluation	Monitoring

Table 3. Direct Influence Matrix (MDI) between variables in sustainable mangrove management based on *Scylla* spp.

	Habitat	**Biodiver**	**Pollution**	**Conservat**	**Income**	**Infratec**	**Market**	**Diversific**	**Participat**	**Education**	**Welfare**	**Conflict**	**Policy**	**Collaborat**	**Funding**	**Monitoring**
Habitat	0	3	2	3	2	1	1	2	3	2	2	2	2	3	2	3
Biodiver	3	0	3	3	2	2	2	2	3	3	2	3	3	3	2	2
Pollution	3	3	0	3	2	1	2	2	2	2	2	2	3	3	3	3
Conservat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Income	2	3	1	3	0	2	2	1	3	2	2	1	1	3	3	2
Infratec	2	3	2	3	3	0	2	2	2	2	2	2	2	2	3	3
Market	1	2	2	2	3	2	0	2	2	2	3	2	3	2	2	2
Diversific	3	3	2	3	3	2	3	0	2	3	2	3	3	3	3	3
Participat	3	3	3	3	3	2	2	2	0	3	2	3	3	3	3	3
Education	3	3	3	3	3	2	2	3	3	0	2	3	3	3	3	3
Welfare	2	2	2	2	3	2	2	2	3	2	0	3	3	1	3	2
Conflict	3	2	3	3	2	1	3	3	3	3	3	0	3	3	3	2
Policy	3	3	3	3	3	1	2	3	3	2	3	3	0	3	3	3
Collaborat	3	3	3	3	3	3	3	3	3	3	3	3	3	0	3	3
Funding	3	3	3	3	3	2	2	3	3	3	2	2	3	2	0	2
Monitoring	3	3	3	3	3	3	2	3	2	2	2	2	3	2	3	0

Note: Influences range from 0 to 3, with the possibility to identify potential influences: 0: No influence; 1: Weak; 2: Moderate influence; 3: Strong influence; P: Potential influences

Limiting habitat complexity in mangrove ecosystems affects biodiversity across several trophic levels. The fall in mangrove cover results in a corresponding decrease in the richness of macrofauna and flora, constituting the ecosystem's food web. The loss of biodiversity can disturb predator-prey dynamics for *Scylla* spp., which rely on a consistent prey supply, impacting their development, reproduction, and survival (Karniati et al. 2021). Habitat deterioration may enhance the bioaccumulation of contaminants, including mercury, in mangrove-dwelling species, adversely affecting the health and reproductive capabilities of *Scylla* spp. and other aquatic creatures (Nur et al. 2021). These contaminants act as bioindicators of extensive ecosystem deterioration, underscoring the immediate necessity for comprehensive conservation strategies (Purnama et al. 2024). The deterioration of mangrove ecosystems adversely impacts essential ecological functions, including water filtering, carbon sequestration, and nutrient cycling, in addition to their direct effects on *Scylla* spp. (Islam et al. 2022). Eliminating these services undermines the resilience of mangrove ecosystems and jeopardizes the lives of coastal populations reliant on these ecosystems for commodities such as fisheries and lumber. The destruction of mangroves intensifies the consequences of climate change, as these forests are essential for moderating global warming through carbon sequestration (Agustriani et al. 2024; Dharmayasa et al. 2024).

Restoration initiatives are essential for alleviating these enduring ecological consequences. Research has shown that focused restoration efforts, including reforestation and rehabilitation, can enhance the structural complexity of mangrove ecosystems and benefit species such as *Scylla* spp. (Hasibuan et al. 2021; Wongprom et al. 2023). These initiatives augment macrozoobenthos variety, bolster ecological stability, and facilitate carbon absorption, enhancing the ecosystem's potential to resist climate change effects (Dharmayasa et al. 2024). Ecological monitoring is essential for evaluating the efficacy of these restoration initiatives. Monitoring critical biological characteristics, including vegetation structure, soil quality, and water chemistry, is vital for assessing enhancements in habitat quality. These characteristics directly affect *Scylla* spp. populations and other species reliant on mangrove habitats (Askar et al. 2021; Sukmawati et al. 2022). Furthermore, employing bioindicators, like the variety and abundance of related fauna, offers significant insights into the efficacy of restoration techniques (Siblos and Tabugo 2024).

Addressing interconnected environmental priorities

Mangrove habitats are crucial for sustaining marine biodiversity, enhancing water quality, and supporting many species, including *Scylla* spp. (Rinaldy et al. 2023; Swasta et al. 2023). These functions enhance the mangrove ecosystem's resiliency and the stability of neighboring ecosystems, such as coral reefs and seagrass habitats. Additionally, mangrove forests serve as essential intermediaries between terrestrial and marine ecosystems, enabling the establishment of critical connections for the nutrient cycle and species migration. Consequently, prioritizing mangrove protection can enhance and strengthen initiatives to resolve other environmental challenges, resulting in a more cohesive and successful conservation approach.

Mangrove forests operate as natural barriers against storm surges and coastal erosion, mitigating the effects of extreme weather events and safeguarding coastal populations from possible devastation (Pratiwi and Dimenta 2021; Bakri et al. 2023). These protective functions diminish reliance on expensive technical solutions and catastrophe recovery initiatives, conserving substantial resources for governments and local communities. The structural complexity of mangrove ecosystems, characterized by their complicated root systems, stabilizes sediments, and preserves water quality, which is essential for the health of neighboring habitats, such as coral reefs and seagrass meadows. The deterioration of mangroves, which depend on pristine and stable water conditions, can initiate cascade consequences that compromise the mangrove ecosystem and the integrity of adjacent marine ecosystems (Swasta et al. 2023). Mangrove protection bolsters ecological resilience and alleviates the financial strain on coastal towns that would otherwise incur rising expenses for reconstruction and recovery. Consequently, preserving mangroves immediately enhances other ecosystems' resilience, rendering it a strategic and economical method to tackle other environmental issues concurrently.

