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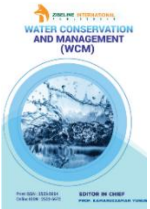

RESEARCH ARTICLE

MANAGING RAPID SEDIMENTATION THROUGH MANGROVE ASSISTED COLONIZATION: LAND FORMATION, WATER CONSERVATION, AND CARBON SEQUESTRATION IN THE AJKWA ESTUARY, PAPUA, INDONESIA

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ABSTRACT

Ajkwa Estuary, located in Mimika Regency, Central Papua Province, Indonesia, represents a dynamic and biodiverse ecosystem that plays a pivotal role in providing ecosystem services. However, like many estuarine systems globally, the intensification of its use has led to significant environmental challenges. The estuary is particularly susceptible to ecosystem alterations caused by accelerated sedimentation from undeposited tailings originating from mining operations. This study investigates the novel approach to sedimentation area management involving the construction and deployment of estuarine structures, including Geotube and Bamboo E-Groins, to confine sedimentation within designated zones. These interventions aim to manage the land formation, facilitate mangrove colonization, enhancing the estuary's capacity for water conservation and carbon sequestration as a climate change mitigation measure. Empirical findings demonstrate that the implementation of 2,700-meter-long Geotube structures and 2,800-meter-long bamboo E-Groins effectively increased sediment deposition to a depth of 0.74 meters, creating optimal conditions for mangrove establishment. Mangrove seedlings introduced to the newly formed sedimentary zones exhibited a survival rate of 99%. Carbon sequestration potential was quantified for the 500-hectare mangrove-assisted colonization area, with results indicating an atmospheric carbon dioxide sequestration capacity of 422,272.08 tons CO2 equivalent, corresponding to 115,374.88 tons of stored carbon. Projections for a 50,000-hectare expansion of mangrove colonization suggest a total carbon stock of 3,953,566.77 tons, equivalent to the sequestration of 14,470,054.36 tons CO2.

KEYWORDS

Carbon sequestration, estuary structure, mangrove, sedimentation, Ajkwa estuary

1. INTRODUCTION

Estuaries are dynamic ecosystems characterized by a diverse array of habitats that deliver critical ecosystem services (ES), including sediment catchment, water resources for consumption and transportation, food production, flood protection, water purification, primary productivity, and recreational opportunities (Boerema and Meire, 2017). Many estuaries play a vital role in supporting economic activities; however, such utilization often disrupts ecosystem functioning, impacting hydrodynamics, ecological structures, and biodiversity. These disruptions can lead to significant environmental challenges, including eutrophication, altered hydrological regimes, biodiversity loss, and marsh reclamation (Barbier et al., 2011). Furthermore, estuaries serve as significant sediment accumulation zones, receiving inputs from rivers, shore erosion, primary production, marine sources, and atmospheric deposition (Brunskill et al., 2004; Setyadi et al., 2021).

Ajkwa Estuary, situated in Mimika Regency, Central Papua Province, Indonesia, marks the confluence of the Ajkwa River and the Arafura Sea, traversing dense mangrove forests. This estuary supports five major mangrove genera-Bruguiera sp., Rhizopora sp., Xylocarpus sp., and Avicennia sp-with tree heights reaching 25–30 m in height (Brunskill et al., 2004). mangrove tree densities the estuary ranges from 767 – 1,345 trees per ha-1, with canopy heights extending up to 43 m. Aside from providing ecosystem services to humans-water and food resources, water for transportation, flood protection, water purification, and other primary production-the estuary also acts as critical sediment deposition zones. However, sediment deposition in Ajkwa Estuary includes both natural sediments and tailings from mining activities, significantly altering water flow patterns and sediment dynamics. This rapid

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sedimentation poses risks of uncontrolled land formation and aquatic habitat changes. Paradoxically, study conducted from 1998 to 2010 reveal that the rapid sedimentation in the Ajkwa Estuary has contributed to the expansion of mangrove colonies. Fine tailings from mining, deposited within the estuary, trapped by mangrove roots, elevating land and fostering mangroves to further grow underscoring the potential for managing sedimentation through mangrove-assisted colonialization, enhancing the estuary's resources (Fajri, 2012).

In general, mangrove colonization not only enhancing the estuary resources but also plays an important role in supporting water conservation through several interconnected ecological and hydrological mechanisms. A primary route is the reduction of soil salinity, where mangrove systems facilitate the flushing of hypersaline soils through tidal and rainwater inputs (Kathiresan, 2004). This process enhances the soil's capacity to retain water and nutrients, thereby improving moisture availability in coastal zones. Equally important is the high water-use efficiency exhibited by mangrove species, which is achieved through specialized physiological adaptations such as salt exclusion at the root interface, osmotic adjustment, and the selective uptake of less saline water (Reef and Lovelock, 2015). These traits enable mangroves to conserve water under saline and drought-prone conditions. The structural complexity of mangrove root systems further contributes to water conservation by stabilizing intertidal sediments and dissipating wave energy. This function reduces shoreline erosion, limits sediment runoff, and helps maintain water quality in adjacent aquatic ecosystems. Mangrove colonization also plays a critical role in promoting coastal accretion, as the root networks effectively trap fine sediments, leading to vertical land build-up that enhances shoreline stability and mitigates the impacts of sea-level rise (Chow, 2018; Weaver and Stehno, 2024). Moreover, mangrove ecosystems support natural water purification processes, with microbial communities capable of degrading organic pollutants and reducing nutrient loads, thereby improving the quality of water in estuarine and nearshore environments (Bouchez et al., 2013). In addition, mangroves contribute to climate adaptation and hydrological resilience by sequestering atmospheric carbon, moderating local microclimates, and preserving freshwater gradients despite increasing salinity and rising sea levels (Field, 2011).

Mangroves are recognized as significant carbon sinks due to their biomass and sediment accumulation. They deliver critical ES, including raw material provision, water purification, fisheries conservation, coastal protection, erosion control, carbon sequestration, and opportunities for recreation, education, and research (Barbier et al., 2011). Adapted to intertidal zones, mangroves contribute substantially to aquatic food webs and support fisheries by providing breeding grounds for various species. However, mangrove productivity is influenced by climatic, edaphic, hydrological, and anthropogenic factors, as well as forest structural characteristics, directly impacting photosynthetic capacity (Candra et al., 2016; Chatting et al., 2022; Nyanga, 2020; Tue et al., 2020).

