Post-Rehabilitation Dynamics of Mangrove Vegetation in Tarakan, North Kalimantan

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Abstract

This research examined the post-rehabilitation dynamics of the mangrove ecosystem in the Mangrove and Crab Conservation Area, Tarakan, North Kalimantan, four years after the launch of a community-based restoration program in 2019. The objectives were to evaluate species composition, vegetation structure, and the survival of mangrove seedlings within rehabilitated plots. The sampling was done on purpose in areas that show the main ecological features of the site. This study found five types of mangrove trees: Avicennia alba, Rhizophora mucronata, Avicennia marina, Sonneratia alba, and Xylocarpus granatum. It is fewer than the ten species that were there in the past. Among these, Avicennia alba consistently dominated both the mature and seedling stages, recording the highest relative density (72.56%), frequency (42.86%), and canopy cover (78.08%). Its naturally regenerating seedlings reached a survival rate of 52%, substantially higher than the 17% recorded for planted Rhizophora mucronata. The Avicennia alba is particularly well adapted to the prevailing site conditions, mainly owing to its tolerance of sediment disturbance and variable salinity. This outcome highlights the importance of Assisted Natural Regeneration (ANR) that employs locally adapted species, offering a more practical, cost-effective, and sustainable approach than conventional planting methods. Although there have been some improvements, the decrease in species numbers shows the ecosystem is still in the early stages of recovery. To make sure it stays healthy and strong for the future, it is important to keep the water flowing properly, reduce human impact, and keep up with regular checks and monitoring.

Keywords: *Avicennia alba, coastal restoration, community-based conservation, mangrove survival*

Introduction

Mangrove ecosystems serve as vital coastal buffers, offering a wide range of ecosystem services, including shoreline stabilization, nutrient cycling, carbon sequestration, and critical nursery habitats for marine biodiversity (Luederitz *et al*., 2015; Malhi *et al*., 2019; Choudhary *et al*., 2024). However, their ecological integrity is increasingly threatened due to anthropogenic pressures such as land conversion, aquaculture expansion, pollution, and infrastructure development (Capparelli *et al*., 2024; Kanjin and Alam, 2024). These direct stressors are compounded by climate change-induced phenomena such as sea-level rise, salinity shifts, extreme weather events, and sediment instability, which disrupt hydrological regimes, submerge pneumatophores, and increase tree mortality (Krauss *et al*., 2014). The degradation of mangrove forests subsequently reduces their capacity to support fisheries, regulate coastal microclimates, and act as carbon sinks, thereby endangering both ecological and socio-economic systems (Friess *et al*., 2016; Cheng and Li, 2024).

Amidst these challenges, the Mangrove and Crab Conservation Area (*Kawasan Konservasi Mangrove*

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dan Kepiting, "KKMK" – in Bahasa) in Tarakan Island, Indonesia, provides an important case study for evaluating mangrove regeneration success under disturbed conditions. Originally covering 35 hectares, this area was previously exploited for tiger prawn (*Penaeus monodon*) and milkfish (*Chanos chanos*) farming. However, after sluice gates and embankments collapsed, the site became hydrologically stagnant and was eventually abandoned. Over time, natural colonization by *Avicennia marina* and other species signaled the site's regenerative potential, prompting the Tarakan City Government to designate the area as a conservation zone in 2015 (Aziz *et al*., 2023; Bidayani *et al*., 2024). Comparable passive recovery processes have been documented across Southeast Asia in abandoned aquaculture zones, particularly where partial tidal connectivity was retained (Kodikara *et al*., 2017; Soroye *et al*., 2022; Liang *et al*., 2023).

In 2016, however, the construction of the Pamusian River Canal altered the site's natural hydrology, disrupting the trajectory of spontaneous regeneration. Consequently, a formal rehabilitation program was launched in 2019 that involved replanting *Rhizophora mucronata*, restoring water channels, and enhancing sedimentation dynamics to reinstate tidal exchange (Amaral *et al*., 2023; Anu *et al*., 2024). These measures aimed to improve forest structure and ecosystem function, drawing upon global principles of ecological engineering and integrated watershed management (Alongi, 2008; Lai *et al*., 2025).