Moreover, protecting mangroves is crucial in carbon sequestration, offering supplementary advantages in climate change mitigation. Research indicates mangroves are exceptionally proficient at sequestering and storing carbon within their biomass and sediments (Usman et al. 2022; Dharmayasa et al. 2024). The carbon storage potential of mangrove forests establishes them as significant partners in mitigating greenhouse gas emissions, a critical objective for global climate initiatives. Incorporating mangrove conservation into climate policy, including carbon credit initiatives and advocating for sustainable resource management, can alleviate the impacts of climate change and create new funding opportunities for conservation activities (Sugiatmo et al. 2023). Consequently, preserving mangroves mitigates local ecological issues and supports extensive worldwide initiatives to counteract climate change. The worldwide acknowledgment of mangroves' significance in carbon sequestration underscores the necessity of cooperative international strategies to safeguard these ecosystems for their ecological and economic worth.

Engaging local communities in conservation efforts

Effectively involving local populations in mangrove conservation while addressing their economic demands is essential for the ecosystem's long-term preservation. Coastal communities depend significantly on mangroves for resources like fuelwood, construction materials, and seafood; hence, it is imperative to include conservation in their economic practices. To do this, it is essential to acknowledge that local populations are not only passive recipients of ecosystem services but also active participants who must benefit directly from conservation initiatives

(Polidoro et al. 2010). By associating conservation with the economic sustainability of local communities, mangrove management can develop into a symbiotic relationship (Maina et al. 2021). A pragmatic strategy involves livelihood diversification via environmentally sustainable practices, like the sustainable aquaculture of *Scylla* spp. and ecotourism, which can yield consistent income while promoting mangrove conservation (Siikamäki et al. 2012).

Moreover, participatory management approaches that include local populations in decision-making are essential for effective conservation (Majesty and Fadmastuti 2018; Permana et al. 2024). Studies have shown that community involvement in resource management leads to adopting more sustainable practices, enhancing conservation efforts and economic results. Engaging local populations in creating protected areas and monitoring systems enhances adherence to sustainable harvesting techniques (Hasan et al. 2022). This strategy engenders a sense of ownership and accountability among local stakeholders, augmenting conservation initiatives' efficacy.

Integrating scientific and traditional ecological knowledge is crucial for maintaining cultural relevance and flexibility of conservation measures. Integrating the optimal aspects of both domains facilitates more comprehensive and contextually relevant decision-making (Sabai and Sisitka 2013). Combining indigenous knowledge with scientific understanding guarantees that conservation efforts are customized to local socio-economic and environmental contexts, enhancing community engagement, and promoting sustainable practices.

Integrating ecological and economic justifications for mangrove conservation

In addressing the contention that mangrove protection's ecological and economic advantages may not warrant the expenses associated with their preservation and maintenance, it is crucial to acknowledge the diverse functions that mangrove ecosystems fulfill, which transcend mere financial considerations. Although the upfront expenses of mangrove protection may appear substantial, several studies underscore the enduring ecological and economic advantages these habitats offer, rendering their preservation both environmentally essential and financially prudent.

Mangroves are ecologically significant as natural barriers against storm surges and coastal erosion. Their complex root systems attenuate wave energy, mitigating the effects of severe weather phenomena, such as floods and coastal erosion (Bakri et al. 2023; Pratiwi et al. 2023). This natural defense substantially reduces the necessity for expensive infrastructure improvements to address coastal erosion and alleviate catastrophic effects. Areas with intact mangrove ecosystems incur lower costs for disaster assistance and repairs, highlighting the economic efficiency of conserving these environments. Research indicates that the expenses associated with preserving healthy mangrove forests are readily compensated by the savings in disaster recovery, rendering them an essential and economically advantageous element of coastal protection (Fatonah et al. 2023). Consequently, protecting mangroves safeguards coastal populations and mitigates prospective economic consequences associated with climate-related effects.

Mangroves are essential for coastal protection and serve as vital habitats for biodiversity, sustaining numerous marine species, including commercially significant fish and crabs. These ecosystems function as nurseries, breeding grounds, and feeding habitats for several species, many of which are vital to local fisheries and support the livelihoods of coastal populations (Askar et al. 2021; Natsir et al. 2023). The varied and fruitful ecosystems established by mangroves support sustainable fisheries, which are vital for the sustenance and livelihood of millions. Moreover, the symbiotic association between mangrove ecosystems and tourists yields supplementary economic advantages. Ecotourism programs centered on healthy mangrove ecosystems can yield substantial money, bolstering local economies and advancing conservation efforts (Askar et al. 2021). The twin advantages of safeguarding biodiversity and enhancing local livelihoods illustrate the fundamental link between ecological well-being and economic stability in coastal areas.

Mangroves are vital for carbon sequestration, a critical ecological service aiding global climate change mitigation efforts. Mangrove forests sequester carbon in their biomass and sediments, frequently at rates considerably above terrestrial forests (Usman et al. 2022; Sugiatmo et al. 2023). This renders them an essential instrument in the battle against climate change. Furthermore, the carbon sequestered in mangroves possesses significant economic value via nascent carbon credit markets. Governments and communities can gain cash by selling carbon credits, mitigating the expenses associated with conservation and restoration initiatives (Purnama et al. 2024). Consequently, by investing in mangrove protection, stakeholders safeguard an essential ecological function while accessing a novel financial resource to further other environmental and socio-economic objectives.

Furthermore, incorporating sustainable resource extraction and community-based management strategies enhances the economic rationale for mangrove protection. Research indicates that restored mangrove forests, particularly those with *Rhizophora apiculata*, may sustain harvesting techniques while preserving the ecological integrity of the ecosystem (Usman et al. 2022). This strategy enables local populations to utilize the natural benefits offered by mangroves while preserving the biological integrity of the environment. Mangrove management can yield enduring economic advantages by integrating conservation with sustainable resource utilization, hence preserving the ecosystem's ability to maintain biodiversity and local economies (Kasihiw et al. 2024).