Despite covering only 0.7% of the global coastal zone, mangroves significantly contribute to global carbon sequestration and reducing CO2 emissions as an effort to mitigate global warming and climate change by capturing and storing CO2 from the atmosphere for long periods of time (Pant et al., 2023). Carbon sequestration refers to the process of capturing carbon dioxide from the atmosphere and storing it in various reservoirs such as oceans, terrestrial environments (including vegetation, soil, and sediments), and geological formations (Solomon, 2023). It is also defined as the potency of a system or an ecosystem to absorb and store carbon in biomass, sediments, or water more than what is being released to the atmosphere. About 15-40% of carbon has remained in the atmosphere for more than 1000 years. An additional one ton of CO2 emissions causes a larger increase in the CO2 load in the atmosphere but causes a smaller increase in radiation forcing (Knutti and Rogelj, 2015). The mangroves are known to remove CO2 from the atmosphere through photosynthesis and fix greater amounts of CO2 per unit area in comparison to the phytoplankton in tropical oceans. Field studies have shown mangroves to have high above-ground biomass, productivity, soil carbon, below-ground to above-ground biomass ratios, and high rates of carbon sequestration (Bindu et al., 2020; Ha et al., 2018; Jennerjahn, 2020; Rahman et al., 2021; Ray et al., 2011).

This paper reports on sedimentation management in the Ajkwa Estuary through mangrove-assisted colonization as a climate adaptation and hydrological resilience strategy. This approach addresses the dual challenges of managing mining tailings sedimentation and reducing atmospheric carbon, contributing to global climate mitigation efforts with the additional water conservation capability as an ecosystem service. By fostering the natural establishment of mangrove ecosystems, this method not only stabilizes sediment deposits but also enhances coastal resilience against rising sea levels and extreme weather events driven by climate change. Additionally, this nature-based solution serves as a scalable and transferable model for integrating ecological restoration into corporate environmental management, particularly in regions facing similar challenges from extractive industries. Beyond its local benefits, the project contributes to the broader discourse on sustainable land-use practices, biodiversity and water conservation, and community-led climate adaptation strategies. By demonstrating how industrial sectors can proactively engage in climate-positive actions, this approach underscores the potential for harmonizing economic development with environmental stewardship on a global scale.

2. RESEARCH METHODS

2.1 Study Location

This study was conducted in the lower area of Ajkwa Estuary, located at coordinate 136°49'35.231" E - 137°3'42.333" E 4°51'33.022" S - 4°57'52.267" S, Mimika Regency, Central Papua Province, Indonesia. as presented in the Figure 1. The Ajkwa Estuary is the meeting point of the Ajkwa River, which flows through a dense mangrove forest and the Arafuru Sea. The estuary also serves as a sediment deposition area, receiving both natural sediments and a fraction of sediments generated by mining activities.

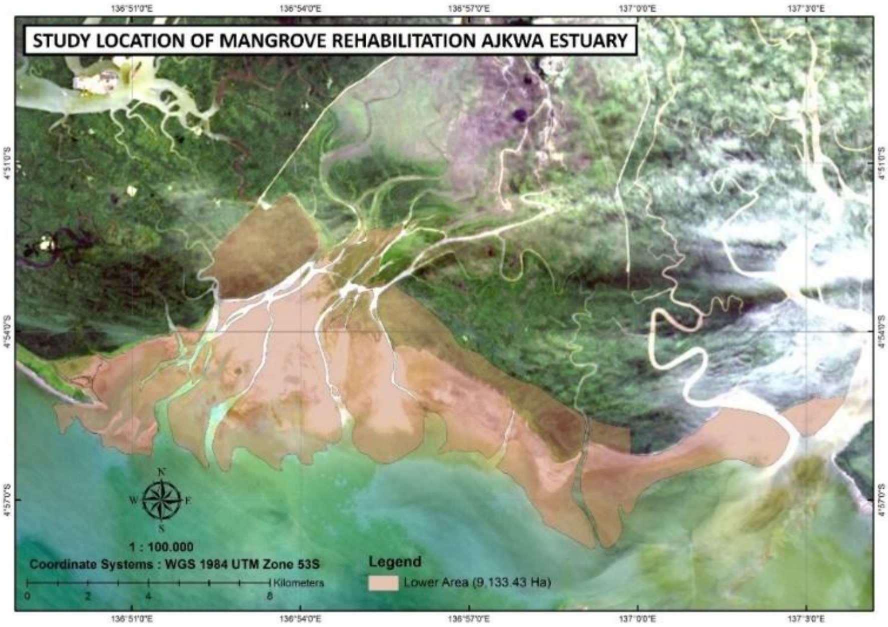

Figure 1: Study Location in the Lower Area of Ajkwa Estuary

2.2 Estuary Structures to Accelerate Mangrove Colonization

The sedimentation process in the Ajkwa Estuary can be accelerated

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through modified sustainable engineering constructions designed to localize sediment deposition within designated areas, thereby accelerating mangrove colonization. The innovation involves the construction of estuary structures with the aim to increasing the rate of sedimentation and create a suitable substrate elevation for mangrove establishment. While this process can occur naturally over time, the creation of nature-based nearshore structures can expand the area and significantly reduce the time required for mangrove colonialization. These structures also create protected environments where mangrove propagules are more likely to settle and thrive, minimizing the need for intensive planting efforts.

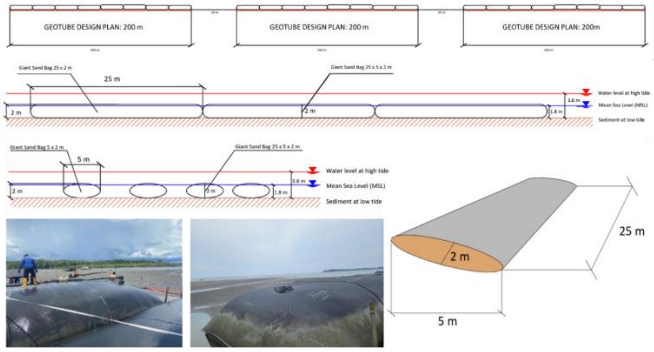

Figure 2: Geotube design construction plan in Ajkwa Estuary

Bamboo-based E-groins, which are shore-perpendicular structures, are designed to stabilize updrift beaches and regulate longshore sediment transport. By design, these structures capture sand transported by longshore currents, thereby reducing sediment depletion in adjacent areas. Each Bamboo-based E-groin, standing at 4 m in height and 10-12 cm in diameter, were arranged in a specified configuration with a total hybrid engineering length of 200 m in an E-shaped design with groins extending to 50 m as depicted in Figure 3. The construction of estuary structures began at priority locations, with approximately 2,700 meters of Geotube structures and 2,800 meters of Bamboo-based E-groins constructed as depicted in Figure 3.

2.3 Sedimentation Rate Monitoring

Monitoring the height of sediment accumulation is crucial for assessing sedimentation rates and understanding deposition patterns in Ajkwa estuary especially after the establishment of Geotubes and Bamboo-based E-groins. The sedimentation rate was calculated by measuring the height increment of sedimentation within the period of time using in-situ monitoring. Additionally, remote sensing methods, including satellite and drone-based imagery, are used to detect sediment accumulation over the areas.

