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Mangrove vegetation dynamics in support of adaptive ecosystem restoration, governance and sustainable coastal management

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ABSTRACT

BACKGROUND AND OBJECTIVES: Subject to escalating threats from land conversion, coastal erosion, and socio-economic pressures, the mangrove ecosystems along northern Java require strategic interventions. The study objectives were to develop a proposed adaptive governance prototype specifically for mangrove restoration at the Mangrove Center in Tuban, East Java. This framework is established through a multi-faceted methodology that integrates Normalized Difference Vegetation Index-based vegetation health metrics, stakeholder power-interest mapping, and Participatory Policy Analysis.

METHODS: Vegetation greenness was analyzed using the Normalized Difference Vegetation Index, with values ranging from minus 1 to 1. These values were classified into: high greenness (values 0.35 to 1; area 2.84 hectares), moderate greenness (values 0.26 to lower than 0.35; area 3.83 hectares), low greenness (values 0.16 to lower than 0.26; area 2.88 hectares), very low greenness (values minus 0.04 to lower than 0.16; area 2.07 hectares), and non-vegetated land (values minus 1 to lower than minus 0.04; area 0.01 hectares). Stakeholder analysis was executed utilizing a power-interest matrix to identify and categorize relevant actors according to their relative influence and engagement levels regarding mangrove management. Participatory Policy Analysis was employed to explore governance challenges and formulate intervention alternatives.

FINDINGS: The vegetated area was dominated by the moderate greenness class (32.9 percent or 3.83 hectares), followed by low greenness (24.8 percent or 2.88 hectares), high greenness (24.4 percent or 2.84 hectares), and very low greenness (17.8 percent or 2.07 hectares). The average compound annual growth rate for the vegetated area was minus 13.36 percent per year for the 1997 to 2004 period, 21.08 percent per year for 2004 to 2011, 1.70 percent per year for 2011 to 2018, and minus 0.014 percent per year for 2018 to 2025. While these descriptive figures do not infer causality, they establish a foundational baseline for engagement. Stakeholders exhibiting high power and high interest were prioritized through a manage closely strategy, whereas alternative groups were managed through keep satisfied, keep informed, and monitor approaches.

CONCLUSION: The proposed prototype emphasizes adaptive co-management, Normalized Difference Vegetation Index -based monitoring, and cross-level policy. Normalized difference vegetation index indicates spectral greenness levels rather than mangrove species composition or overall ecological health. Consequently, any ecological assertions derived from this prototype should be treated as preliminary hypotheses requiring empirical testing.

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34	6	2

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INTRODUCTION

Indonesia possesses the largest mangrove forest area in the world, covering 3,489,140.68 hectares (ha), representing 23 percent (%) of the global mangrove ecosystem. Currently, 47.89% (1,671,140.75 ha) of Indonesia's mangrove forests remain in good condition, while 52.1% (1,817,999.93 ha) are degraded (Hasani *et al.*, 2023). These mangrove ecosystems have experienced substantial forest degradation, manifested primarily through canopy cover reduction. Such regional degradation stems from anthropogenic land-use changes, including conversion into aquaculture ponds, tourism infrastructure, agricultural plots, and commercial plantations—thereby compromising critical coastal protection functions (Nugraha *et al.*, 2019; Hasani *et al.*, 2023). Sustainable management and the restoration of mangrove areas help maintain ecosystem functions for coastal communities and overall biodiversity (Thahira *et al.*, 2023; Damastuti *et al.,* 2023). Furthermore, community involvement in conservation and the rehabilitation of degraded mangrove lands has been shown to improve both ecosystem quality and the local economy (Adani *et al.*, 2023; Pattiasina *et al.*, 2024). Holistic management strategies—including community education on ecological value, are essential for ensuring the long-term resilience and sustainability of mangrove ecosystem (Thahira *et al.*, 2023). Mangrove ecosystems are critical components of environmental preservation and coastal landscape stabilization. These coastal forests serve as essential habitats for diverse marine species, provide natural buffering against coastal erosion, and play a vital role in the global carbon cycle through substantial carbon sequestration (Choudhary *et al.*, 2024). Mangroves ecosystems exhibit exceptionally high carbon storage capacities per unit area, particularly within their sediment profiles, rendering them vital contributors to climate change mitigation (Choudhary *et al.*, 2024). Furthermore, active local community engagement remains paramount to conservation success; participatory approaches in wetland rehabilitation and sustainable resource management consistently enhance the efficacy of environmental initiatives (Rumondang *et al.*, 2024). Conversely, mangrove ecosystems face various pressures from human activities, such as clearing for agriculture and aquaculture, leading to a decline in the extent and quality of mangrove habitats in many regions (Lang *et al.*, 2023; Heck *et al.*, 2024). Various studies demonstrate that restoring these ecosystems not only benefits the environment but also yields positive economic implications for local communities through sustainable coastal development (Su *et al.,* 2021), allowing them to derive benefits from mangrove resources without damaging the ecosystem (Ebeler *et al.,* 2025). Therefore, sustainable management and policies supporting mangrove protection and restoration are essential to ensure the health of coastal ecosystems and the well-being of the communities that depend on them (Choudhary *et al.*, 2024). Coastal conditions conducive to mangrove ecosystem development are governed by complex interactions among environmental determinants, specifically hydrological, edaphic, and biological parameters. First, mangroves possess a unique ability to thrive in muddy, high-salinity soils typical of coastal areas (Adani *et al.*, 2023). Furthermore, tidal influences in coastal areas create ideal conditions for mangroves, where seasonal inundation helps regulate soil salinity and provides organic nutrients essential for growth (Li *et al.*, 2022). These underlying environmental determinants empower mangrove ecosystems to confer vital ecological services, including coastal erosion mitigation, multi-trophic marine habitats, and substantial carbon sequestration (Choudhary *et al.*, 2024; Rumondang *et al.*, 2024). Preserving mangrove areas allows coastal communities to benefit from ecosystem services, including protection against coastal erosion and carbon sequestration, that aid in climate change

mitigation. Community involvement in mangrove management, through the application of traditional knowledge and collaboration with the government, is crucial for achieving coastal environmental sustainability. Through community-led initiatives in mangrove rehabilitation and conservation, these ecosystems are expected to sustain their ecological functions and continue providing vital services for future generations (Damastuti *et al.*, 2022). Involving the community in management processes, such as through training on conservation techniques and natural resource management, renders mangrove management projects more effective and responsive to local needs. Community-based mangrove management has been associated with better biodiversity conservation outcomes in Central Java (Damastuti *et al.,* 2022). Furthermore, collaboration among stakeholders, including the government, non-governmental organizations (NGOs), and academia, is essential for formulating inclusive, sustainability-oriented policies and strategies (Nijamdeen *et al.,* 2023). This collaborative approach fosters mutually reinforcing synergies that advance mangrove conservation while concurrently stimulating regional economic growth and enhancing community livelihoods in coastal areas (Fadilah *et al.,* 2026). Mangrove ecosystems are found in various parts of East Java, including Tuban Regency. Tuban Regency is home to a 56-ha mangrove conservation area known as the Mangrove Center Tuban (MCT), which is managed by the Mangrove Center Tuban Foundation. The operational management of the center actively engages local farming communities residing in the surrounding landscape. Tourism attractions developed by Yayasan Mangrove Center Tuban (YMCT) include a field study center, mangrove and sea pine forests, a sports center, and beach tourism facilities. YMCT's activities are currently evolving into a sustainable mangrove conservation hub focused on environmental issues. Local communities engaged in these ecotourism initiatives can be effectively empowered to steward natural resources and uphold sustainable land-use practices. The Indonesian Disaster Information Data/*Data Informasi Bencana Indonesia* (DIBI) and the National Agency for Disaster Countermeasure / *Badan Nasional Penanggulangan Bencana* (BNPB) recorded severe tidal flooding in the coastal areas of Tuban Regency in 2022, affecting several districts, namely Palang, Tuban, Jenu, and Bancar. The BNPB reported that the Jenu mangrove coast was severely affected by tidal flooding, resulting in damage to several buildings and attractions within the MCT tourism site. Consequently, these conditions underscore the imperative for a practical and adaptive governance framework to ensure the long-term sustainable management of MCT. Stakeholder engagement, involving local communities, the government, and NGOs, is crucial for gaining a holistic perspective on the challenges at hand, including those related to mangrove conservation (Drew *et al.*, 2024). Community involvement in conservation programs, such as reducing emissions from deforestation and forest degradation (REDD+), not only yields environmental benefits but also strengthens governance and mangrove protection in threatened areas (Bernardino *et al.*, 2024). Collaboration among the government, the community, and NGOs can lead to more effective strategies (Drew *et al.*, 2024; Asio *et al.*, 2026). An effective governance framework is anticipated to generate dual benefits, bolstering the long-term sustainability of the mangrove ecosystem while supporting local communities whose livelihoods depend on its resources. Nationwide, Indonesian mangrove ecosystems encounter persistent sustainability challenges. At a local scale, conservation initiatives within the Tuban coastal area, administered by the YMCT, face notable operational barriers. Notably, ecosystem management lacks comprehensive integration, across its ecological, social and economic dimensions, resulting in suboptimal coordination