Scientific evidence confirms that successful mangrove rehabilitation is site-specific, influenced by factors such as species selection, substrate quality, hydrological connectivity, and community participation (Hashim *et al*., 2010; Jamero *et al*., 2019; Wu *et al*., 2020). Active community engagement enhances long-term restoration outcomes by fostering stewardship, reducing maintenance costs, and ensuring post-planting survival (Armitage *et al*., 2008; Rodrigues *et al*., 2021). Moreover, mixed-species plantations generally outperform monospecific stands by increasing ecological resilience and regeneration success under fluctuating salinity and sediment regimes (Bakhshandeh *et al*., 2017; van Woesik *et al*., 2021; Holmes *et al*., 2025). Despite these insights, empirical assessments of community-based mangrove rehabilitation projects under disturbed hydrological and socio-political contexts remain limited, especially in northern Kalimantan.

This study aims to evaluate the ecological condition of the rehabilitated KKMK area four years after active intervention. The assessment focuses on vegetation structure, species composition, and regeneration success, comparing natural and artificial regeneration mechanisms. Results from this study will offer insights for adaptive management and provide an evidence base for scaling up site-specific mangrove conservation strategies in Indonesia and other climate-vulnerable regions of Southeast Asia.

Materials and Methods

This study was conducted within the Mangrove and Crab Conservation Area, located in Pamusian Village, Tarakan Island, North Kalimantan Province, Indonesia (3° 17' 52.39" N; 117° 36' 27.36" E). Encompassing approximately two hectares, the site was purposively selected based on its dual ecological characteristics: (1) a history of degradation due to abandoned aquaculture activities and (2) observable signs of spontaneous mangrove regeneration. These features made the area particularly suitable for assessing vegetation structure and dynamics during the post-disturbance recovery phase, as emphasized in recent studies by Bidayani *et al*. (2024) and Mulyani *et al*. (2024). To provide spatial and visual context, Figure 1 presents a satellite map delineating the boundaries of the conservation area. Fieldwork was carried out during the post-monsoon season (September to October 2023), a period generally associated with favorable climatic conditions for mangrove seedling establishment and early growth (Sukmarani *et al*., 2023).

A total of twelve transects were established across the study site, oriented perpendicular to the shoreline to capture ecological gradients. Within each transect, nested quadrats were placed: 5m × 5 m plots were used to assess sapling communities, while 10m × 10 m plots were employed for mature trees. One transects was located in a former *Rhizophora mucronata* enrichment zone, covering 300 m^2, with a uniform planting density of one seedling per square meter. This plot enabled a comparative analysis between natural and assisted regeneration outcomes (Ariyanti *et al*., 2023).

Vegetation data collected from each quadrat included species identity, growth stage classification, and stem diameter. Species identification was conducted through field observations based on morphological characteristics, roots, bark texture, leaf shape, stem structure, and reproductive organs, and cross-referenced with standard botanical keys (Reddy, 2008). Regional taxonomic studies by Sukmarani *et al*. (2023) and Ariyanti *et al*. (2023) were also consulted to ensure accuracy. The breast height (DBH) diameter was measured using a measuring tape at 1.3 m above the ground. To maintain consistency, all quadrat boundaries were clearly marked using raffia rope.

Figure 1. Study site, Map image of the sampling site

Quantitative ecological metrics were calculated to evaluate vegetation structure and regeneration success. These included species density, relative density, frequency, relative frequency, dominance, relative dominance, Basal Area (BA), and the Important Value Index (IVI). Analytical procedures followed established methodologies as described by Rahim *et al*. (2023), and recent mangrove monitoring frameworks proposed by Susilo *et al*. (2023). Basal area was computed using formulas outlined by Syarif *et al*. (2022), Nuraini *et al*. (2021), and Puna *et al*. (2023), while canopy cover and survival rate assessments were guided by vegetation-based indicators from Bengen (2020, 2022) and Hilmi *et al*. (2015, 2021c).

It is important to note that this study focused exclusively on aboveground vegetation parameters. Soil characteristics and water quality measurements were intentionally excluded to isolate vegetation-based indicators as proxies for ecological status and regeneration success. This approach aligns with current best practices that emphasize structural metrics as effective indicators of rehabilitation performance in mangrove ecosystems (Bidayani *et al*., 2024; Mulyani *et al*., 2024).