2.4 Mangrove Assisted Colonization

Mangrove-assisted colonization is an effort to accelerate the natural colonization by planting mangroves in suitable habitats. This process is conducted after the sedimentation area has been sufficiently developed for the formation of mangrove ecosystems. A study mangrove zonation in Mimika began with low tidal zones, defined as areas ≤0.5 above mean sea level (Setyadi et al., 2021). Assuming the lower Ajkwa Estuary has an elevation of ≤ 1.5 m, sedimentation within the range of 1 – 1.8 m is considered suitable for mangrove colonialization (Setyadi et al., 2021). The estimation is based on the maximum tidal range in Mimika Regency, measured at 3.6 m. The estuary structures, consisting of E-groins and Geotubes, are expected to accelerate sedimentation rates by 5–10 times. This acceleration would create suitable conditions for mangrove planting within one year. Once the area is prepared, the availability of mangrove seedlings (propagules) becomes a critical factor for the success of mangrove planting. A total of 1,250,000 propagules of Rhizophora mucronata (Black Mangrove) were planted across 500 hectares of the estuary structure, with each seedling spaced approximately 1 meter apart. The planting density was designed to mimic natural dispersal patterns while optimizing survival and growth rates. The plantation involving stakeholder and local community.

2.5 Mangrove monitoring

Monitoring of the planted mangroves in the lower Ajkwa Estuary is conducted routinely. This includes measuring the growth rate by assessing trunk diameter, the number of leaf pairs, the number of branches, and the height of the mangroves. Additionally, the natural succession of mangroves in and around the planting area is evaluated. The method used for these assessments is based on the internal standard operating procedure related to mangrove growth rate within the 10 X 10 m plot.

The structure consists of Geotubes and Bamboo-based E-groins. Geotubes are large, tube-shaped bags made of porous, weather-resistant geotextiles filled with sand slurry, forming artificial coastal structures. Each Geotube measures 25 m in length, 5 m in width, and 2 m in height, packed with sand sediments. These Geotubes are installed in series of 8, covering a total length of 200 m followed by a 50 m void space before another set of Geotubes, as illustrated in Figure 2.

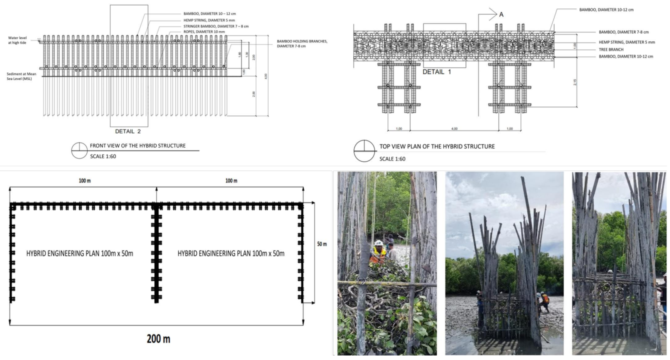

Figure 3: E-Groin design construction plan in Ajkwa Estuary

2.6 Bulk Density assessment

Soil bulk density was measured based on the procedures outlined in SNI 7724:2019 – Pengukuran dan Perhitungan Cadangan Karbon: Pengukuran Lapangan untuk Penilaian Cadangan Karbon Hutan (Measurement and Calculation of Carbon Stocks – Field Measurements for Forest Carbon Stock Assessment). Sampling was conducted in a 5 × 5 m plot, with five sampling points selected—one at each corner and one at the centre. At each point, soil was collected from a depth of 0–30 cm using a metal core sampler. Surface litter was gently removed, and the core was vertically inserted into the soil with minimal disturbance. The soil was trimmed flush with the top and bottom of the core, extracted, and placed into labelled containers. In the laboratory, each sample was oven-dried at 105°C for 24 hours, cooled in a desiccator, and weighed. Bulk density (g/cm^3) was calculated by dividing the dry weight of the soil by the volume of the core.

2.7 Calculation and projection of aboveground carbon stock for mangrove ecosystems

Mangrove-assisted colonization, following the construction of estuary structures and subsequent mangrove planting, is calculated for carbon sequestration potential. Prior to these calculations, monitoring and evaluation of the assisted colonization process are conducted. The measurement and calculation of carbon stocks for existing and predicted mangrove plantations follow the Indonesian National Standard SNI 7724:2019 "Measurement and Calculation of Carbon Stocks – Field Measurements for Forest Carbon Stock Assessment" and biomass calculations use which is calculated using the allometric equation per species (Kauffman and Donato, 2012). Of the five carbon pools, two were calculated based in the aboveground biomass of the mangroves. The calculation of carbon from biomass uses the following equation (1).

$$Cb = B \text{ x } \%\, C \text{ organic} \qquad (1)$$

Where:

Cb: Carbon content of biomass (kg)

B : Total biomass (kg)

%C: Percentage of carbon content (generally 0.47 or as determined by laboratory analysis)

The prediction of biomass and the mangrove plantation roadmap is estimated using the corelation between carbon stock and the Dimeter Breast Height (DBH) of mangroves (Rhizophora mucronata.) developed by Kauffman and Donato, 2012. The model estimates aboveground carbon stocks through total biomass using a logistic growth model expressed as equation (2) (Kauffman and Donato, 2012).

$$y = 0{,}1709xDBH^{2{,}516}$$
(2)

Where:

y: Carbon stock of Rhizophora mucronata. (ton C/ha)

x: DBH of mangrove trees (cm)

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DBH of mangrove trees projection until 2032 was calculated using theoretical average growth rate of mangrove species Rhizophora mucronate 1.0–1.8 cm/year (Tamin et al., 2011)

3. RESULTS AND DISCUSSIONS

3.1 The Effect of Estuary Structure on Sedimentation Rate and Sedimentation Level

The construction of estuary structures in the Ajkwa estuary is expected to enhance natural sedimentation rates, thereby accelerating the formation of habitats suitable for mangrove colonization in controlled areas. While this process occurs naturally over time, the implementation of nature-based nearshore structures can significantly increase the total area and decrease the timescale required for sediment deposition. These structures create protected environments where mangrove propagules are more likely to settle and survive, thereby facilitating mangrove colonization and minimizing the need for extensive planting efforts. The estuary structure is constructed in a shallow area formed by sediment deposition from the Ajkwa River, with sediments predominantly consisting of sand and silt. The Geotube structures is approximately 2,700 meters in length, while bamboo-based E-groin structures extend to about 2,800 meters (Figure 4).