among stakeholders. Furthermore, low levels of engagement from the surrounding community in supporting conservation efforts have limited participation in conservation and monitoring activities. Previous studies have used normalized difference vegetation index (NDVI) to map mangrove density and its change (Tran *et al.*, 2022; Hasani *et al.*, 2023; Pattiasina *et al.*, 2024; Yusiyanti *et al.*, 2025; You *et al.*, 2023; Ilhami *et al.*, 2026), while others have examined stakeholder collaboration, co-management and adaptive governance of coastal ecosystems (Nijamdeen *et al.*, 2023; Drew *et al.*, 2024; Asio *et al.*, 2026). These two dimensions are rarely integrated within a single community-led restoration initiative, particularly when rehabilitation relies on mangrove-associated species under the management of a local foundation with limited and restricted public funding. The contribution of this study is therefore methodological and case-specific: it links a multi-decadal, fixed-boundary record of vegetation greenness with stakeholder power–interest mapping and participatory policy analysis (PPA) in order to derive a governance prototype for such a site and submit it to structured stakeholder review. The specific objective is to measure the 2025 spatial pattern and temporal changes in coastal vegetation greenness, based on NDVI, from 1997 through (–) 2025 within a fixed 11.63 hectare study area at MCT. The second objective is to identify stakeholder power characteristics and levels of importance, as well as to examine the perceptions of community members, government officials, and YMCT staff regarding mangrove conservation. Finally, the third objective is to formulate an adaptive governance prototype through PPA and validate it through stakeholder consultation. Species composition, stand structure, and ecosystem functions, such as carbon storage, support for fisheries, and coastal protection, were not measured. Therefore, these aspects are discussed only as potential implications. This study was conducted at MCT in Jenu District, Tuban Regency, East Java, Indonesia, in 2025 and 2026.

MATERIALS AND METHODS

This study was conducted at the Mangrove Center Tuban Foundation, located on the Tuban-Semarang highway in Jenu Village, Jenu District, Tuban Regency, East Java Province, Indonesia (Fig. 1). The village lies at approximately 6°52′–6°56′ south (S) and 111°57′–112°00′ east (E.) MCT covers approximately 56 ha, which includes vegetated coastal land as well as ecotourism, education, camping and supporting infrastructure. The remote-sensing analysis was restricted to a fixed area of interest (AOI) of 11.63 ha enclosing the 1997 shoreline rehabilitation stand—representing the segment of the MCT where restoration efforts have been concentrated along a low-lying, erosion-prone coastline. The same AOI polygon was applied without modification to all five observation years (1997–2025), so that areas and percentages are directly comparable between years. Consequently, the ecological findings are restricted to the 11.63-ha AOI, whereas the governance assessment encompasses the MCT in its entirety, drawing upon comprehensive socio-institutional data rather than remote-sensing vegetation indices alone. Operated by YMCT, MCT functions as an integrated conservation, education, and ecotourism zone in collaboration with local communities and government agencies. This location was selected for three primary reasons. First, it is one of the longest-running community-based coastal rehabilitation sites on the north coast of East Java. The initiative was launched by a local farmer in 1997, organized as a community forum in 2000, and formally established as the YMCT Foundation in 2005. Second, the site features a sandy coastline that is vulnerable to abrasion. Restoration efforts rely primarily on *Casuarina* species growing alongside mangroves, as well as true mangrove species. Third, the site's management involves various stakeholders, including the local foundation,

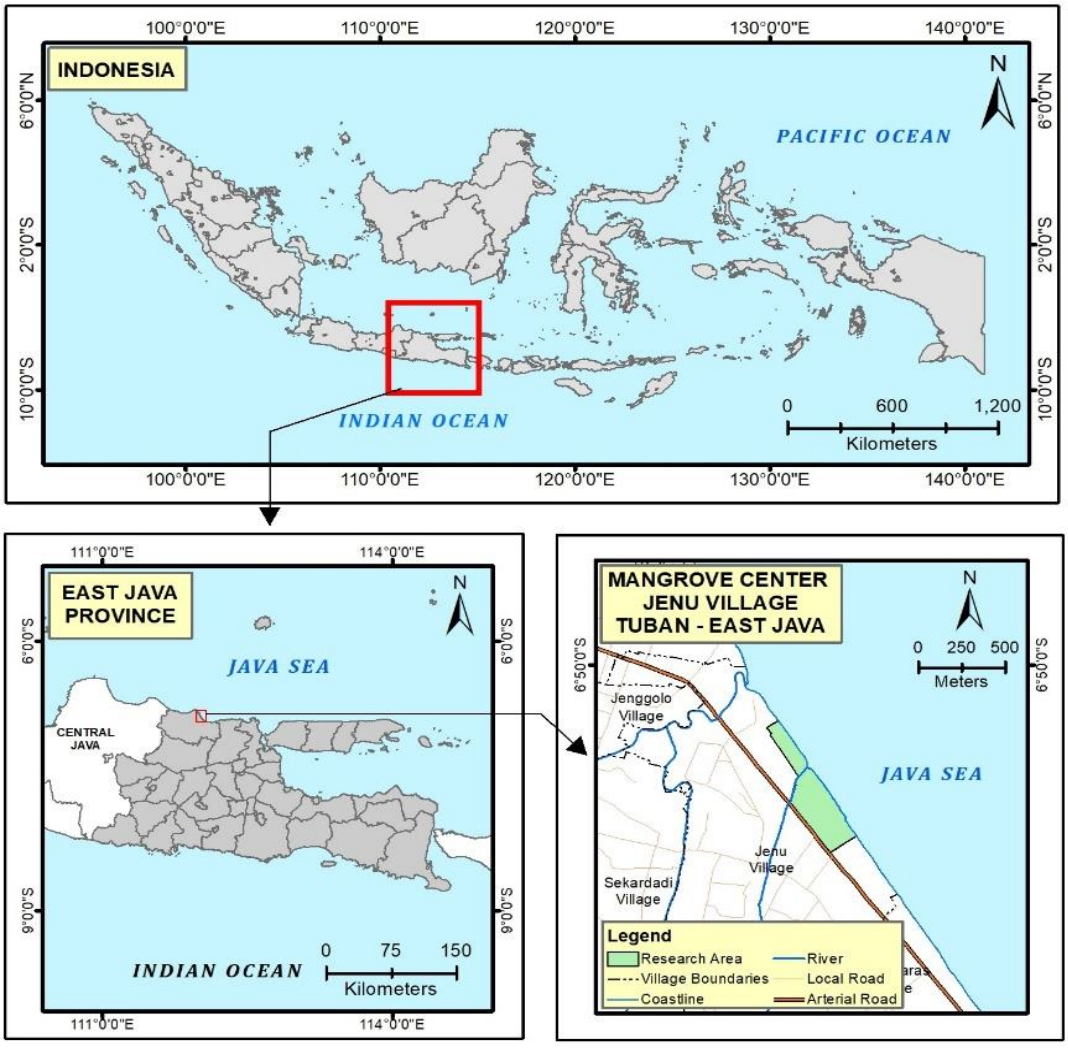

Fig. 1: Geographical location of the study area in MCT Foundation, located on the Tuban-Semarang highway in Jenu Village, Jenu District, Tuban Regency, East Java Province, Indonesia