Variable position of sustainable mangrove management Based on *Scylla* spp.

The MICMAC analysis and Direct Influence/ Dependency Map offer significant insights into the intricate linkages and interdependencies among ecological, economic, social, and institutional factors in sustainable mangrove management. By categorizing the factors into four quadrants-influence factors (Quadrant 1), bridging variables (Quadrant 2), dependency variables (Quadrant 3), and autonomous variables (Quadrant 4), stakeholders may ascertain which aspects warrant prioritization for intervention. This facilitates enhanced decision-making and resource allocation in sustainable mangrove management, specifically for protecting *Scylla* spp. in Banten Bay. Effective regulatory frameworks must account for local socio-economic settings, adapt to environmental changes, and emphasize community engagement to address governance difficulties in coastal regions.

Strategies highlighting the socio-economic and ecological advantages of mangrove ecosystems must be prioritized to tackle the problems of community participation. Combining mangrove protection with community-oriented economic prospects, such as sustainable aquaculture of *Scylla* spp., can improve local engagement. Bioeconomic assessments indicate that meticulously managed fisheries and aquaculture of mud crabs optimize resource utilization while fostering long-term sustainability (Ananto et al. 2023). This strategy can reduce the danger of overexploitation and provide financial incentives for communities to use sustainable management methods. Integrating economic rationale with conservation goals can harmonize conflicting stakeholder interests by illustrating that preserving mangroves benefits *Scylla* spp. populations are directly linked to enhanced economic yields from fisheries.

The results of the MICMAC analysis are depicted in Figure 4 as a direct influence/dependence map. This map categorizes variables into three main quadrants based on their influence and dependency: influence variables (Input), relay variables (Intermediate), and dependent variables (Results). The classification of each variable into these quadrants is determined by calculating its driving force (ability to influence other variables) and dependency (how much other variables influence it) (Zhang et al. 2022; Zhu et al. 2023).

Several interrelated factors profoundly affect the sustainable management of mangrove ecosystems, especially the conservation of *Scylla* spp. in Banten Bay. These include education and awareness, infrastructure and technology, markets and pricing, product diversification, social welfare, and conflict management; these factors are included in the first quadrant, referred to as the influencing (input) variables. The enduring success of mangrove conservation efforts is contingent upon each attribute, contributing to the realization of the United Nations' Sustainable Development Goals (SDGs) (Gong et al. 2024). Implementing hatchery techniques for *Scylla* spp., along with spatial management zones and community-based monitoring systems, provides a practical framework for mitigating the overexploitation of these species (Vay 2001; Liew et al. 2023; Watchorn et al. 2023).

Education and awareness are critical drivers for sustainable mangrove management. An informed and erudite populace is more predisposed to engage in conservation initiatives that foster enduring ecological stability. Educational initiatives emphasizing the advantages of sustainable aquaculture and the significance of hatchery systems in alleviating fishing pressure represent an effective strategy to mitigate the overexploitation of *Scylla* spp. (Kamara 2023). Conversely, the difficulty of efficiently coordinating and managing these initiatives in coastal regions, where governance structures are frequently disjointed and institutional backing is insufficient, persists in obstructing advancement (Diederichsen et al. 2024).