Results and Discussion

A total of 85 mature mangrove individuals were recorded within the 1,200 m² study area in the Mangrove and Crab Conservation Area, consisting of three species: *Avicennia alba, Sonneratia alba,* and *Rhizophora mucronata*. The most abundant species was *A. alba*, with 76 individuals, followed by *S. alba* (7 individuals) and *R. mucronata* (2 individuals). These values correspond to species densities of 0.063 individuals m^{-2} (*A. alba*), 0.006 individuals.m^{-2} (*S. alba*), and 0.002 individuals.m^{-2} (*R. mucronata*), as illustrated in Figure 2. Regarding basal area (BA), *A. alba* also had the highest value at 1.058 $m^2.ha^{-1}$, while *S. alba* and *R. mucronate* recorded 0.105 $m^2.ha^{-1}$ and 0.021 $m^2.ha^{-1}$, respectively.

The predominance of *Avicennia alba* is consistent with its pioneer ecological characteristics, including high salinity tolerance, resistance to wave action, and rapid colonization in disturbed environments (Alongi, 2008). Such attributes make *A. alba* well-suited for early successional stages and structural recovery of degraded mangrove habitats. This observation aligns with findings by Bidayani *et al*. (2024), who reported the dominance of *A. alba* in restored mangroves on degraded coasts. In contrast, the minimal occurrence of *R. mucronata* a species that typically requires stable, organic-rich substrates (Onrizal and Kusmana, 2004; Tomlinson, 2016; Sitio *et al*., 2023), suggests that site conditions, including altered hydrology and sediment quality, may remain suboptimal post-rehabilitation (Sari *et al*., 2023).

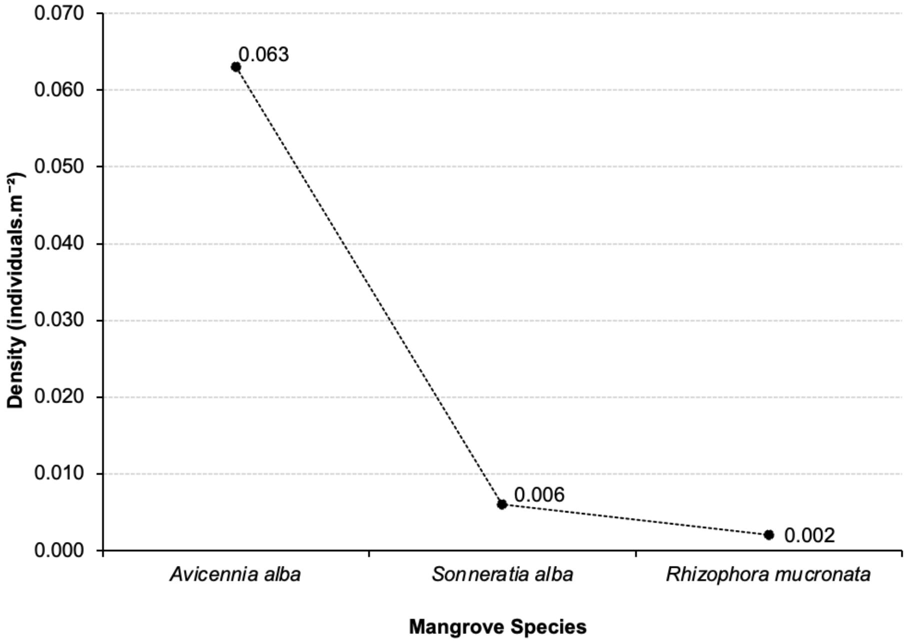

Figure 2. Species composition of mature mangrove trees and their respective densities (individuals.m^{-2}).

To quantify the ecological significance of each species, the Important Value Index (IVI) was calculated, integrating relative density, relative frequency, and relative dominance. *A. alba* exhibited the highest IVI, reflecting its central role in structuring the early-successional mangrove community. IVI is a critical indicator in ecosystem recovery because it represents species abundance and their functional contribution to canopy formation, litter input, and sediment stabilization (Sudarno *et al*., 2024). Similar findings were reported by Putri *et al*. (2022), who emphasized the contribution of *A. alba* to habitat complexity and nutrient cycling in restored mangroves associated with *Scylla* spp. populations.

The underrepresentation of *R. mucronata*, a late-successional species, indicates that the ecosystem has not yet reached a mature structural stage. This condition is further supported by physical factors observed in the field, including residual embankment structures and restricted tidal flow, as reported in similar studies (Badriana *et al*., 2023). Moreover, the diversity of mangrove gastropods, often used as bioindicators of environmental quality, was also low at this site (Baharuddin and Satyanarayana, 2024), reinforcing the early-stage regeneration status.