village and sub-district governments, and corporate social responsibility (CSR) partners. This governance structure makes the site an ideal location for studying adaptive governance. Characterized by a tropical monsoonal climate with distinct wet and dry seasons, the site is dynamically influenced by Java Sea tidal regimes. Consequently, local mangrove stands are exposed to continuous wave action, sedimentary shifts, and compounding anthropogenic pressures, including land-use conversion, pollution, and infrastructure expansion.

NDVI-based assessment of mangrove condition

NDVI is the most commonly used spectral index in remote sensing to measure the greenness and health of vegetation, including mangrove ecosystems, using Eq. 1 (Tran *et al.*, 2022):

$$NVDI = \frac{(NIR - RED)}{(NIR + RED)} \quad (1)$$

Near-Infrared (NIR) refers to near-infrared reflectance, while red refers to red light reflectance. NDVI values range from minus (−) 1 to positive (+) 1. Higher values indicate greater

canopy greenness, whereas values approaching zero or falling in the negative range indicate surfaces devoid of vegetation, such as water bodies or bare soil. Because mangrove canopies exhibit strong reflectance in the near-infrared spectrum, NDVI is widely utilized for mapping mangrove spatial extent (Tran *et al.*, 2022). However, as a spectral index, NDVI lacks species-level discrimination capabilities and cannot independently differentiate mangroves from co-occurring coastal vegetation, such as *Casuarina* stands. Consequently, while elevated NDVI values signify enhanced canopy greenness, they do not inherently equate to superior mangrove cover, vitality, biodiversity, or carbon storage. The NDVI classification used in this study is presented in Table 1. Class boundaries are defined as mutually exclusive, half-open intervals: high greenness more than or equal to (≥) 0.35 (up to 1.00); moderate greenness 0.26 to lower than (<) 0.35; low greenness 0.16 to < 0.26; very low greenness −0.04 to < 0.16; and non-vegetated land −1.00 to < −0.04. Data were obtained from satellite imagery of the MCT site acquired on July 23, 1997 [Landsat 5 Thematic Mapper (TM)]; December 9, 2004, and June 4, 2011 [Landsat 7 Enhanced Thematic Mapper Plus (ETM+)]; November 22, 2018 [Landsat 8 Operational Land Imager (OLI)]; and September 14, 2025 [Sentinel-2 Level-2A, surface reflectance, 10 meters (m)]. Priority was given to images with low cloud cover, and acquisition dates were selected based on seasonality (Roy *et al.,* 2016). Bands B4 (red) and B8 (near-infrared) were used, with a standard resolution of 10 m for Sentinel-2. Each satellite image scene was clipped to match the study area of 11.63 ha. Subsequently, NDVI values were classified in accordance with Ministry of Forestry Regulation P.12/Menhut-II/2012 concerning guidelines for preparing technical plans for forest and land rehabilitation in watersheds. Sentinel-2 vegetation indices have also been utilized for mapping mangrove carbon stocks in Indonesia (Suardana *et al.*, 2023). A majority filter was applied prior to vectorization to reduce noise, with class areas subsequently calculated based on the filtered spatial output. Field plot locations were determined using a stratified random sampling method across three vegetation density strata (low, medium, and high), following the stratified even sampling approach for accuracy assessment (Dong *et al.*, 2020). Plot dimensions were matched to the Sentinel-2-pixel size (10 m), following Suardana *et al.* (2023). A minimum of 30 plots was calculated based on Geospatial Information Agency standards, and surveys were conducted on 40 plots. The greenness level of each plot was assessed using the Monmang 2 application, which measures the visual greenness of leaves, and trees with a diameter at breast height (DBH) of at least 10 centimeters (cm) were recorded.

Stakeholder analysis and PPA

The scope of stakeholders included 127 coastal community members, 30 YMCT members, and five government agencies. All 127 community members were included in the census sample; of these, 17 individuals completed the questionnaire, and their data were analyzed. All 30 YMCT members were included in the census sample, and 20 YMCT staff members completed a staff-specific questionnaire. Five government agencies were purposively selected as key informant organizations, resulting in a total of 15 administrative respondents who completed the structured questionnaire. Two focus group discussions (FGDs) were conducted: FGD 1 to identify governance issues, and FGD 2 to validate the draft governance model. Each institution was represented by one participant. FGD 1 involved nine participants from nine institutions: the Tuban Regency Environmental Agency; Tuban Regency Tourism Agency; Jenu District; Jenu Village; Trans-Pacific Petrochemical Indotama Limited Tuban; Limited Liability Company/*Perseroan Terbatas* (PT) Semen Indonesia (Semen Indonesia Group (SIG)).; Pertamina Patra Niaga Marketing Operation Region V; the fuel terminal operator; and YMCT. FGD 2 involved seven participants from seven institutions: YMCT, Pertamina Patra Niaga

Table 1: NDVI classification

Code	Class	NDVI range	Description	Map color	Area (ha)
5	High greenness	≥ 0.35 to 1.00	Higher spectral greenness	Dark green	2.84
4	Moderate greenness	0.26 to < 0.35	Moderate greenness	Light green	3.83
3	Low greenness	0.16 to < 0.26	Low greenness	Yellow	2.88
2	Very low greenness	−0.04 to < 0.16	Very low greenness	Orange	2.07
1	Non-vegetated land	−1.00 to < −0.04	Non-vegetated land	Red	0.01

Marketing Operation Region V, the Environmental Agency, the Tourism Agency, PT Semen Indonesia (SIG), Jenu District, and Trans-Pacific Petrochemical Indotama Limited Tuban. Both FGDs were conducted during the research period, spanning from August 2025 to March 2026. Ethical approval was granted by the Research Ethics Committee of the Faculty of Psychology, Syarif Hidayatullah State Islamic University/*Universitas Islam Negeri* (UIN) Jakarta (Letter No. B-109/Kep-FPsi/TL.00/VIII/2025, dated August 29, 2025). Written informed consent was obtained from all participants prior to data collection. PPA was employed to anticipate future governance challenges and identify leverage points. A problem tree analysis was structured around the core challenge of ineffective organizational governance in mangrove ecosystem services management. This diagnostic process identified underlying root causes alongside their ecological, socioeconomic, and institutional consequences, providing a robust foundation for the subsequent development of a corresponding solution tree. The analytical findings informed the design of a conceptual governance prototype tailored to the MCT case, a model that remains to be implemented or empirically tested.