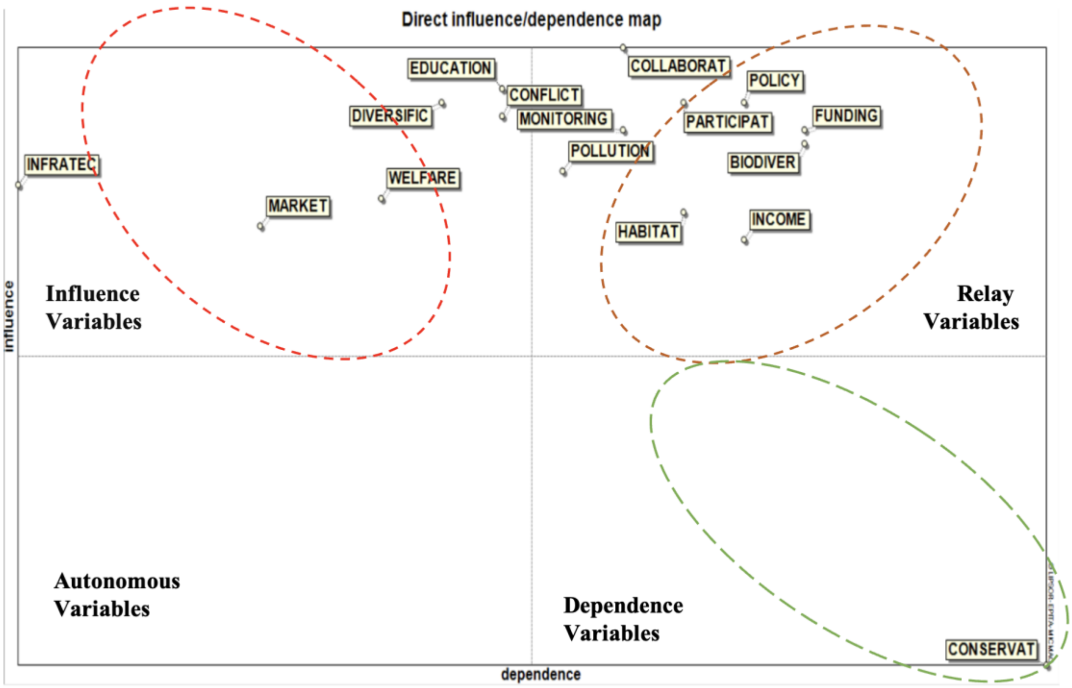

Figure 4. Direct effect/dependency map from MICMAC analysis

Aghdam et al. (2022) contend that public education significantly improves local comprehension of mangroves' ecological and economic importance, empowering people to make educated choices regarding resource management and protection. Tailored educational initiatives, particularly those addressing local needs, have effectively altered harmful practices, such as illegal mangrove logging or overfishing, that threaten the sustainability of *Scylla* spp. fisheries (Hami and Boikh 2024). Furthermore, educational initiatives focused on the SDGs, especially regarding environmental sustainability, climate action, and biodiversity conservation, can be crucial in integrating these global objectives into local conservation strategies (Olugbade et al. 2023). When communities recognize the various benefits of mangroves, including their role in carbon sequestration, coastal protection, and sustainable living, their participation in conservation efforts frequently increases (Mohamed et al. 2023). These teaching methods are by SDG 13 (Climate Action) and SDG 14 (Life Below Water), as they equip communities with the necessary knowledge to mitigate environmental degradation and enhance coastal resilience.

Infrastructure and technology are essential for the facilitation of sustainable mangrove management, in addition to education. The necessity of sustainable infrastructure systems to enhance community resilience is underscored by the intrinsic connection between developing robust infrastructure and realizing SDG 9 (Industry, Innovation, and Infrastructure). Augmented infrastructure, including advanced transit systems and coastal amenities, facilitates communities' interaction with mangrove resources more effectively. Establishing sustainable fisheries infrastructure enables local communities to collect *Scylla* spp. more efficiently while minimizing environmental impact (Akomea-Frimpong et al. 2023). Improvements in transportation infrastructure enhance the efficient distribution of fishing products to local and regional markets, fostering economic growth and encouraging sustainable practices (Ananto et al. 2023). Incorporating technology in mangrove management substantially aids in achieving SDG 13 (Climate Action) by facilitating real-time ecological monitoring. Technologies, such as remote sensing and Geographic Information Systems (GIS), facilitate evaluating mangrove ecosystem health and monitoring biodiversity changes, essential for adaptive management and informed decision-making (Song and Technological advancements in aquaculture and fisheries enhance resource efficiency, reduce waste, and promote sustainable utilization of marine resources) (Han et al. 2024).

According to Mahmood et al. (2024) the interaction of infrastructure, technology, and finance systems significantly improves the prospects for sustainable mangrove management. Green funding is essential for advancing sustainable infrastructure and promoting new technologies. Green financing systems provide essential capital for ecosystem restoration initiatives, monitoring technology deployment, and sustainable infrastructure advancement. This strategy is consistent with SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land), as it prioritizes the long-term preservation of mangrove ecosystems while simultaneously addressing the socio-economic requirements of coastal communities.

Markets and price structures are essential in promoting sustainable conservation practices. Koda (2023) stated that economic incentives are crucial motivators for community engagement in protecting mangrove ecosystems. The economic value of mangrove resources is primarily derived from *Scylla* spp. fisheries substantially incentivize local communities to embrace sustainable practices. Sustainable fishing methods compatible with environmental conservation may be promoted by accurately evaluating these resources using market-based pricing systems. This is consistent with SDG 8 (Decent Work and Economic Growth), which emphasizes the importance of fostering sustainable economic growth and equitable job opportunities through the sustainable utilization of mangrove resources (Ananto et al. 2023). The comparison between the biological value of mangrove ecosystems and market pricing by Kurniawati et al. (2022) motivates and encourages stakeholders to prioritize long-term conservation over immediate economic benefit. This method ensures the sustainable utilization of mangrove resources without compromising long-term sustainability, thereby promoting SDG 12 (Responsible Consumption and Production).

Ecotourism presents a significant opportunity for generating income and promoting conservation in mangrove habitats. Fanggi et al. (2023) assert that developing mangrove regions for ecotourism attracts visitors, fosters environmental awareness, and generates income for residents. Engaging local communities in ecotourism activities alleviates economic constraints on mangrove habitats and promotes conservation efforts. This supports SDG 14 (Life Below Water), which aims to protect and sustainably use marine resources. Ecotourism enables communities to earn sustainable revenue, foster responsible tourism, and conserve mangrove environments for future generations (Agustin and Suliantoro 2024).

The SDGs are facilitated by the critical factor of product diversification within mangrove ecosystems. Diversifying goods produced from mangrove resources, including *Scylla* spp., blue carbon credits, and ecotourism, enables local people to reduce their reliance on a single resource and enhance their economic resilience. Kairo et al. (2021) contend that product diversification creates various revenue streams and facilitates the sustainable management of mangrove ecosystems. Ecotourism significantly contributes to diversifying revenue streams and raising awareness about the importance of mangrove protection. Maulana et al. (2022) emphasize that ecotourism yields economic benefits and fosters environmental conservation, which is essential for preserving the biological integrity of mangrove habitats. Moreover, effective fisheries management for *Scylla* spp. can ensure stable livelihoods for local fishermen while aiding in biodiversity conservation. Fanggi et al. (2023) underscore the necessity of comprehending the biological and ecological requirements of *Scylla* spp. to develop sustainable fishing strategies that preserve biodiversity and safeguard coastal ecosystems.

Social well-being is essential for the effective management of mangrove ecosystems. Social welfare programs enhance local communities' well-being, thereby augmenting conservation initiatives' efficacy. Junaidi et al. (2022) contend that including *Scylla* spp. cultivation inside mangrove ecosystems can yield economic stability and enhance food security for local communities. This methodology advances Sustainable Development Goals 1 (No Poverty) and 2 (Zero Hunger) by fostering income diversification, generating employment opportunities, and improving food security through sustainable practices. Moreover, fair access to the advantages of mangrove habitats is crucial for cultivating community backing for conservation efforts. Golebie et al. (2021) assert that governance frameworks fostering equity and social cohesion enhance community engagement in mangrove management. When local populations recognize the equitable benefits that the ecosystem provides, they are more likely to adopt sustainable behaviors and support conservation efforts.