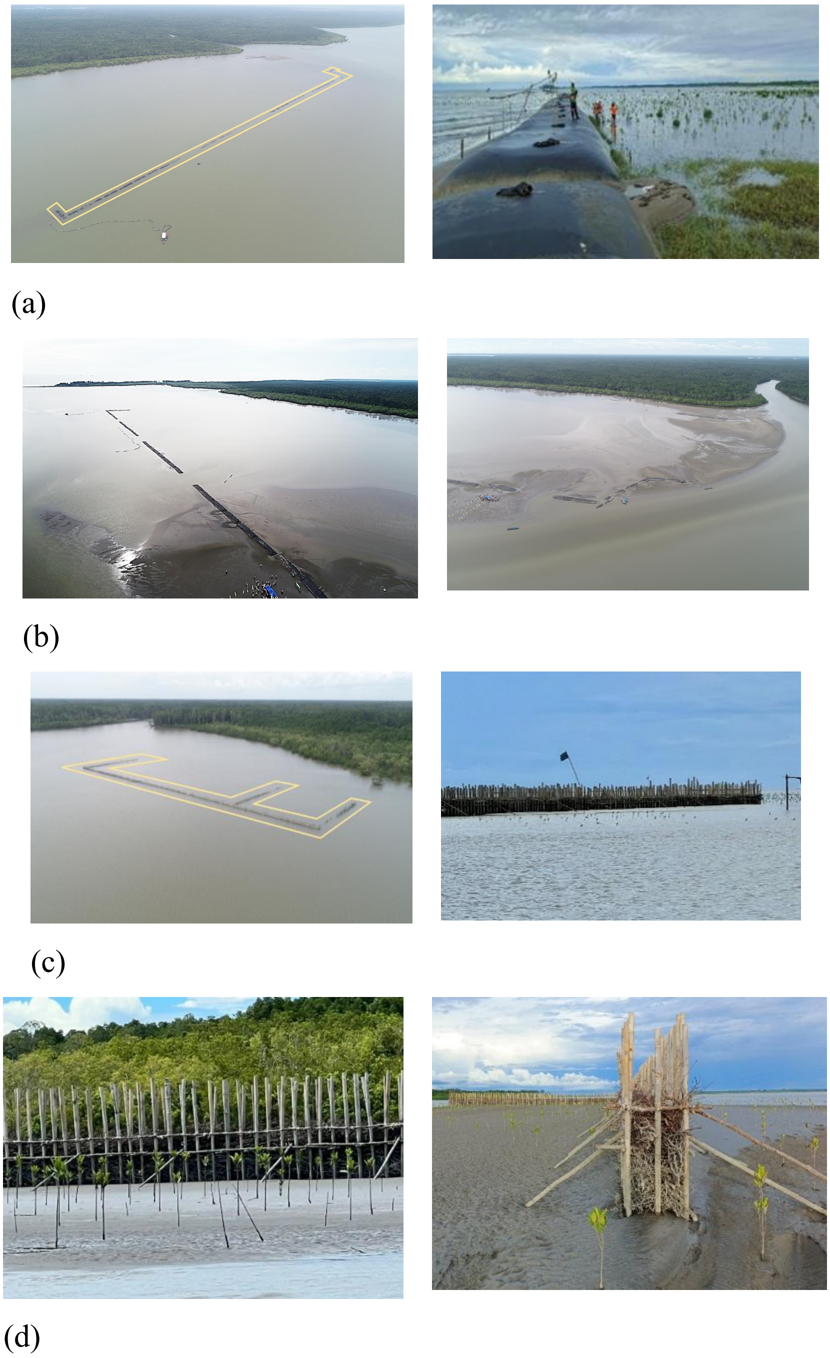

Figure 4: Estuary structures built in Ajkwa Estuary: (a) Geotube construction; (b) sedimentation occurred in the area of Geotube; (c) E-groin construction: (d) sedimentation occurred in the area of E-groin

From the monitoring results after 14 months the construction established, it is observed that sedimentation rates in the Ajkwa River Estuary have increased significantly, particularly in areas where estuary structures have been constructed. This increase in sedimentation is evident from the rising levels of sediment accumulation around the estuary structures, both behind and in front of the structures. Presented in the Figure 5(a) the sedimentation levels varied between 0.3-0.74 m/year, confirming the effectiveness of Geotube and E-groin structures as sediment traps. Other factors influencing sedimentation include tidal re-suspension, elevation, and aerial root structures (Setyadi et al., 2021a).

The high sedimentation at the Ajkwa River Estuary has led to the formation of raised land, some of which is now covered with new mangrove colonies due to natural succession and planting efforts. Changes in land use in the coastal area of the Ajkwa River Estuary are visible in satellite imagery, showing a decrease in mangrove areas that have converted to non-mangrove areas in the upper estuary, narrowing of the river estuary in the middle estuary, and an increase in raised land and young mangrove colonies in the lower estuary.

In the Ajkwa estuary ecosystem, mangrove area decreased by 158.1 hectares from 2023 to 2024, primarily in the mid estuary. Satellite image

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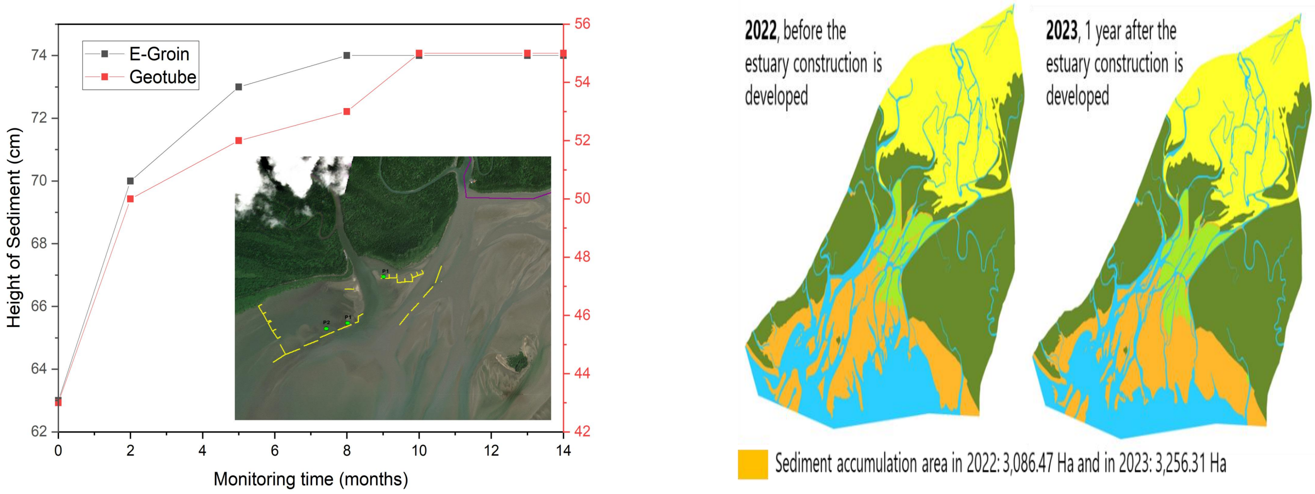
analysis also indicates that the river estuary has narrowed due to sedimentation from the upper reaches of the Ajkwa River. Between 2023 and 2024, water bodies (river waters, river estuaries, and sea) have narrowed by 378.9 hectares, mostly at the mouths of rivers and sea waters. This narrowing has led to siltation, reducing water depth and forming raised land in the lower estuary. Satellite image analysis identified two types of raised land: non-vegetated and vegetated, the latter being areas of young mangrove colonies. These young mangrove colonies are predominantly found at the river mouth, where the influence of the Ajkwa River's water flow is strong. Non-vegetated raised land is more common in open sea waters, influenced by coastal dynamics such as tides, currents, winds, and waves in the Ajkwa River Estuary. The newly developed land in the Ajkwa Estuary was approximately 3,086.47 Ha, increasing by 5.5% following the construction of estuary structures illustrated in Figure 5b.