Data collection instruments

Community-level data were gathered utilizing a structured questionnaire divided into six sections. The first section captures demographic and socioeconomic characteristics, including gender, age, educational attainment, occupation, and duration of residence. The second section evaluates the frequency of and accessibility to information pertaining to mangrove conservation, while the third section gauges respondents' awareness regarding ecological benefits, anthropogenic threats, restoration efforts, and relevant regulatory frameworks. The fourth section measures the level of awareness regarding six statements using a five-point Likert scale, ranging from “strongly agree” to “strongly disagree.” The fifth section examines participation in conservation activities organized by YMCT. The sixth section provides respondents with the opportunity to offer open-ended suggestions. YMCT staff completed a separate questionnaire covering respondent characteristics, formal education and its relevance to their work, and training undertaken in the past three years. Government key informants furnished data concerning regulatory frameworks, budgetary allocations, operational programs, and enforcement mechanisms through semi-structured interviews and FGDs.

RESULTS AND DISCUSSION

NDVI-derived mangrove condition

NDVI classification revealed heterogeneous vegetation conditions across the 11.63 ha of MCT (Fig. 2). Moderate greenness (NDVI 0.26–0.35) dominated the site, covering 3.83 ha (32.9%). Low greenness (0.16–0.25) occupied 2.88 ha (24.8%), and high greenness (0.35–1.00) occupied 2.84 ha (24.4%). Very low greenness (-0.04–0.15) accounted for 2.07 ha (17.8%), while non-vegetated land was minimal, at 0.01 ha (0.1%) (Fig. 2). The dominance of moderate and high NDVI classes (over 57% of the area) indicates that restoration at MCT has successfully established relatively dense, photosynthetically active mangrove stands over much of the site. However, the combined proportion of low and very low greenness (4.95 ha, approximately 42.6%)

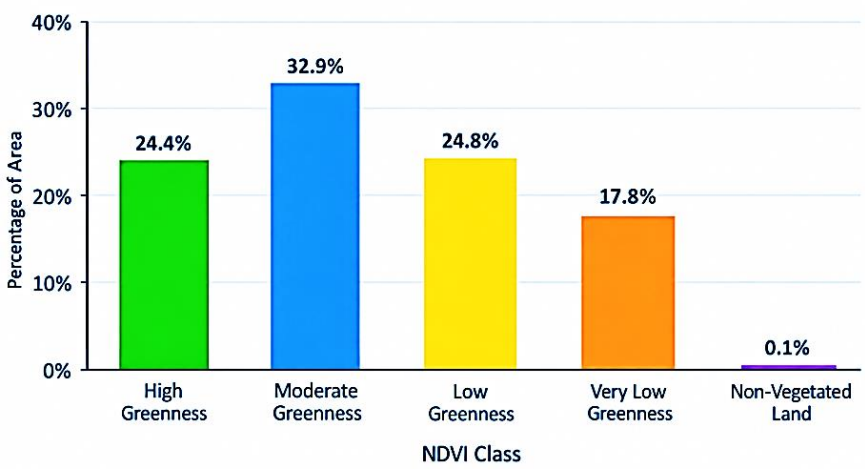

Fig. 2: NDVI analysis results for MCT

indicates that a substantial fraction of the rehabilitated zone exhibits suboptimal canopy closure and likely undergoes persistent environmental stress. While empirical evidence confirms that mangrove rehabilitation initiatives effectively mitigate coastal erosion, enhance biodiversity, and restore environmental quality (Ilham *et al.*, 2026), persistent low-greenness pockets within the study site likely reflect younger plantation cohorts, hydrologically marginal micro-sites, or areas experiencing chronic disturbance, high mortality, and subsequent replanting cycles. Fig. 3 clearly shows that the mangrove condition at the study site is generally still quite good, as more than 50% of the area falls into the moderate-to-high category. However, some areas require rehabilitation to improve mangrove density and ecosystem quality, particularly through targeted restoration, improved vegetation cover, and long-term ecological monitoring programs. As illustrated in Fig. 3, approximately 5 ha fall into the low-to-very-low greenness category, necessitating an integrated management framework to safeguard the ecological and socioeconomic functions of the Mangrove Center Tuban area. Initial interventions should prioritize rehabilitation and replanting within these degraded zones, utilizing indigenous mangrove species adapted to local substrate conditions, tidal regimes, and salinity levels to maximize survival and growth. Additionally, areas near the shoreline that are prone to abrasion should be prioritized as rehabilitation zones to strengthen natural protection against wave action and coastal erosion. For areas classified as having moderate, low, or very low NDVI values, management strategies must prioritize the maintenance and enrichment of vegetation through targeted, site-specific mangrove enrichment planting. These targeted interventions seek to enhance canopy density and refine stand architecture, thereby progressively transitioning the site toward a high-density classification. Additionally, weeds and invasive plants must be controlled to prevent them from hindering mangrove growth or disrupting natural ecological processes. Furthermore, institutional strengthening and community participation are equally crucial. Mangrove governance should involve local community groups, fishers, and ecotourism operators in a participatory and inclusive co-management scheme. This collaborative framework must integrate local government agencies, academic institutions, and community stakeholders. Such cooperative engagement enhances local stewardship and cultivates shared accountability for the long-term sustainability of mangrove ecosystems (Arifanti *et al.*, 2022).

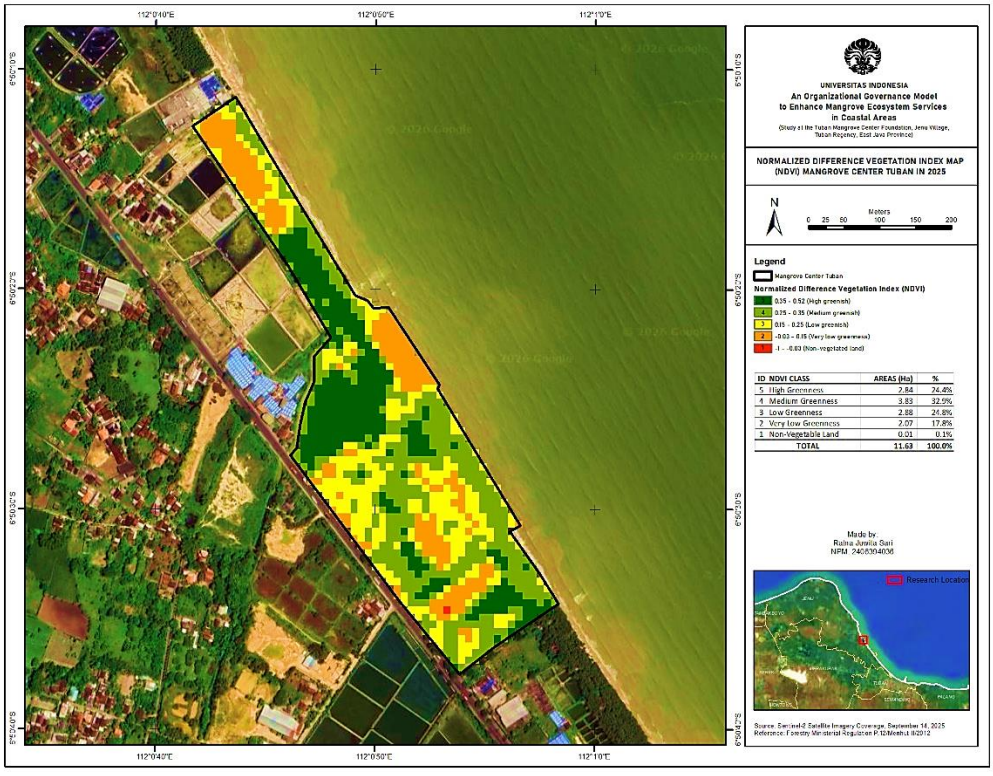

Fig. 3: NDVI greenness class map of the 11.63-ha AOI at MCT derived from Sentinel-2 MSI imagery (14 September 2025)