Ultimately, conflict management is essential for the sustained stewardship of mangrove ecosystems. Conflicts frequently emerge from conflicting land-use demands, such as agricultural expansion or urban growth, which jeopardize the integrity of mangrove ecosystems. Choi et al. (2022) underscore that these conflicts have the potential to obstruct conservation initiatives and undermine the equilibrium that is necessary for the preservation of biodiversity. Inclusive and participatory strategies that involve all stakeholders, such as local communities, governmental bodies, and non-governmental organizations, are essential for effective conflict management. Arfan et al. (2024) stated it is crucial to enable local populations, including women's organizations, to engage in decision-making about mangrove management, as this facilitates conflict resolution and ensures fair outcomes. Moreover, community-based and co-management strategies that amalgamate local knowledge with official management frameworks have demonstrated efficacy in mitigating disputes and enhancing the sustainability of mangrove conservation initiatives (Kairo et al. 2021).

The sustainable management of mangrove ecosystems in Banten Bay, especially for *Scylla* spp. protection, necessitates a holistic and integrated strategy. Local conservation initiatives can be aligned with global sustainability objectives by focusing on key factors such as education and awareness, infrastructure and technology, market dynamics, product diversification, social welfare, and conflict management. This comprehensive strategy ensures the long-term sustainability of mangrove ecosystems while enhancing the socio-economic well-being of the populations that rely on them. By integrating these factors, we may advance the attainment of the SDGs and promote a sustainable future for both mangrove ecosystems and their dependent populations (Arfan et al. 2024).

The second quadrant, which includes relay (intermediate) variables, encompasses interagency coordination, pollution control, monitoring and evaluation, community engagement, regulation and policy, financial and technical assistance, biodiversity conservation, and sustainable income generation. These factors are crucial for the sustainable management of mangrove ecosystems, as they are interrelated and significantly influence one another. Interagency coordination is essential for attaining environmental sustainability. In Indonesia, managing marine resources, including coral catsharks, necessitates collaborative efforts among policymakers, stakeholders, and fishermen to promote biodiversity and sustainable resource utilization (Lelono et al. 2023). This collaborative methodology is crucial for mangrove conservation, as it ensures collective accountability among organizations striving to achieve the SDGs, including Target 14, which focuses on Life Below Water. Pollution control is a vital factor, as industrial activities frequently compromise ecosystems. Effective pollution control, encompassing land use monitoring, mitigates biodiversity loss and promotes ecosystem health (Younis et al. 2022). The significance of monitoring and evaluation is underscored through methodologies such as forest health monitoring (Safe'I et al. 2021), which may also be utilized in mangrove ecosystems to evaluate restoration initiatives and refine tactics. The active participation of local populations significantly bolsters conservation initiatives, as seen in sustainable farming practices and wetland management (Yusuf et al. 2021; Leo et al. 2022). Communities possess inherent knowledge that can aid in the management of biodiversity, thereby promoting sustainable income generation through activities such as ecotourism, thereby supporting Sustainable Development Goals such as Decent Work and Economic Growth (SDG 8) (Mukarrom et al. 2022). Regulatory frameworks and financial assistance are essential for establishing an environment favorable to sustainability, wherein varied financing techniques enhance the long-term viability of conservation initiatives (Ridwan et al. 2023). This research highlights the necessity of coordinated policy measures that promote ecological and socio-economic sustainability through various SDGs while ensuring a balanced strategy for mangrove management in Banten Bay.

The third quadrant, which includes dependent variables (outcomes), highlights the importance of conserving mangrove ecosystems in preserving coastal biodiversity and providing essential ecological services. This variable is significantly affected by habitat conditions, pollution control, and sustainable resource utilization. Mangrove habitats are well-documented for their roles in coastal protection and biodiversity conservation, with research emphasizing their significance for marine and terrestrial species (Kundu and Perwez 2022; Zhang et al. 2022). The safeguarding of mangroves is inextricably linked to numerous SDGs, particularly SDG 13 (Climate Action), as these ecosystems function as essential carbon sinks, thereby mitigating the consequences of climate change (Pricillia et al. 2021; Diederichsen et al. 2024). Integrating mangrove conservation into national climate policies, including Nationally Determined Contributions (NDCs) (Pricillia et al. 2021), underscores the significance of mangrove preservation for global climate change mitigation.

Mangrove protection is particularly relevant to SDG 14 (Life Below Water) since these ecosystems offer essential habitat for juvenile fish, *Scylla* spp., and other marine species, hence enhancing biodiversity and sustaining fisheries (Askar et al. 2021; Ewaldo et al. 2023). The correlation between mangrove health and marine production underscores the necessity for sustainable mangrove management to secure enduring ecological and economic advantages for local populations reliant on fisheries (Tjiong et al. 2021). Additionally, SDG 8 (Decent Work and Economic Growth) is supported by ecotourism initiatives that are focused on mangrove ecosystems, which generate economic opportunities and promote environmental awareness and conservation efforts (Ewaldo et al. 2023). This highlights the capacity of mangrove ecosystem protection to enhance ecological sustainability and socio-economic advancement. Mangrove ecosystem protection also supports SDG 15 (Life on Land) by mitigating land degradation, preserving soil stability, and promoting biodiversity (Zulhalifah et al. 2021; Kasihiw et al. 2023). Collaborative initiatives among local communities, governments, and NGOs (SDG 17) are crucial for effective conservation strategies, guaranteeing the achievement of ecological and socio-economic objectives via collective responsibility and resource management (Aipassa et al. 2023; Bakri et al. 2023). Consequently, protecting the mangrove ecosystem in Banten Bay is both an environmental imperative and a crucial component in attaining several sustainable development goals, fostering resilience, and ensuring sustainable development.

Relationship between variables of sustainable mangrove management based on *Scylla* spp.