In conclusion, the dominance of *A. alba*, as shown in IVI values and species composition (Figure 2), highlights the site's reliance on pioneer species for initial recovery. To advance the ecosystem toward a more mature and functionally diverse state, targeted enrichment planting and continued monitoring are recommended (Sari *et al*., 2023). These findings underline the importance of adaptive management in mangrove restoration, particularly in post-aquaculture landscapes such as KKMK.

In the sapling category, a total of 215 mangrove saplings were identified within the 300 m^2 sampling area, comprising five species: *Avicennia alba, Rhizophora mucronata, Sonneratia alba, Xylocarpus granatum*, and *Avicennia marina*. Among these, *A. alba* was the most dominant, with 156 individuals and a corresponding density of 0.520 individuals.m^{-2}. This was followed by *R. mucronata* (51 individuals, 0.170 individuals.m^{-2}), while other species were found in much lower numbers: *S. alba* (4 individuals; 0.013 individuals.m^{-2}), *X. granatum* (3 individuals; 0.010 individuals.m^{-2}), and *A. marina* (1 individual; 0.003 individuals.m^{-2}). The species composition and density patterns are presented in Figure 3.

The sapling assemblage reflects a reduced diversity, with only five of the ten mangrove species previously recorded in the KKMK appearing at this developmental stage. This reduction in species richness may signal ecological constraints linked to post-disturbance conditions, such as sediment instability, previous aquaculture activity, and altered hydrological connectivity (Yuliana *et al*., 2019). Despite the resilience of mangrove species, manifested in traits like vivipary, vertical accretion, and landward migration (McKee, 2011), successful regeneration remains contingent upon suitable sediment composition, freshwater availability, and propagule dispersal pathways. The dominance of *A. alba* and *R. mucronata* may be attributed to their high propagule viability and tolerance to a wide range of salinity and sediment conditions (Srikanth *et al*., 2015). These characteristics allow them to outperform other species in regenerating disturbed zones. Similar patterns of colonization and regeneration success have been documented in other degraded mangrove ecosystems undergoing natural or assisted recovery (Eddy *et al*., 2019; Raganas *et al*., 2020).

The mature mangrove community structure analysis revealed that three species, *Avicennia alba, Sonneratia alba*, and *Rhizophora mucronate*, were present in the study area. Among these, *A. alba* dominated all structural metrics, recording the highest values for relative density (89.41%), relative frequency (60.00%), and relative cover (89.36%), as shown in Figure 4. In contrast, *S. alba* and *R. mucronata* exhibited markedly lower contributions, each registering below 10% in both relative density and cover

The dominance of *A. alba* can be attributed to its high ecological plasticity, particularly in degraded and recovering mangrove habitats such as the KKMK. Its rapid seedling establishment, high salinity tolerance, and efficient lateral expansion through pneumatophores confer competitive advantages over other species in sediment-rich and hydrologically altered environments (Muliawan *et al*., 2020). Additionally, *A. alba* is known for its capacity to swiftly colonize newly accreted mudflats, a likely condition in KKMK following hydrological disruptions from former aquaculture practices.

Functionally, although both *A. alba* and *R. mucronata* contribute to nutrient cycling, their litter quality influences decomposition rates and nutrient availability differently. *R. mucronata* litter, with higher lignin content, decomposes more slowly, thereby delaying the release of nitrogen and phosphorus (Muliawan *et al*., 2020). Conversely, the carbon-rich and more labile litter of *A. alba* enhances sediment fertility through faster decomposition and nutrient turnover (Alongi, 2008). Recent studies also underscore that successful regeneration and dominance of Avicennia species are influenced by tidal inundation gradients, substrate porosity, and legacy effects of anthropogenic disturbance (Xiong *et al*., 2021; Ai *et al*., 2025). Moreover, resilience to oxidative stress and phenotypic plasticity under climate variability further support *A. alba's* expansion in managed conservation settings (van Loon *et al*., 2016; Atia *et al*., 2021).

In the sapling category, five mangrove species were identified in the study area: *Avicennia alba, Rhizophora mucronata, Avicennia marina, Sonneratia alba*, and *Xylocarpus granatum*. Among these, *A. alba* exhibited clear structural dominance with the highest relative density (72.56%), frequency (42.86%), and cover (78.08%). *R. mucronata* followed with values of 23.72%, 42.86%, and 19.82% for the same parameters, respectively. The remaining species, *A. marina, S. alba*, and *X. granatum*, recorded marginal contributions below 8% across all structural metrics (Figure 5).