Temporal dynamics of vegetated area and greenness classes, 1997–2025

Table 2 and Fig. 4 report, for each observation year, the area of each greenness class and the vegetated area as a percentage of the fixed 11.63-ha AOI. In 1997, no area reached the moderate or high greenness classes; very low greenness covered 5.75 ha (49.4%), low greenness 1.65 ha (14.2%) and non-vegetated land 4.23 ha (36.4%). In 2004, non-vegetated land expanded to 8.92 ha (76.7%), and the remaining 2.71 ha (23.3%) was in the very low class. By 2011, non-vegetated land had decreased to 1.29 ha (11.1%), very low greenness covered 8.49 ha (73.0%), and low and moderate greenness 0.93 ha (8.0%) each. In 2018, the entire AOI was classified as vegetated, with low greenness dominating (5.19 ha; 44.6%), followed by very low (4.20 ha; 36.1%), moderate (1.97 ha; 16.9%) and high greenness (0.27 ha; 2.3%). In 2025, moderate greenness dominated (Fig. 2). Throughout the 28-year observational record, land-cover composition transitioned from non-vegetated terrain and sparse greenness toward moderate and dense canopy classes. Because sensors specifications and spatial resolutions varied across years (Table 2), shifts among the intermediate classes warrant cautious interpretation; conversely, the net transition from non-vegetated to vegetated states remains highly robust. Interval-averaged rates of change in vegetated area are presented in Table 2. Between 1997 and 2004, vegetated area decreased from 7.40 ha (63.6%) to 2.71 ha (23.3%), corresponding to -13.37% per year. Between 2004 and 2011 it increased to 10.34 ha (88.9%), or +21.08% per year; between 2011 and 2018 it increased to 11.63 ha (100%), or +1.69% per year; and between 2018 and 2025 it remained practically unchanged at 11.62 ha (99.9%), or -0.012% per year, a difference of 0.01 ha that is well below the resolution-related uncertainty of the data, indicating sustained mangrove cover stability during this period.

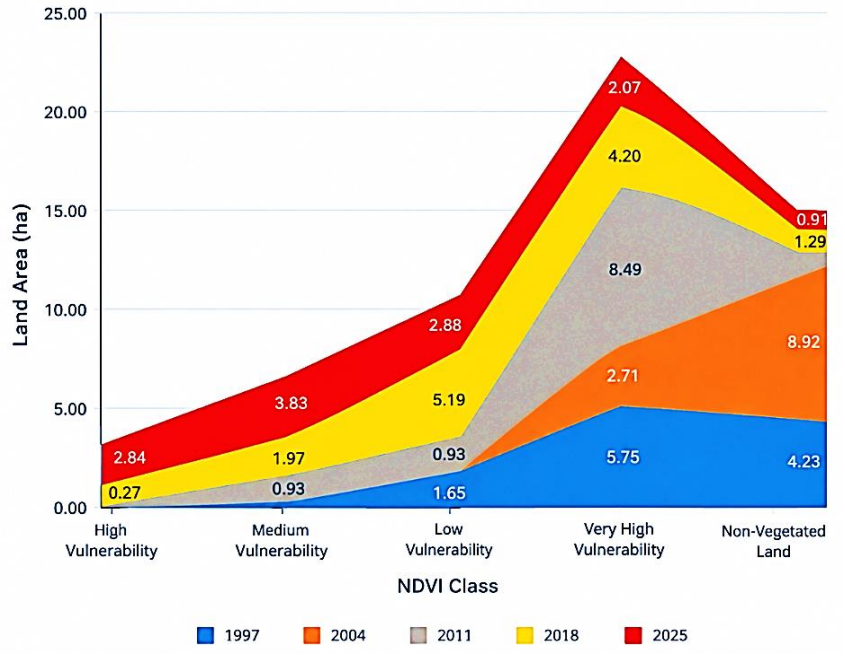

Fig. 4: Area of NDVI greenness classes within the fixed 11.63-ha AOI, 1997–2025

These rates reflect mean changes across a seven-year interval rather than continuous annual trajectories. Consequently, the empirical record aligns with, but does not conclusively verify, the following interpretation. According to YMCT and local accounts, self-initiated rehabilitation began in 1997 with the planting of mangroves and *Casuarina* (cemara udang), the planting group became a community forum in 2000, and YMCT was established as a foundation in 2005. According to stakeholder accounts, initial mangrove planting efforts experienced high mortality along the sandy, erosion-prone coastline. Consequently, subsequent restoration shifted toward vegetative species better adapted to sandy substrates, predominantly *Casuarina equisetifolia* and *C. glauca*. The 1997–2004 decline may therefore reflect early planting failure and abrasion (Muhammad *et al.*, 2025), and the 2004–2011 increase the expansion of *Casuarina* and other coastal vegetation after restoration efforts were reorganized. However, the analysis includes no comparison site, no dated planting or mortality records and no measurements of shoreline change, sedimentation or hydrology, and differences in image acquisition (sensor, season, tide and Scan Line Corrector-off gaps) may also have contributed to the apparent changes. The 1997–2025 trajectory therefore shows a temporal association with the history of restoration and governance at MCT but does not identify its causes. Similarly, the nearly constant vegetated extent observed after 2018 indicates that the area of interest has maintained continuous canopy cover. However, this stability does not inherently signify ecological equilibrium, structural maturity, resilience or the complete functional recovery of mangrove ecosystem, attributes that evolve over decades and require multi-parameter evaluation, including species composition, stand architecture, recruitment, pedogenesis, and hydrological connectivity (Osland *et al.*, 2020). Quantitative metrics regarding ecosystem growth rate are detailed in Table 2.The MCT area has maintained a relatively stable extent (as the rehabilitation site remains fixed), though conditions within it vary. The challenge lies not only in preserving the area but also in upgrading low and very low NDVI

Table 2: Vegetated area and rate of change (CAGR) within the fixed 11.63 ha boundary, 1997–2025

Period	Period (years)			
	1997–2004	2004–2011	2011–2018	2018–2025
Vegetated area, start (ha)	Decreased from 7.40 to 2.71	Decreased from 2.71 to 10.34	Decreased from 10.34 to 11.63	Decreased from 11.63 to 11.62
Vegetated area, start (% of 11.63 ha)	Decreased from 63.6 to 23.3	Decreased from 23.3 to 88.9	Decreased from 88.9 to 100.0	Decreased from 100.0 to 99.9
CAGR (% per year)	-13.36	+21.08	+1.70	-0.014
Descriptive phase	Decline	Increase	Slower increase	Near-saturation
Remarks	Observed decline; causes not tested here.	Observed increase; not attributable to rehabilitation or governance without control data.	Growth slowed as cover approached the boundary limit.	Cover saturated; does not indicate equilibrium or ecosystem quality.