Direct influence diagrams provide significant insights into the governance of mangrove ecosystems in Banten Bay by illustrating the magnitude and orientation of interrelationships between variables that influence the sustainability of such ecosystems (Nielsen et al. 2023). Consequently, applying this diagram to formulate appropriate policies and strategies is essential for achieving integrated and sustainable conservation goals in coastal areas.

Figure 5 illustrates the direct influence graph derived from the Micmac study. This graph visually illustrates the direct relationship between the variables involved in sustainable mangrove ecosystem management. This visual tool facilitates understanding the complex inter-relationships between ecological, economic, social, and institutional variables that influence mangrove management, particularly regarding *Scylla* spp. in Banten Bay.

The research indicates that infrastructure and technology variables have the most significant influence, with the least dependency. Infrastructure and technology variables influence sustainable income and mangrove conservation variables. Market and price variables have a strong influence on sustainable income variables. Product diversification variables have a significant influence on mangrove conservation and biodiversity. The social welfare variable strongly influences community participation, funding, technical support, and sustainable income. Conflict management variables strongly influence habitat variables, mangrove conservation, market and price dynamics, and funding and technical support. Education and awareness variables strongly influence habitat variables, pollution control, mangrove plant conservation, sustainable income generation, and regulation and policy.

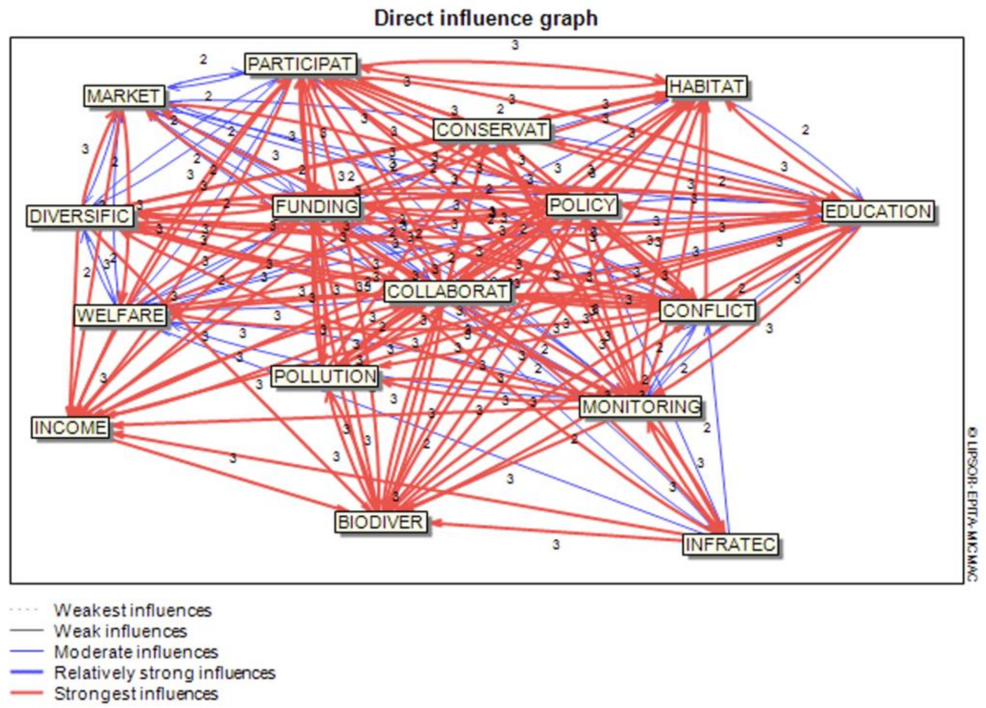

Figure 5. Direct effect graph of MICMAC analysis

These findings indicate that the variables most influencing other variables are the education and awareness variables. On the other hand, the variable with a significant influence is the least dependent with a significant influence. Still, the infrastructure and technology variables with a significant influence are the least dependent variables. Still, the least dependent on dependency are the infrastructure and technology variables. Recent trends highlight the critical role of infrastructure and technology in supporting community resilience and promoting sustainable economic growth (Singh et al. 2024). Education and public awareness are critical components in mangrove ecosystem management centered on *Scylla* spp., which are key elements that support behavior modification promoting sustainable mangrove ecosystem preservation. Contemporary studies show that improving public understanding of mangrove forests' ecological and economic benefits can increase active engagement in conservation initiatives (Hami and Boikh 2024; Izzudin et al. 2024). Educational initiatives involving local communities, especially those living near mangrove habitats, have successfully limited destructive practices, such as cutting mangrove trees and degrading essential habitats for *Scylla* spp. (Permana et al. 2024). This perspective aligns with the conclusions drawn by Izzudin et al. (2024), who emphasize that collaborative efforts among government entities, the public sector, and private stakeholders, driven by education and increased awareness, will enhance the long-term success of sustainable mangrove ecosystem management based on *Scylla* spp. This research highlights the importance of education and awareness, which are crucial in shaping community behavior and attitudes toward mangrove ecosystem management.

The findings of this study show that the most influenced variable is mangrove conservation, with 13 variables that play an essential role in its success, namely habitat, biodiversity, pollution control, sustainable income, infrastructure, and technology, product diversification, community participation, education and awareness, conflict management, regulation and policy, inter-agency collaboration, funding and technical support, and monitoring and evaluation. Mangrove conservation involves various ecological, economic, social, and institutional factors to ensure sustainability (Jahan and Sujarajini 2024). Recent research has revealed that ignoring the interactions between these variables can hinder achieving long-term goals in mangrove ecosystem management. Ispiryan et al. (2024) successful conservation depends on integrating policies that support holistic natural resource management, active community participation, and efficient monitoring. Sari (2024) emphasized the importance of a community-based approach, considering local social and economic welfare to create sustainable incentives in mangrove conservation efforts. Therefore, an approach that links mangrove conservation to these variables will be more effective in maintaining the sustainability of mangrove ecosystems and associated resources, such as *Scylla* spp.