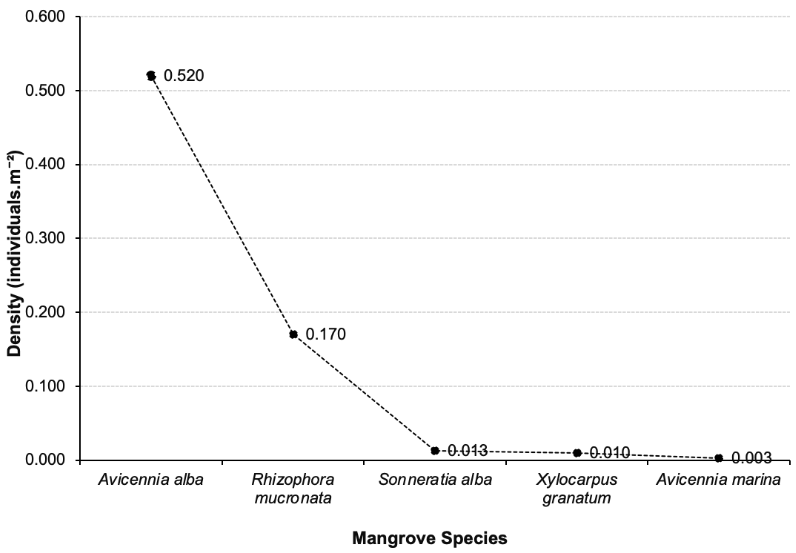

Figure 3. Sapling category: species composition of mangrove saplings and their respective densities (individuals.m^{-2})

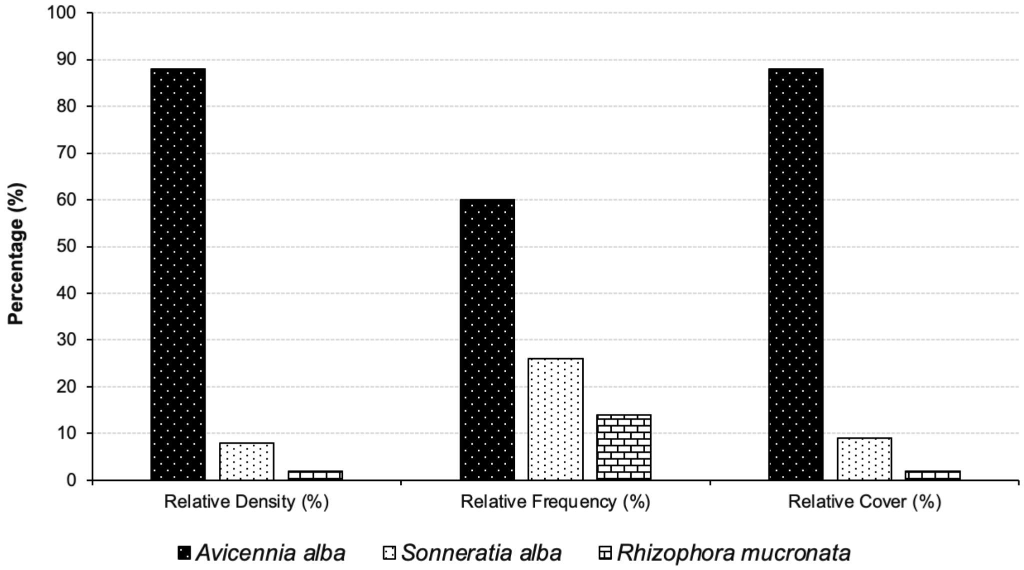

Figure 4. Comparative metrics of relative density, frequency, and canopy cover (%) for mature mangrove species identified in the conservation area