classes to medium and high categories through targeted silviculture and hydrological management. Furthermore, the localized concentration of low and very low NDVI categories within the MCT highlights potential vulnerability zones. This spatial distribution serves as an early indicator of prospective vegetative degradation if left unmitigated—a process that could be severely compounded by ongoing pressures, including sedimentation and dynamic coastal hydrodynamics. NDVI patterns at the MCT site, where only 24.4% of the area exhibited high greenness levels, highlight the need for management strategies that progressively increase the proportion of this healthiest class, mirroring the targeted conservation priorities recommended for Tanjung Piai. NDVI results from the MCT demonstrate successful mangrove conservation, evidenced by gradual and measurable improvements in both vegetation cover and quality over time. The compositional transition of NDVI classes, moving from a predominance of unvegetated terrain and sparse greenness to moderate and high greenness categories, demonstrate that active rehabilitation and management interventions have successfully fostered mangrove recovery. This progression indicates concurrent gains in vegetation extent, canopy structure, canopy quality, and the functional optimization of ecosystem services. These findings align with research by Osland *et al.* (2020), which identifies NDVI as a crucial indicator for assessing the condition and dynamics of mangrove ecosystems across spatial and temporal scales. NDVI effectively represents vegetation density and health; thus, changes in its values can be used to evaluate conservation success, detect degradation, and monitor ecosystem recovery processes over time. Consequently, the use of NDVI in this study reinforces the validity of the analysis regarding the effectiveness of governance and mangrove conservation interventions in the coastal area of Tuban. However, variations in greenness observed in certain parts of the area indicate that local ecological pressures persist and may affect vegetation stability. Factors such as coastal human activity, sedimentation dynamics, shoreline changes (due to abrasion or accretion), and sandy substrate characteristics directly influence mangrove growth success and canopy density (Santoso *et al.,* 2026; Marino *et al.,* 2025). The heterogeneity of NDVI classes suggests that, while vegetation cover has generally expanded, ecosystem quality and resilience remain spatially variable across the site. Crucially, these results underscore that the success of mangrove conservation at the MTC does not automatically guarantee long-term ecosystem stability unless accompanied by strengthened governance, periodic monitoring, and consistent oversight regarding potential environmental pressures. Because ecosystem recovery is a dynamic process vulnerable to external disturbances, management frameworks must remain responsive to uncertainty and shifting biophysical conditions. This approach necessitates institutional flexibility, continuous organizational learning, and robust multi-stakeholder collaboration to navigate

complex environmental changes. Consequently, the long-term sustainability of mangrove conservation is dictated not merely by quantitative gains in vegetation cover, but by the adaptive capacity of governance systems to manage change and sustain coastal ecosystem resilience over time.

Stakeholder mapping

During the policy formulation phase of the organizational governance model, stakeholders influencing coastal mangrove ecosystem services will be categorized using a power–interest matrix based on their capacity to impact project objectives and their level of interest in project outcomes. A Power-Interest quadrant diagram illustrates stakeholder governance at the Mangrove Center Tuban site. Based on the stakeholder mapping results, the following categories were identified in Fig. 5. Given these characteristics of high power and high interest, the appropriate management strategy is "Manage Closely." This framework necessitates engaging all primary stakeholders in strategic decision-making while ensuring an equitable accommodation of each party's distinct needs, aspirations, and contributions. The ideal action within this framework is the establishment of a Mangrove Governance Steering Committee comprising core representatives from the Tuban Regency Government, the YMCT farmer group / management team, and corporate partners. This committee is mandated to convene regularly to formulate long-term strategies, align budgetary allocations, reinforce regulatory frameworks, and appraise program performance, thereby ensuring that future YMCT governance is increasingly integrated, participatory, and sustainable. Meanwhile, for Quadrant 2 (High Power, Low Interest), the appropriate strategy is "Keep Satisfied." This involves ensuring these stakeholders remain adequately informed and feel included, thereby maintaining their support and preventing them from using their authority to hinder ongoing programs. The proposed approach is communicative, concise, and data-driven, while highlighting the strategic benefits of the mangrove management program. Proposed actions include providing concise, systematic annual or semi-annual progress reports to the Tuban Regency Regional House of Representatives/*Dewan Perwakilan Rakyat Daerah Republik Indonesia* (DPRD) that emphasize economic, social, and environmental impact achievements. At the same time, a clear, specific, and measurable proposal must be drafted to support rehabilitation efforts. The proposal should outline rehabilitation targets, success indicators, and funding requirements. Subsequently, it needs to be submitted to relevant ministries, such as the Ministry of Environment and Forestry/*Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia* (KLHK) and the Ministry of Marine Affairs and Fisheries/*Kementerian Kelautan dan Perikanan Republik Indonesia* (KKP) This strategy enhances the prospects of garnering statutory backing and fiscal allocation. In Quadrant 3 (Low Power, High Interest), there are stakeholders who have a high level of interest in the sustainability of the mangrove ecosystem but lack significant power or authority to determine policy direction. Based on these attributes, the designated engagement strategy is "Keep Informed," which involves providing these stakeholders with clear, transparent, and consistent updates regarding programmatic advancements. Furthermore, they should be integrated into consultation mechanisms to ensure that their perspectives, feedback, and contributions are duly evaluated during decision-making. Despite lacking significant formal power, this group has the potential to become strong supporters and guardians of social legitimacy for the mangrove management program's sustainability. A proposed course of action involves convening periodic Public Consultation Forums, biannually or triannually, to establish a structured dialogue channel among program managers, coastal communities,

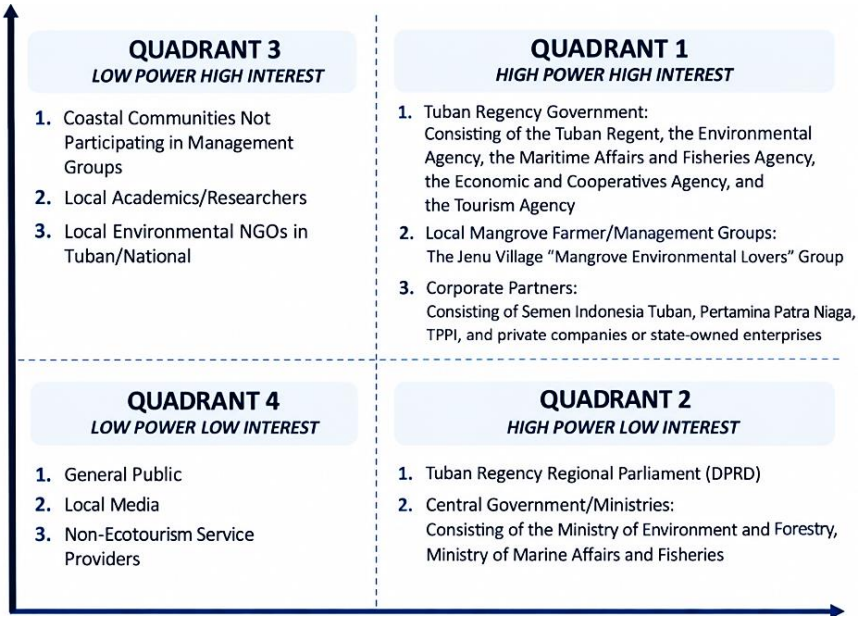

Fig. 5: Power-Interest quadrant diagram for stakeholder governance

academics, and NGOs. These platforms facilitate the systematic dissemination of progress reports and the active elicitation of stakeholder feedback. Additionally, involving academics in the drafting and evaluation of the Management Plan is a strategic move to ensure that formulated policies are comprehensive, science-based, and of higher quality than those of previous years. Finally, Quadrant 4 (Low Power, Low Interest) comprises stakeholders with relatively low levels of both power and interest regarding the mangrove management program. Based on these characteristics, the strategy to be applied is "Monitor" (Minimum Effort), which involves basic monitoring and the provision of general information without the need to allocate excessive communication resources. This strategy seeks to maintain transparency and forestall misunderstandings while prioritizing communication and engagement efforts toward stakeholders within higher-influence and higher-interest quadrants. To achieve this, general programmatic information will be disseminated via official digital channels, institutional websites, and strategically located physical notice boards. Thus, access to information remains open to the general public, while the allocation of communication resources can be prioritized to support the active engagement of stakeholders in the quadrant characterized by higher levels of power and interest. The regulatory environment surrounding MCT reflects broader challenges in multi-level environmental governance. Law Number 23/2014 restructured mandates for coastal and riverine management, transferring significant authority over coastal areas and forestry from district governments to provincial and central governments. In FGD 2, representatives of the Tuban Environmental Agency stated that no district budget line is specifically allocated to mangrove management, so that conservation activities depend largely on corporate partners and communities despite strong political and moral support. Comparable incongruities between localized priorities and macro-level institutional mandates have been widely documented across diverse environmental governance contexts (Song *et al.*, 2021; Arifanti *et al.*, 2022). Consequently, MCT's governance is marked by a paradox: strong attitudinal and