Incorporating the SDGs into mangrove ecosystem management, particularly in Banten Bay, provides a comprehensive framework for ensuring long-term ecological sustainability. Additionally, Aipassa et al. (2023) underscore the importance of interagency coordination in the management of complex coastal ecosystems, as emphasized by SDG 14 (Life Below Water) and SDG 13 (Climate Action). This cooperation ensures the effective implementation of mangrove conservation projects, which are crucial for mitigating climate change and preserving biodiversity. The promotion of collaboration among government agencies, NGOs, and local communities promotes a more comprehensive and inclusive conservation strategy. Additionally, community engagement is inextricably linked to SDG 10 (Reduced Inequalities) and SDG 11 (Sustainable Cities and Communities), as it allows residents to participate in decision-making and assume responsibility for conservation initiatives (Sadono et al. 2020). Active community participation, as demonstrated by the mangrove replanting initiative in Kupang Bay, has been proven to be a crucial determinant of the effectiveness of environmental management (Sadono et al. 2020). Moreover, educational and awareness-raising programs are crucial for fostering community support for sustainable practices, augmenting local capacity for resource management, and guaranteeing that future generations benefit from these ecosystems (Yadav 2024). Environmental literacy is improved by fostering community engagement in protecting mangrove ecosystems and preserving their livelihoods, and conservation initiatives are linked to Sustainable Development Goals, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Mawardi et al. 2022). Moreover, adaptive management approaches that incorporate local knowledge and adaptable governance structures, as proposed by Natsir et al. (2023), are essential for addressing the evolving challenges of coastal ecosystems. This methodology promotes ecological sustainability and socio-economic advancement, facilitating several Sustainable Development Goals, particularly SDG 17 (Partnerships for the Goals). Thus, an integrated emphasis on cooperation, community engagement, and education is essential for the sustainable management of mangrove ecosystems in Banten Bay, fostering resilience and advancing the overarching global sustainability goal.

Ranking variables based on direct-indirect effect and dependency

Figure 6 illustrates a comparative study of rankings based on the impact and dependency of variables, classifying them into two principal dimensions: their capacity to effect changes and their dependence on other factors. This research emphasizes the strategic importance of these critical variables in determining long-term conservation and socio-economic outcomes, which are directly associated with SDG 15 (Life on Land). This goal focuses on the conservation and restoration of ecosystems, including mangroves. The study identifies a hierarchy of significant factors, with collaboration placed first, education second, product diversification third, community participation fourth, and regulations and policies fifth. This hierarchical framework clarifies the direct impact of each variable on mangrove ecosystem management. When assessing the indirect effects, the hierarchy alters. Product diversification has fallen to fifth place, while community participation has risen to third, surpassing product diversification. Once rated fifth, the regulations and policies variable ascends to fourth, indicating the growing significance of policies in attaining sustainable ecological outcomes. Based on their indirect effects, the revised hierarchy of factors is as follows: collaboration, education, community participation, regulations and policies, and product diversification.

This analysis demonstrates that the collaboration variable has the most substantial direct impact, followed by education, product diversification, community participation, and regulations and policies. The explicit emphasis on collaboration is consistent with SDG 17 (Partnerships for the Goals), underscoring the significance of multi-stakeholder collaboration in attaining sustainable environmental management. The preservation of mangrove ecosystems and their associated species, including *Scylla* spp., necessitates the collaboration of governmental entities, local communities, NGOs, academic institutions, and the corporate sector. Abeysinghe et al. (2023) contend that these relationships are essential for achieving successful and sustainable conservation outcomes. Moreover, the second-ranked component, education, underscores the necessity of augmenting public knowledge and comprehension to improve the sustainability of mangrove ecosystems, thus aligning with SDG 4 (Quality Education). Izzah and Islam (2024) assert that education is crucial in altering public perceptions of natural resource management. Comprehensive educational programs empower individuals to adopt sustainable habits, leading to informed decisions that benefit the environment and local communities.

The hierarchy of factors significantly alters when examining the indirect impacts. Product diversification, formerly ranked third, has fallen to fifth, while community participation ascends to third, supplanting product diversification. The significance of active community engagement in conserving natural resources is underscored by SDG 11 (Sustainable Cities and Communities), consistent with this transition, Sattayapanich et al. (2022) underscore the importance of community engagement in the administration of mangroves, as it will enhance the resilience of the ecosystem. This is especially applicable in regions such as Banten Bay, where indigenous knowledge and active involvement in conservation initiatives are crucial for preserving the integrity of mangrove ecosystems. Local communities implementing sustainable practices can substantially alleviate the stresses on mangrove ecosystems resulting from over-exploitation while enhancing socio-economic resilience. Moreover, once positioned in sixth place, regulations ascend to fourth place, indicating an increasing acknowledgment that strong and well-implemented regulations are crucial for the long-term preservation of mangrove ecosystems. The growing impact of Regulations and Policies is intricately linked to SDG 16 (Peace, Justice, and Strong Institutions), which underscores the significance of robust governance frameworks in fostering the fair and sustainable management of natural resources. Effective policies ensure that ecosystem management is both environmentally sustainable and socially inclusive, promoting equitable access to resources and safeguarding the rights of local populations.