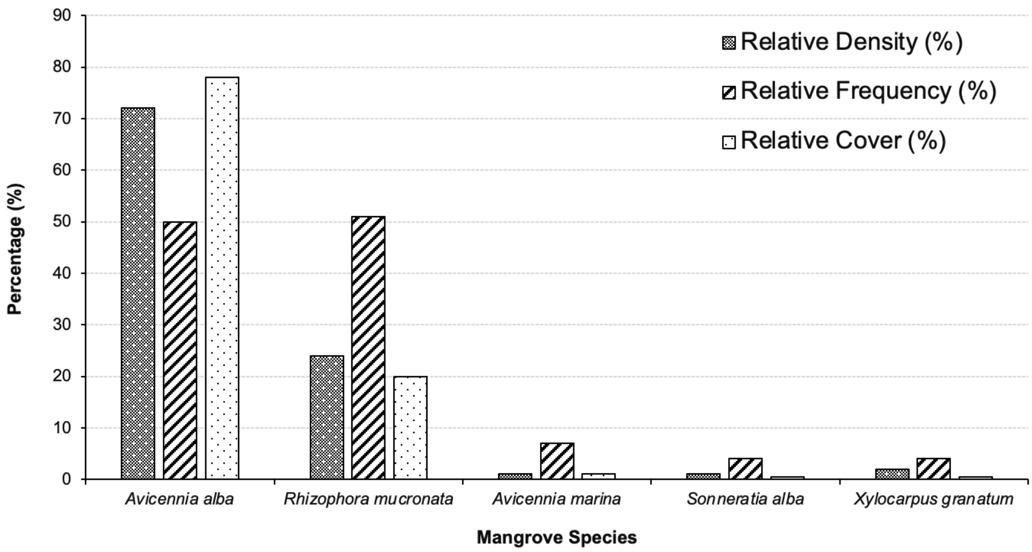

Figure 5. Structural parameters of mangrove saplings in the study area present the relative density, frequency, and cover (%) of the five identified species

The ecological preeminence of *A. alba* reflects its high adaptability to dynamic coastal environments, particularly those characterized by sediment accretion and hydrological disturbance. Its ability to regenerate naturally and establish dense sapling stands aligns with findings from other disturbed mangrove zones in Southeast Asia (Hu *et al*., 2023). The equal relative frequency shared between *A. alba* and *R. mucronata* suggests both species are similarly distributed spatially; however, the notably higher density and cover of *A. alba* indicate more successful recruitment and canopy development, key indicators of regeneration success.

The findings underscore the importance of natural regeneration, particularly in conservation areas where passive restoration can be more sustainable and cost-effective than active interventions (Dewi *et al*., 2021; Kusumadewi *et al*., 2024). *A. alba* and *R. mucronata* are also well-documented contributors to carbon sequestration due to their rapid growth, biomass accumulation, and structural attributes (Fatonah *et al*., 2023; Zhirenko *et al*., 2023). Moreover, recent studies highlight their ecological importance in rehabilitating hydrologically impaired sites and enhancing soil stabilization (Kuenzer *et al*., 2011; Alharbi *et al*., 2023). These qualities reinforce the need to prioritize these two species in regional mangrove management frameworks, particularly in community-based and climate-resilient conservation strategies.

The Important Value Index (IVI) analysis provides robust insights into mangrove species' structural dominance and ecological status within the KKMK. As shown in Figure 6, *Avicennia alba* exhibited an exceptionally high IVI of 238.77% in the mature vegetation category, significantly surpassing the values recorded for *Sonneratia alba* (43.77%) and *Rhizophora mucronate* (17.46%). This substantial IVI indicates that *A. alba* not only dominates in terms of stem density and basal area but also maintains consistent frequency across transects, highlighting its ecological resilience and successful long-term establishment in this rehabilitated landscape.

A parallel trend was observed in the sapling population. As depicted in Figure 7, A. alba again demonstrated the highest IVI at 193.51%, followed by *R. mucronata* (86.40%), while *A. marina, S. alba*, and *Xylocarpus granatum* contributed marginally, each below 10%. The consistency of *A. alba*'s dominance across both maturity stages illustrates its strong life-cycle persistence. It suggests a high capacity for natural regeneration under the specific environmental conditions of the study area.

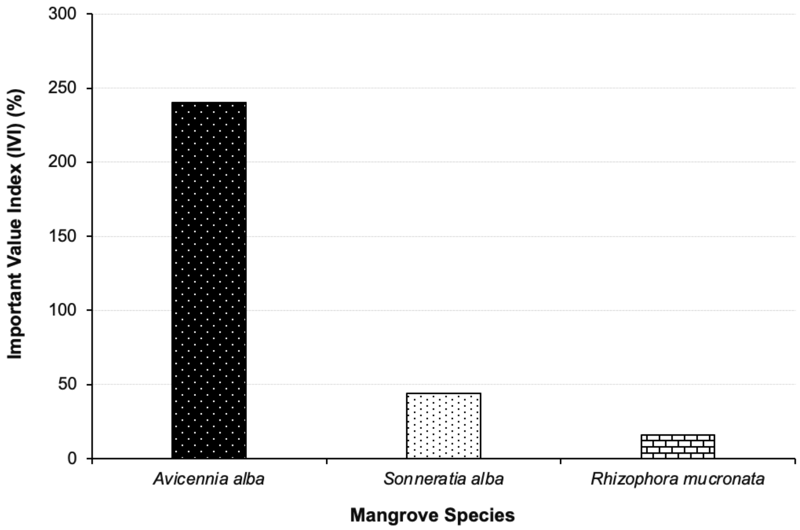

Figure 6. Important Value Index (IVI) of mature mangrove vegetation in the study area