policy-level support from local government, yet weak direct material backing. Officials contribute through symbolic recognition, attendance at events, and informal support, while YMCT is encouraged to secure funding from CSR programs and project-based grants. This arrangement may suffice for short-term or small-scale initiatives but is ill-suited to sustain infrastructure, monitoring systems, and long-term planning. Compounding these budgetary constraints are spatial planning policies that still allow land conversion in sensitive coastal areas and unresolved land tenure conflicts in zones where mangroves have recolonized previously eroded land. In the absence of dedicated district-level regulations for mangroves, such disputes lack clear legal recourse mechanisms, which risks eroding community trust and dampening local willingness to invest labor in restoration. The problem tree derived from FGD 1 highlights how these ecological, social, economic, and institutional roots converge to undermine the effectiveness and sustainability of restoration efforts. Perceived impacts encompass the ongoing vulnerability of coastal settlements to erosion and storm surges, the under-provision of critical ecosystem services such as fisheries support and carbon sequestration (Ketaren *et al.,* 2026), and the hazard of community fatigue should stakeholder expectations remain unmet. Integrating mangrove-based silvofishery and ecotourism into restoration planning may also strengthen coastal landscape resilience and support local livelihoods (Utomo *et al.,* 2026).

Participatory policy analysis and proposed solution pathways

Through PPA, the central governance problem identified in FGD 1 (ineffective formulation and implementation of organizational governance for mangrove ecosystem services) was translated into a solution tree identifying strategic and operational responses (Fig. 6). At the strategic level, participants and the research team identified several proposed pillars. First, strengthening YMCT as a bridging organization was proposed. Bridging organizations facilitate knowledge exchange, coordination, and trust-building among heterogeneous stakeholders, and are recognized for augmenting knowledge utilization and adaptive capacity in environmental governance (Asio *et al.,* 2026). Formal recognition of YMCT in planning documents, participation in multi-stakeholder forums, and support for its organizational development can strengthen its brokerage role. Second, establishing a Mangrove Governance Steering Committee that brings together high-power, high-interest actors (district agencies, YMCT, mangrove farmer groups, key corporate partners) can help overcome fragmentation and ensure stronger policy and budget alignment. The committee can coordinate strategic planning, oversee monitoring, and provide a forum for conflict resolution. Third, establishing a dedicated local regulatory framework, such as a municipal Perda on mangrove conservation, can delineate spatial protection zones, regulate land-use conversion, codify co-management arrangements, and institute a robust legal basis for enforcement and conflict resolution. Aligning this framework with higher-level policies and river basin management plans is essential to avoid regulatory conflicts. At the operational level, the solution framework outlines targeted field assessments for zones exhibiting low and sparse NDVI values. Where necessary, these assessments are followed by strategic rehabilitation or enrichment planting, alongside the establishment of an integrated mangrove data repository to consolidate remote-sensing, ecological, and socio-economic datasets. Furthermore, the framework advocates for innovative financial instruments, such as payment for ecosystem services (PES) schemes and dedicated conservation trust funds, to supplement CSR initiatives and public budgets. By combining the empirical findings with concepts from social–ecological systems and adaptive governance, the proposed prototype is intended to have six characteristics. First, it adopts an explicit social–ecological orientation.

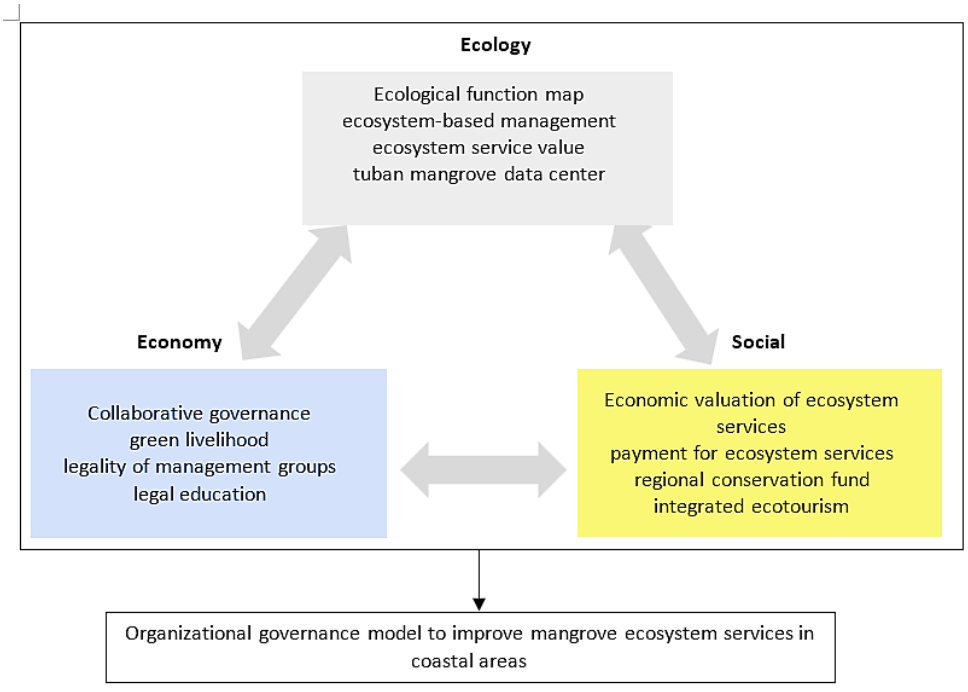

Fig. 6: Proposed (prototype) adaptive governance framework for MCT after stakeholder review in FGD 2 (the framework has not yet been implemented or tested)

Management objectives encompass both potential ecological functions (shoreline protection, habitat provision and carbon storage, none of which were measured in this study) and socioeconomic benefits (livelihoods, education, ecotourism), recognizing that long-term resilience depends on their co-production. Second, it positions YMCT as a central bridging organization that connects community, government, corporate, and academic stakeholders. YMCT facilitates bidirectional communication, translates complex scientific data, such as NDVI metrics, into accessible formats, and arbitrates disputes concerning land-use rights and resource benefits. Third, the model institutionalizes multi-level co-management by distributing responsibilities across the village, district, and national levels and across relevant sectors (environment, fisheries, tourism, education, and CSR). The steering committee serves as a coordination hub for these actors. Fourth, it embeds adaptive monitoring and learning through regular NDVI analysis, community-based field checks, and periodic participatory evaluations. This allows for timely detection of ecological and social shifts, enabling rapid adjustments in strategies and resource allocation. Fifth, the framework fosters inclusive participation and equitable benefit-sharing by transitioning from reliance on voluntary labor toward institutionalized mechanisms that deliver tangible livelihood benefits and decision-making authority to local communities. Examples include ecotourism revenue-sharing, value-added mangrove products, and recognition of community-based management groups. Finally, the strategy advocates for a cohesive legal and policy framework that harmonizes local, district, and national regulations, delineates respective rights and obligations, and minimizes regulatory uncertainty for long-term restoration investments. The stakeholder review of the prototype design during the second FGD confirmed four key elements. First, the current governance system has contributed to