(a)

(b)

Figure 5: (a) Height of sediment monitored in the area of E-Groin (Black colour) and Geotube (Red colour) and (b) Sedimentation accumulation area profile of Ajkwa Estuary

Stuaries are among the most productive ecosystems, generating an abundance of organic matter—far exceeding comparable areas of forest, grassland, or agriculture—making them pivotal centres of ecosystem resources and services (Agung et al., 2020). Enhanced sedimentation rates in estuarine areas can influence amenity values, increase suspended sediments in the water column, and affect deposition on tidal flats, with cascading impacts on the plants and animals that inhabit these areas, including fish and shorebirds. Nevertheless, sedimentation acceleration strategies can be employed to manage sediment distribution, localize sedimentation processes, and enhance ecosystem services in targeted areas. As summarized in Table 1, sedimentation acceleration methods have been applied in various regions to mitigate elevation loss due to relative sea-level rise, protect land, and facilitate habitat rehabilitation. Techniques include permeable wooden structures, geosynthetic bags, sediment control structures, hybrid engineering, and semi-submersible geotextile tubes, achieving varying sedimentation rates. The highest sedimentation rate of 0.7 m/year was achieved using permeable structures made from bamboo, brushwood, and branches.

Table 1: Sedimentation acceleration strategies conducted in Indonesia

Location	Methods	Sedimentation	Ref.
River deltas and estuaries	Sedimentation structures/ permeable wooden structures	20–85 mm/yr	(Cox et al., 2022a)
Demak Regency, Central Java, Indonesia	Permeable Structure (Structures made from bamboo, brushwood, branches, or other materials that can be found around the area)	The sedimentation process around the structures in the third scenario occurs with sedimentation rates at around 0.15 – 0.7 m/year	(Iqbal et al., 2021)
Banyuurip Mangrove Center, Ujung Pangkah, Gresik, Indonesia	Geosynthetic Bags	Sedimentation rates (mg.cm-^{2}.day^{-1}): 305,01 ± 124,53	(Sartimbul et al., 2021)
Jelitik Estuary, Sungailiat - Bangka Regency, Indonesia	Sediment control structure	4.44 cm/year	(Wibowo et al., 2020)
Sayung Regency, Demak, Central Java, Indonesia	Hybrid engineering	(from 0.2 cm/year, to 0.43 cm/year)	(Gemilang et al., 2018)
Pamekasan, Madura, Indonesia	Semi-submersible geotextile tubes	The accretion reached 0.4 meters behind the geotubes (observed after one year)	(Nugroho et al., 2021)
Ajkwa Estuary Mimika Regency, Central Papua Province, Indonesia	Combination of Geotube and Bamboo E-Groin structures	Sedimentation levels varied between 0.3-0.74 m/year	this study

identified four primary sedimentation-enhancing strategies (SES): river sediment diversions, tidal flooding, sedimentation structures, and vegetation planting (Cox et al., 2022). Historically in the 17th–20th century, permeable wooden structures were widely utilized to reduce water flow velocity and promote sediment deposition, achieving accretion rates of 20–85 mm/year (Cox et al., 2022b; Winterwerp et al., 2014). In this study, the hybrid engineering approach, combining Geotube and E-groin structures, effectively elevated shorelines to levels suitable for mangrove colonization . This strategy supports sustainable ecosystem development by enabling natural mangrove colonization and subsequent sediment capture. Over the long-term, it can enhance organic matter production, particularly carbon sequestration, contributing to

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climate mitigation goals.

3.2 Mangrove planting, monitoring, and evaluation

A total of 1,250,000 propagules of Rhizophora mucronata (commonly known as Black Mangrove) were planted across a 500-hectare area, as illustrated in Figure 6. Mangrove plant density varies at the planting site. Mangroves planted in front of the estuary structure have a lower density compared to those planted behind the estuary structure. The structure causes diffraction of currents or sea waves, resulting in mangroves planted in front being carried away or washed away. Conversely, mangroves behind the estuary structure are better protected from currents and waves, allowing them to grow properly. The density of mangrove revegetation ranges from 600 to 2500 individuals per hectare, with an average density of 1804 individuals per hectare.

The height of mangrove plants in revegetation areas varies according to the planting location. Mangroves planted in open areas tend to be taller than those in protected areas (behind estuary structure). The height of mangrove plants ranges from 24 to 118 cm. The diameter of mangrove trunks planted in open areas tends to be smaller than in protected areas (behind estuary structure). Observations show that the diameter of mangrove ranges from 6.2 to 25.6 mm, with the number of mangrove leaves ranging from 2 to 66 pairs and the number of planted mangrove branches ranging from 1 to 23. The trends observed in the number of leaves, branches, and diameter are consistent.

In mangrove planting activities, several considerations need to be made, especially related to changes in sediment movement patterns/dynamics in the Ajkwa Estuary area, which greatly affect the growth of planted mangroves. The dynamics of the sediment will cover the trunks of propagules and mangrove seedlings that have grown. Mangrove seedlings will not grow if the entire plant is buried in sediment. Additionally, mangrove plants buried in sediment will adapt their morphology as they grow and develop. Tidal currents or sea waves significantly impact the growth and development of mangroves planted in the Ajkwa Estuary. Tidal currents or high sea waves can sweep away planted mangrove seedlings or uproot plants entirely. In the estuary structure area, particularly the area in front of the construction, the waves are larger and higher, which results in fewer plant seedlings in front of the structure compared to mangroves behind the construction.