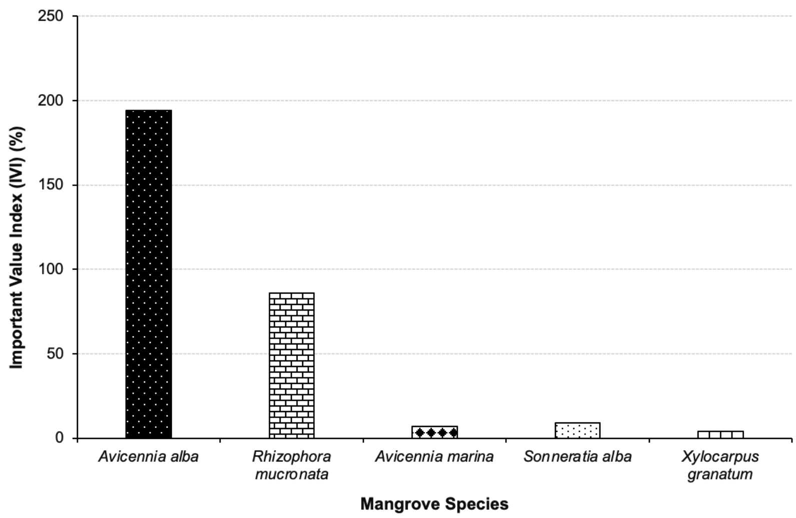

Figure 7. Important Value Index (IVI) of mangrove saplings in the study area

The prominent position of *A. alba* across life stages may be attributed to its physiological and morphological adaptability to the prevailing site conditions, including fluctuating salinity, soft alluvial substrates, and altered hydrology due to legacy aquaculture disturbances. Its pneumatophore system and salt-excreting leaves confer tolerance to saline intrusion and poor aeration, making it an ideal colonizer for degraded tidal lands (Onrizal and Kusmana, 2004; Tomlinson, 2016). Despite ongoing replanting initiatives, the relatively lower IVI of *R. mucronata* points to challenges in artificial establishment, potentially stemming from nursery incompatibilities, altered microtopography, or competition with naturally regenerating species.

These findings carry important implications for mangrove restoration. As evidenced in Figures 6 and 7, species-specific ecological traits must guide restoration strategies. Relying on naturally dominant species like *A. alba* can accelerate recovery and improve structural stability. The species' high IVI and strong performance across both mature and sapling stages underscore its regenerative success and suitability as a pioneer species in conservation-driven landscapes. Moreover, promoting such naturally regenerative dynamics aligns with recent ecological restoration frameworks advocating minimal intervention and reliance on ecosystem self-repair processes (Wang *et al*., 2024).

The survival data of mangrove saplings collected from transects initially used for the 2019 replanting program further reinforces the adaptive advantage of *A. alba*. Out of the 300 *R. mucronata* seedlings planted initially, only 51 individuals (17%) survived the current monitoring period. Conversely, 156 saplings of *A. alba* were recorded in the same area without prior planting, indicating spontaneous colonization through propagule dispersal facilitated by tidal currents and sediment transport. These saplings reflect a survival rate of approximately 52%, threefold higher than the artificially planted *R. mucronata*.

This discrepancy strongly supports the argument for embracing Assisted Natural Regeneration (ANR) techniques over conventional planting. While *R. mucronata* is widely favoured for its structural and carbon sequestration potential (Fatonah *et al*., 2023; Zhirenko *et al*., 2023), its establishment success appears context-dependent and may require more site-specific nursery-to-field alignment. In contrast, *A. alba*'s high survival and spontaneous establishment suggest ecological compatibility and the presence of an active propagule source, likely from adjacent mangrove stands or remnant parent trees.