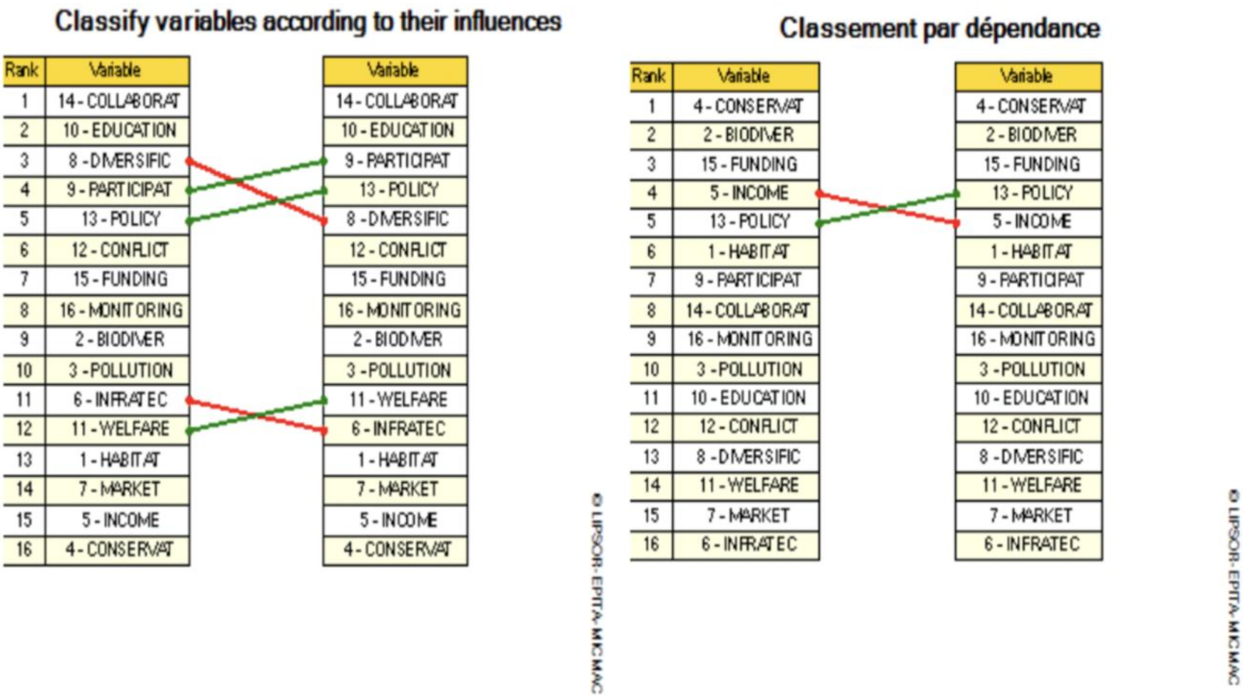

Figure 6. Comparison of rankings based on influence and dependence in sustainable mangrove management based on *Scylla* spp.

The study examines the dependence links among the variables, indicating that the conservation variable exhibits the most significant direct dependency, followed by biodiversity, policies, regulations, and funding. The conservation and rehabilitation of terrestrial ecosystems, including mangrove forests, are emphasized in this framework, which emphasizes the critical significance of SDG 15 (Life on Land). Conservation initiatives are crucial for preserving the integrity of mangrove ecosystems, as emphasized by Jahan and Sujarajini (2024), who advocate for stringent conservation measures to protect these key habitats. Biodiversity and funding are critical pillars in managing *Scylla* spp. dominated mangrove ecosystems. Policies that advocate for biodiversity protection facilitate species' survival, such as mangrove crabs, which rely on mangrove ecosystems and are essential for the livelihoods of coastal populations. Nonetheless, when assessing indirect reliance, the hierarchy is altered. Income rises from fifth to fourth position, while regulations and policies, formerly in fifth position, move up to fourth. This transition suggests that, although economic variables such as income are significant, the impact of regulations and policies is increasingly crucial in the long-term preservation of mangrove forests. Mohamed et al. (2023) contend that policies advocating community-based conservation initiatives bolster the sustained preservation of mangrove ecosystems. Gong et al. (2024) further substantiate this assertion, indicating that policies designed for mangrove conservation enhance ecosystem resilience, with economic aspects, such as income, being more dependent on these policies for long-term sustainability.

The decrease in the ranking of the income variable, alongside the increase in regulations and policies, indicates that management and policy-related factors exert a more substantial influence over time. While income remains a vital component of the socio-economic sustainability framework, implementing appropriate policies and incorporating natural resource management into governmental strategies have demonstrated greater efficacy in attaining enduring environmental and economic objectives (Bharali et al. 2024). This underscores the importance of policies that balance ecological and economic objectives in managing mangrove ecosystems. This approach supports SDG 8 (Decent Work and Economic Growth) by promoting sustainable livelihoods and ensuring the health of the ecosystems that support these livelihoods.

The identification of 16 critical factors affecting the sustainable management of *Scylla* spp. based mangrove ecosystems in Banten Bay provide a comprehensive framework for understanding mangrove management's ecological, economic, social, and institutional aspects. The results of the MICMAC analysis elucidate the hierarchy of influence and dependence among these factors. Crucial elements, including education and awareness (most influence) and infrastructure and technology (significant influence, minimal reliance), are vital for facilitating systemic transformation. SDG 4 (Quality Education) and SDG 9 (Industry, Innovation, and Infrastructure) accentuate the significance of enhancing education and infrastructure to foster sustainable development. Inter-institutional collaboration and community participation are essential for improving ecosystem sustainability, particularly in the context of indirect impacts that reinforce the overall management framework. Mangrove conservation, while the principal objective, depends on 13 additional factors, such as habitat quality, sustainable income, and policies, underscoring the necessity for a comprehensive approach to ecosystem management. Strategic goals should emphasize enhancing public awareness via education, fortifying supporting infrastructure, and cultivating synergy among stakeholders to mitigate undue reliance on external sources.

The alteration in the hierarchy of variables when contrasting direct and indirect effects (e.g., the decline in priority of product diversification while community participation rises) underscores the necessity of integrating short-term interventions with long-term, sustainable policies. These findings provide critical insights for policymakers, suggesting that evidence-based solutions must incorporate ecological, economic, and social dimensions to enhance system resilience through adaptive management. This comprehensive approach is consistent with SDG 13 (Climate Action), as the sustainable utilization of natural resources and the improvement of coastal resilience through the effective management of mangrove ecosystems can mitigate the effects of climate change.

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