Figure 6: Mangrove Monitoring

A study reported that Rhizophora mucronata in designated ponds exhibited growth rates of approximately 0.012 cm/month in stem diameter and 0.38 cm/month in height (Hastuti and Budihastuti, 2016). Based on the analysis, observed an average growth rate of Rhizophora sp. at 0.016 cm/month in diameter and 1.44 cm/month in height (Dewiyanti et al., 2023). Meanwhile, the study stated that the growth in diameter of Rhizophora mucronata was 1.0–1.8 cm/year, and this assumption was used to calculate carbon projections in the Ajkwa Estuary, namely with a diameter growth of 1.4 cm/year (Tamin et al., 2011).

Mangrove seedlings adapt their morphology based on environmental conditions, particularly in response to water dynamics. In protected areas with low currents and minimal wave action, seedlings take longer to develop their root systems. Conversely, in open areas with strong currents and high waves, seedlings adapt by growing roots more rapidly to enhance stability. In the mangrove revegetation process at the Ajkwa Estuary, Rhizophora mucronata propagules are commonly used due to their availability and ease of planting. However, natural succession in some areas has led to the growth of other mangrove species, such as Sonneratia sp. Given these ecological dynamics, it is necessary to incorporate a variety of mangrove species beyond Rhizophora mucronata to enhance biodiversity and resilience. While Rhizophora mucronata is preferred for revegetation due to its abundant propagules and straightforward planting process, field observations indicate that naturally growing seedlings of this species are rarely found in the Ajkwa Estuary.

Several environmental parameters are known to influence mangrove seedling growth. While factors such as soil organic carbon, soil fraction, nitrogen (N total), potassium (K), dissolved oxygen (DO), pH and temperature have been shown to have limited impact on the growth of Rhizophora sp., however, phosphorus and salinity significantly contribute to growth (Dewiyanti et al., 2023). This study found that magnesium, pH, sodium and organic carbon accounted for 53% of mangrove growth in terms of height (Akpovwovwo, 2020). Studies conducted emphasized the importance of water quality, particularly salinity and pH, in supporting mangrove seedling growth (Hastuti and Budihastuti, 2016). On the other hand, another study conducted in the Bintuni riverbank area, Bintuni Bay, West Papua, Indonesia, found that mangroves in general can grow in such extreme and unbalanced environmental niches (Sraun et al., 2023).

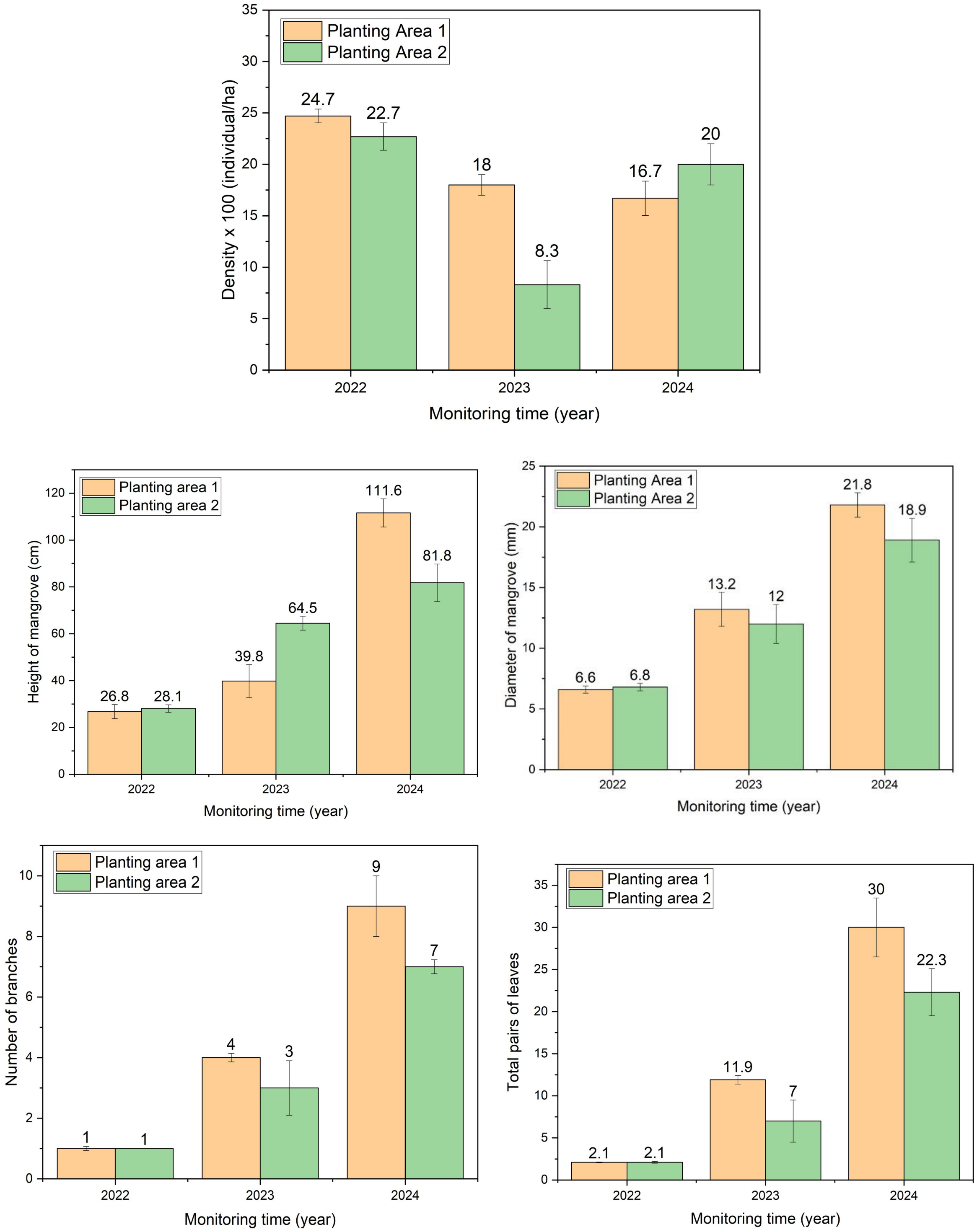


Figure 7: Mangrove Monitoring Statistics (density, height, diameter, number of branch and number of leaves)

The Ajkwa Estuary is a critical coastal ecosystem that is shaped by both natural and anthropogenic factors. The sediment composition within this estuary primarily consists of fine materials, including mud, sand, and silt, with finer silts and clays dominating areas further inland and closer to mangrove forests. The sedimentation process in this estuary is heavily influenced by the discharge from the Ajkwa River, which transports large quantities of suspended sediments. Additionally, tidal action plays a significant role in transporting sediments, with deposits being left in the estuary's lower-energy areas, including mudflats and wetlands. The rapid sedimentation assisted by the estuary structures creates suitable areas of mangroves colonization with 99% of survival rate in the area of 500 hectares.