The role of the KKMK in ecological recovery and service provisioning is substantial. This conservation area provides essential functions such as sediment trapping, shoreline stabilization, nursery habitat for fisheries, and opportunities for community-based ecotourism (Hilmi *et al*., 2022b; Soares *et al*., 2018; Usman *et al*., 2023). Though present at lower densities, less dominant species like *A. marina* and *X. granatum* contribute to biomass heterogeneity and enhance regeneration niches in gaps created by canopy fragmentation (Widyastuti *et al*., 2018; Chen *et al*., 2021). *A. marina*, in particular, often occupies marginal zones and acts as a boundary stabilizer, a pattern also evident in this study, where it was mainly found along landward edges, consistent with zonation models described by Tomlinson (2016).

Despite this progress, the mangrove system in KKMK remains vulnerable. Various forms of degradation, pollution, channelization, urban runoff, and saltwater intrusion compromise nutrient availability, soil structure, and recruitment potential (Zhang *et al*., 2019). These pressures manifest most severely in mid-intertidal zones, where tidal connectivity has been partially restored but remains insufficient to support late-successional species or sustain seedling recruitment over multiple seasons. Such findings are echoed in recent studies from other Indonesian conservation zones, highlighting restoration success's limitations without full ecosystem process recovery (Turner and Lewis, 1997).

Restoration strategies must evolve beyond replanting into more holistic and adaptive management frameworks to address these limitations. Reestablishing hydrological flow, restoring sediment delivery pathways, and regulating anthropogenic stressors, especially at micro-catchment levels, are critical to enabling self-sustaining recovery (Wang *et al*., 2023). These strategies are particularly effective when combined with local community participation and traditional ecological knowledge, which have been shown to enhance restoration stewardship and adaptive learning (Duarte *et al*., 2009; Andradi-Brown *et al*., 2013).

Furthermore, the observed success of *A. alba* in this study resonates with regional efforts in Southeast Asia that promote species-specific management. Recent research emphasizes that species like *A. alba* and *Bruguiera gymnorhiza*, due to their high recruitment potential and environmental resilience, should form the backbone of rehabilitation in semi-disturbed tidal ecosystems (Onrizal *et al*., 2017; Wang *et al*., 2024). However, caution must be exercised to prevent monoculture domination, which may reduce overall ecosystem diversity and resilience in the long term.

The concept of "natural regeneration" adopted in this study is consistent with ANR principles, whereby site conditions are improved to facilitate the recruitment and survival of naturally dispersed propagules. This approach differs from passive restoration, which relies solely on spontaneous succession without intervention, and active restoration, which involves planting and engineering interventions. ANR offers a cost-effective, ecologically grounded, and socially inclusive pathway to restoration, particularly in community-managed conservation areas like KKMK. In conclusion, this study reinforces the ecological value of Avicennia alba as a keystone species in the recovery trajectory of the KKMK. Its high IVI across life stages, strong natural regeneration capacity, and compatibility with local edaphic and hydrological conditions suggest its central role in future management scenarios. Equally, the relatively low performance of *R. mucronate* underlines the importance of matching species traits with site characteristics rather than relying solely on replanting history or preference. The comparative evidence presented in Figure 6 and 7, along with survival data and ecosystem context, collectively supports the prioritization of natural regeneration strategies integrated with ecosystem-based management to achieve sustainable mangrove restoration.

Conclusion

This study demonstrates the post-rehabilitation status of the mangrove ecosystem in the Mangrove and Crab Conservation Area, Tarakan Island, four years after the application of active and passive restoration measures. Five mangrove species were recorded, with *Avicennia alba* emerging as the dominant species across both mature and sapling stages. *Avicennia alba* had a survival rate of 52%, which is significantly better than the 17% survival rate for *Rhizophora mucronata*. It demonstrates that utilizing assisted natural regeneration with plants that benefit the local environment can be beneficial for the ecosystem. The results show that ANR is a good, affordable, and eco-friendly method for restoring forests, surpassing older methods of tree planting. However, even though some plants are beginning to grow again, there is limited variety in the types of plants, and many of the species that appear in more mature forests are not yet present. These circumstances indicate that mangrove rehabilitation is still at an early stage, and achieving long-term ecosystem resilience will depend on enhancing hydrological connectivity and minimizing anthropogenic pressures. Overall, this study emphasizes the importance of prioritizing natural regeneration in mangrove restoration frameworks and identifies *A. alba* as a keystone species offering a scalable model for resilience-based coastal rehabilitation

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