conservation and community empowerment efforts. However, its institutional structure and sustainability remain weak, as acknowledged by the founder of YMCT. Second, although collaborative frameworks involving local government, corporate partners, and the community are already established, interactions remain fragmented and lacks effective coordination. Third, the regency government does not allocate a specific budget for mangrove conservation. Consequently, diverse funding mechanisms, such as CSR partnerships, PES, and local conservation funds, are required. Fourth, stakeholders perceive a holistic approach that integrates ecological, social, and economic dimensions as the most effective strategy for strengthening mangrove governance. Participants recommended strengthening the organizational capacity of YMCT, institutionalizing a multi-stakeholder coordination forum, preparing a district regulation on mangroves, developing sustainable financing and building community capacity; these recommendations were incorporated in Fig. 6. The role proposed for YMCT as a bridging organization rests on its presence at the site since 1997, its 20 staff members, whose mean scores on conservation-attitude and perceived-benefit items ranged from 4.05 to 4.50 on a five-point scale, and the support expressed by village, district and corporate participants in both FGDs. While these metrics reflect institutional commitment and recognition, they do not constitute an independent audit of performance or legitimacy, an evaluation that remains unperformed. Accordingly, the prototype should be regarded as a proposed, case-specific framework. Its review in FGD 2 was a structured stakeholder consultation and not a formal validation exercise such as a Delphi process, feasibility scoring, pilot implementation or scenario testing. Its effectiveness in improving vegetation condition, ecosystem services or community welfare has not been evaluated, and its transferability to other community-based mangrove restoration sites is a hypothesis. The transferability of these findings is most plausible in contexts mirroring the MCT, specifically, small-scale, community-initiated restoration site along sandy coastlines managed primarily by local foundation, operating with limited dedicated public financing alongside active corporate social responsibility CSR partners.

Limitations

This study has several limitations. First, it is a single-site study of an 11.63-ha AOI. Second, the ecological analysis relies on NDVI only: species composition, stand structure, biomass, carbon stocks, hydrology and ecosystem services were not measured, and the vegetation signal cannot separate true mangroves from *Casuarina* and other coastal vegetation. Third, field validation was possible only for 2025, and the historical comparison combines four sensors with different spatial resolutions, acquisition seasons and tidal stages without cross-sensor calibration, so class-level changes carry unquantified uncertainty. Fourth, because the temporal record is restricted to five observations spanning seven-year intervals and lacks a spatial control site, definitively attributing vegetation changes directly to restoration interventions or governance frameworks remains methodologically unfeasible. Fifth, stakeholder positions in the power–interest matrix were assigned qualitatively by the researchers. Sixth, the governance prototype was reviewed by stakeholders but has not been implemented or independently evaluated. Despite these various limitations, this study presents a multi-decade record of vegetation greenness at a rehabilitation site on the north coast of East Java, a location where such records are rare. Furthermore, the study presents a replicable methodological workflow alongside stakeholder-derived insights regarding institutional bottlenecks, such as restricted municipal budgets and regulatory hurdles, that impede local restoration initiatives. These findings serve as baseline data and a set of testable hypotheses rather than proof of restoration success. These

findings delineate dimensions of uncertainty alongside the metrics required to address them, while providing a robust baseline for municipal authorities and foundations to design field verification and monitoring protocols. Future work should combine species-resolved field inventories with harmonized, higher-resolution time series in a before–after–control–impact design, and should evaluate the prototype through pilot implementation with explicit performance indicators.

CONCLUSION

This study combined an NDVI-based record of coastal vegetation greenness with socio-institutional surveys, stakeholder power–interest mapping and PPA to propose a preliminary adaptive governance prototype for mangrove restoration at Mangrove Center Tuban, East Java. Within the fixed 11.63-ha AOI, moderate greenness accounted for 3.83 ha (32.9%) in 2025, followed by low greenness at 2.88 ha (24.8%), high greenness at 2.84 ha (24.4%), very low greenness at 2.07 ha (17.8%) and non-vegetated land at 0.01 ha (0.1%). Moderate and high greenness together covered 6.67 ha (57.3%), and low and very low greenness 4.95 ha (42.6%). Vegetated area declined from 7.40 ha (63.6%) in 1997 to 2.71 ha (23.3%) in 2004, increased to 10.34 ha (88.9%) in 2011 and 11.63 ha (100%) in 2018, and remained at 11.62 ha (99.9%) in 2025, corresponding to interval-averaged rates of −13.37, +21.08, +1.69 and −0.012% per year. Although these shifts are temporally correlated with the timeline of community-led rehabilitation and the establishment of the YMCT, the adopted study design precludes a direct causal link to specific restoration or governance interventions. Because the vegetation is dominated by *Casuarina* species and NDVI measures greenness rather than ecological condition, the results describe the extent and greenness of coastal vegetation rather than the recovery of a functional mangrove ecosystem. A socio-institutional assessment demonstrates widespread endorsement for conservation initiatives among local community members, government representatives, and YMCT personnel. However, there are also obstacles, including the absence of a dedicated district-level budget, uncoordinated and sectoral collaboration, and unresolved issues regarding land tenure and regulations. The proposed prototype therefore emphasizes adaptive co-management via a multi-stakeholder steering committee, periodic NDVI monitoring combined with field verification, local regulations regarding mangroves, and diversified financing. This prototype constitutes a site-specific conceptual framework; consequently, its constituent components should be regarded as testable hypotheses rather than validated mechanisms. The prototype was reviewed during a second FGD 2, where stakeholders validated the draft model, but it has not yet been independently implemented or tested. Areas with low and very low greenness (4.95 ha) are candidate sites for field verification prior to any planting activities. Subsequent research must quantify species composition, stand architecture, and ecosystem service dynamics utilizing temporally explicit datasets that have undergone rigorous harmonization and empirical ground-truthing. Furthermore, the prototype should be evaluated through pilot implementation before it can be assumed applicable to other community-based mangrove restoration sites. The study's key contribution is a comprehensive baseline of NDVI-based vegetation cover for the 1997–2025 period, alongside a structured overview of stakeholder positions, which can support field verification and monitoring at this site.

AUTHOR CONTRIBUTIONS

R.J. Sari, contributed to the conceptualization, methodology, data analysis, investigation, data curation, visualization, interpretation of the results, and manuscript preparation. T.E.B. Soesilo, contributed to the methodology, validation, formal analysis, interpretation of the

results, and supervision. S.W. Utomo, contributed to the methodology, validation, formal analysis, interpretation of the results, and supervision. J. Supriatna, contributed to the methodology, validation, formal analysis, interpretation of the results, and supervision. All authors contributed to the review and editing of the manuscript and approved the final version.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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The author(s) declared that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
+	Plus/positive
-	Minus/negative
–	Through
≥	More than or equal to
<	Lower than
AOI	Area of interest
Bands B4	Red
Bands B8	Near-infrared
BNPB	National Agency for Disaster Management (*Badan Nasional Penanggulangan Bencana*)
CAGR	Compound annual growth rate
cm	Centimeters
CSR	Corporate social responsibility
DBH	Diameter at breast height
DIBI	Indonesian Disaster Information Data (*Data dan Informasi Bencana Indonesia*)
DPRD	District and Provincial Parliaments
E	East
ETM+	Enhanced thematic mapper plus
FGD	Focus group discussions
GNDVI	Green normalized difference vegetation index
GVI	Green vegetation index
Ha	Hectare

KKP	Ministry of Marine Affairs and Fisheries (*Kementerian Kelautan dan Perikanan Republik Indonesia*)
KLHK	Ministry of Environment and Forestry (*Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia*)
m	Meters
MCT	Mangrove Center Tuban
MLC	Maximum likelihood classifier
NDVI	Normalized difference vegetation index
NGOs	Non-governmental organizations
NIR	Near-infrared
OLI	Operational land imager
PES	Payment for ecosystem services
PPA	Participatory policy analysis
PT	Perseroan Terbatas/Limited Liability Company
REDD+	Reducing emissions from deforestation and forest degradation
RVI	Ratio vegetation index
SIG	Semen Indonesia Group
S	South
TM	Thematic mapper
UAV	Unmanned aerial vehicle
UIN	Universitas Islam Negeri
YMCT	Yayasan Mangrove Center Tuban

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