3.3 Bulk density assessment in corelation to the ecosystem ability in water conservation

Bulk density is a critical soil physical property that strongly influences the ability of an ecosystem to conserve water. It represents the mass of dry soil per unit volume, including the pore spaces, and serves as an indicator of soil compaction. Bulk density affects soil water retention, which is important for plant growth and water conserving. High bulk density values are typically associated with compacted soils that have low porosity, which limits the infiltration of water and reduces the soil's capacity to retain moisture. In contrast, soils with low bulk density have a more porous structure, allowing for greater water infiltration, higher water-holding capacity in plants (Gubiani et al., 2024; Kool et al., 2019; Talat et al., 2025).

Soil bulk density measured in three consecutive years in the mangrove planting area were depicted in Figure 8. The value is decreasing from 1.473 g/cm3 in 2022 into 1.369 g/cm3 in 2024. After rapid sedimentation has been managed, new areas has naturally formed in coastal zones. Newly accreted sediments typically exhibit high soil density with high compaction, low porosity, and limited organic content, which result in poor infiltration and minimal water retention. This is demonstrated in a number of studies where compaction has a significant role in reducing porosity, particularly in deep-water sedimentary processes. As a result of the mechanical and chemical phases of the compaction process, porosity gradually decreases (Han and Batzle, 2005;

Worden and Utley, 2022). The mangrove-assisted colonization conducted after the land formation becomes an ecologically appropriate approach to improve soil conditions, particularly by lowering soil bulk density and enhancing water conservation capacity. Mangroves growth contributes to the reduction of soil bulk density through several interconnected biological and physical processes. The root systems, particularly the fine roots concentrated in the upper soil layers, physically penetrate and loosen compacted soil, increasing pore space and reducing soil compaction. As roots grow and die, they leave behind channels that enhance soil porosity and facilitate water infiltration and gas exchange. These processes contribute to soil aggregation and the incorporation of organic material, both of which lower soil bulk density that reflected the same in the study (Ola et al., 2018, 2019). Thus, implementing mangrove-assisted colonization following land formation provides not only ecological restoration benefits but also contributes to integrated water conservation strategies in coastal environments.

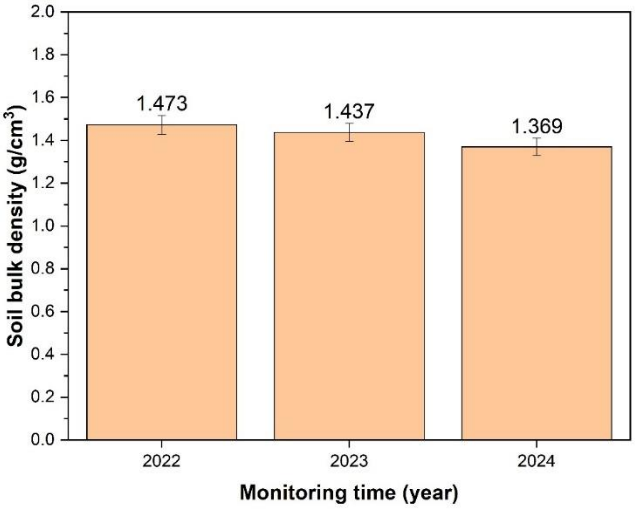
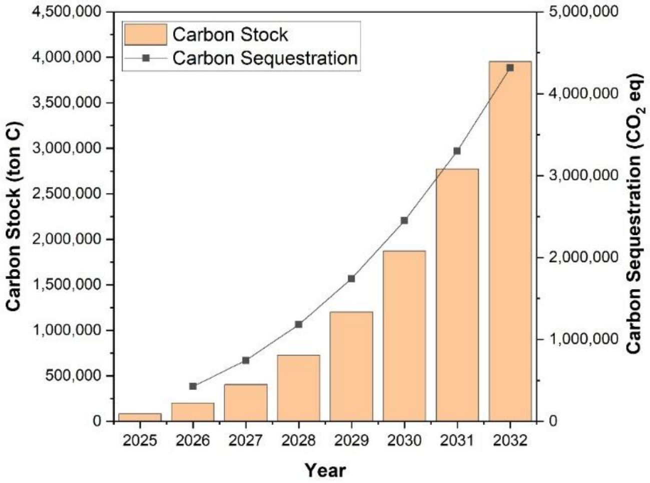


Figure 8: Soil bulk density trends

3.4 Carbon stock aboveground calculation and projection of the mangrove-assisted colonization plan (2025-2032)

The carbon stock capacity of mangroves planted in the sedimentation area, formed after the construction of the Estuary Structure, was assessed by calculating the aboveground carbon stock using an allometric equation that correlates biomass to carbon stock. The total biomass was calculated using the equation from the Indonesian National Standard (SNI 7724:2019) on the Measurement and Calculation of Carbon Stocks, which uses DBH (Diameter at Breast Height) as a variable. The most reliable method for measuring the net primary productivity of mangroves is through the calculation of the aboveground biomass accumulation (Alongi, 2012). For this study, only aboveground biomass was considered to assess the impact of the mangrove-assisted colonization.

The projection of aboveground carbon stock calculation has also been conducted based on the mangrove planting scenario roadmap extending until 2032 with an assumed diameter growth of 1.4 cm/year. The projection was estimated based on the DBH of the Rhizopora mucronata model approach. The carbon stock values for 2025, along with the projection until 2032 are provided in Figure 9. In 2025, the carbon stock was calculated yielding a value of 165,83 tons C/Ha. For an area of 500 ha, this resulted in a total carbon stock of 82,913 tons C, equivalent to an absorption of 303 tons of CO2. The carbon stock in 2026-2032 is expected to increase twice, as the roadmap includes an additional 500 ha of planting. This expansion will continue at a steady pace of 500 ha annually until 2032. By 2032, the mangrove-assisted colonization project will cover a total of 5,000 ha within the sedimentation zone of the Estuary Structure, generating 3,953,567 tons of C equivalent to the absorption of 14,470,054 tons of CO2.



Year	2025	2026	2027	2028	2029	2030	2031	2032
Carbon Stock (ton C)	82,913	199,287	402,753	725,187	1,201,807	1,870,889	2,773,549	3,953,567
Carbon Sequestration (ton CO2 eq)		425,929	744,686	1,180,110	1,744,429	2,448,840	3,303,735	4,318,865

Figure 9: Graphic projection of aboveground carbon stock and carbon sequestration for the mangrove-assisted colonization plan (2025-2032)

The projected carbon stock data in the chart indicates a significant upward trend in both stored carbon (in ton C) and the carbon sequestration poentials equivalent in CO_2 (in ton CO_2 eq) from 2025 to 2032. These values reflect the expansion of mangrove plantations on newly formed sediment beds—created by the implementation of Geo-tube and E-groin technologies—within the Ajkwa Estuary in Mimika, Papua. Over time, as the mangrove forests the data suggest an accelerated capacity to capture and store more carbon each year (Goslee et al., 2014)

From the chart, the total carbon stock in 2025 starts at approximately 82,913 tons C and rises steeply to around 3,953,567 tons C by 2032 with carbon sequestration ability from 425,929 tons CO2 equivalent in 2026 to ten folds in 2032. This trend reflects the growing success of sediment stabilization—achieved through Geo-tube and E-groin technologies—that facilitates mangrove establishment on newly formed sediment beds in the Ajkwa Estuary. The data suggest a near fifty-fold expansion in carbon stored within less than a decade, marking a significant potential for long-term carbon sequestration in this coastal environment.

When compared with published research, these figures align with the widely acknowledged high carbon storage capacity of mangroves. The analysis documented that mangroves can store up to 1,023 $t\,C\,ha^{-1}$ (above- and below-ground), making them among the most carbon-rich forests in the tropics (Donato et al., 2011). Further analysis emphasized that Indonesian mangroves hold an estimated 3.14 ± 0.49 Pg C, highlighting Indonesia's critical position in global climate mitigation efforts (Murdiyarso et al., 2015). The magnitude of carbon accumulation shown in this projection is further supported by studies like which highlight the enhanced carbon burial capacity of coastal "blue carbon" systems under anoxic soil conditions (Mcleod et al., 2011; and Alongi, 2012).

Beyond the large-scale carbon gains, the engineered sediment management in Ajkwa Estuary contributes to rapid mangrove growth and stable soil conditions—key factors in boosting carbon capture. noted that integrating ecological engineering approaches in tropical coastlines can accelerate coastal resilience, while underlined how proper hydrological and sediment management directly improve mangrove restoration outcomes (McLeod et al., 2011; Lewis, 2005). As a result, the newly formed sediment habitats in Ajkwa Estuary create an ideal environment for fast-growing mangrove stands that can store carbon both above and below ground, mirroring the positive outcomes observed in other regions (Huxham et al., 2010; Primavera, 2005). Ultimately, by combining modern sediment capture techniques and robust ecological management, the Ajkwa Estuary stands as a testament to how innovative coastal engineering, aligned with scientific insights, can yield substantial carbon sequestration gains and boost coastal resilience.

A previous study on the Mangrove Forest in Karimunting Bay, West Kalimantan, Indonesia, reported an increase in carbon stock of over 9,000,000 tons of C across a 138-ha area over a 10-year period. This forest was dominated by Avicennia marina, with smaller numbers of Bruguiera gymnorrhiza and Rhizophora stylosa. This suggests that carbon stock values could be much higher in magnitude over time as mangrove biomass grows, leading to an increase in DBH (Dinilhuda et al., 2020). According to the researchers, reported aboveground carbon stock values up to 58 tons C/ha and belowground carbon values of 81 tons C/ha for mangrove ecosystems dominated by Avicennia marina on the southwest coast of India (Harishma et al., 2020). This study highlights the significant potential of mangrove ecosystems, not only due to vegetation but also due to the carbon-rich soils and sediments underneath. Several researchers emphasized that belowground biomass in mangrove ecosystems tends to be much higher in comparison to aboveground biomass (Alongi, 2012). This results in a significantly greater carbon stock belowground, which positions mangrove ecosystems as among the most productive biogeochemical ecosystems globally, playing a vital role in carbon sequestration (Barbier et al., 2011). High belowground biomass is attributed to the accumulation of root biomass in combination with rich soils, as well as saline water conditions that triggers mangroves to invest more fixed carbon into root growth to maximize water absorption (Alongi, 2012).

From a carbon capture and storage (CCS) perspective, mangroves play a critical role as “blue carbon” ecosystems. Their dense root systems and rapid biomass accumulation enable them to sequester carbon at rates often higher than terrestrial forests. Moreover, the submerged and water-logged conditions of mangrove soils reduce the decomposition rate of organic matter, leading to prolonged carbon storage. This phenomenon is confirmed in many studies indicating that mature mangrove forests can store substantial amounts of carbon in both above-ground (e.g., trunks, branches, leaves) and below-ground (e.g., roots, soil) biomass. Over time, the layers of organic-rich sediment build up, thereby contributing to a long-term carbon sink.

CONCLUSION

The development of estuary structures at Ajkwa Estuary, Mimika Regency, Central Papua Province, Indonesia, consisting of 2,700 meters of Geotube structures and a 2,800-meter bamboo-based E-groins structure, has successfully increased the sedimentation level by up to 0.75 m. This newly formed sedimentation area has proven effective in creating additional land for the implementation of mangrove-assisted colonization. As part of the management strategy for the sedimentation area, this approach helps localize sedimentation within the designated site, enhancing the habitat for mangrove colonialization. The mangrove planted in the designated location has the potential to become a new water conservation area and carbon inventory that can sequester CO2 from the atmosphere. The reduction in soil bulk density from 1.473 g/cm^3 in 2022 to 1.369 g/cm^3 in 2024 reflects a notable improvement in soil physical properties. This decrease suggests that the soil has become less compacted, with increased pore space that enhances water infiltration, root penetration, and microbial activity. Such changes are indicative of improving soil health and are likely influenced by ongoing ecological processes such as mangrove colonization. The decline in bulk density also supports the effectiveness of sediment management and ecological restoration efforts in promoting better water retention and overall soil quality in the estuarine environment. Meanwhile, the carbon sequestration capacity of the new mangrove ecosystem is overlooked from its aboveground carbon stock which has exceeded 82,000 tons C across the 500-ha area and is projected to achieve a minimum of 3.9×10^6 tons C by 2032 covering a 5,000-ha area with the ability of sequestering CO2 up to 4.3×10^6 tons CO2 equivalent confirming the potential of the nature based solution to be implemented in restoring the ecosystem.

AUTHOR'S CONTRIBUTION

Denny Nugroho Sugianto and Gesang Setyadi: Conceptualization, Supervision. Pratita Puradyatmika: Validation. Dessy Ariyanti: Methodology, Writing - Original Draft, Writing - Review & Editing. Muhammad Helmi and Pra Luber Agung Wibowo: Visualization, Data Curation. Rudhi Pribadi and Ario Damar: Resources. Benny Osta Nababan and Dadan Mulyana: Investigation. Daisy Radnawati, Roni Bawole, and Selvi Tebay: Formal analysis. Elinna Putri Handayani: Calculation and Writing - Original Draft. Sugio: Validation. Antoni Pramadarsah: Validation

CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial, or financial conflicts and declare the absence of conflicting interests with the funders.

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