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Carbon Capture Potential of Mangrove Ecosystem in Randuboto, Gresik Regency and Its Role in Overcoming Climate Change

Nurina Fitriani[*1], *Dio Alif Hutama*[1], *Dwi Ratri Mitha Isnadina*[1], *M Bagas Pramudya Pratama*[1], *Rafiga Khadijah*[1], *Trisnadi Widyaleksono Catur Putranto*[1]

[1]*Universitas Airlangga, Indonesia*

[*]Corresponding author: nurina.fitriani@fst.unair.ac.id

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Abstract. This study was conducted to examine the carbon capture potential of mangrove ecosystems, with a focus on the Randuboto Mangrove Conservation Area. Biomass was calculated using allometric equations, while carbon storage was estimated based on SNI 7724:2019. The total biomass in the area is 172.031 tons/ha, with carbon storage capacity of 80.855 tons/ha and CO_2 capture of 296.738 tons/ha. The sapling stratum, with higher mangrove density, stores more carbon and produces greater biomass than the mature tree stratum. *Avicennia marina* is the main contributor to biomass, carbon storage, and CO_2 absorption. Mangroves sequester carbon through slow decomposition in waterlogged soils, with tidal exchanges enhancing organic matter deposition. These ecosystems are essential for climate change mitigation, coastal protection, and biodiversity. Effective conservation strategies include preserving native species, strengthening legal frameworks, raising awareness, supporting community-based management, and restoring complementary ecosystems such as seagrass beds and salt marshes.

Keyword:
Blue Carbon, Carbon Capture, Coastal Ecosystem, Mangrove, Randuboto

1. Introduction

Mangrove ecosystems, often referred to as "blue carbon" systems, have gained significant attention in recent years due to their exceptional capacity to capture and store carbon, which contributes to mitigating the adverse effects of climate change [1]. These coastal forests, which thrive in the intertidal zones of tropical and subtropical regions, are characterized by their complex root systems, specialized salt-tolerant vegetation, and unique ability to grow in anoxic, waterlogged environments [2]. Mangroves sequester carbon through both their above-ground biomass—comprising trunks, branches, and leaves—and their extensive root systems, which trap sediment and organic matter, facilitating the burial of carbon in the soil [3]. This carbon is stored for long periods, sometimes centuries, due to the low oxygen levels in mangrove sediments that slow down microbial decomposition, allowing these ecosystems to act as highly efficient carbon sinks.

Indonesia, with its extensive coastline and abundant mangrove forests, is considered one of the most important countries in the global effort to conserve and restore mangrove ecosystems for carbon sequestration. In particular, the coastal regions of Gresik Regency in East Java, Indonesia, host the Randuboto Mangrove Conservation Area, which serves as a significant and representative example of Indonesia's mangrove ecosystems. The Randuboto Mangrove Conservation Area is home to a diverse range of mangrove species, including *Avicennia marina* (grey mangrove) and *Rhizophora mucronata* (red mangrove), both of which are known for their high carbon capture potential [4]. This region, therefore, presents an ideal location to study the carbon storage capabilities of mangroves and their role in climate change mitigation.

As climate change intensifies, with rising global temperatures, increasing frequency of extreme weather events, and accelerating sea-level rise, the need for effective strategies to mitigate these impacts has never been more urgent. Mangrove ecosystems, with their ability to store carbon, provide essential ecosystem services such as coastal protection, biodiversity support, and nutrient cycling, and have thus been recognized as a natural solution for reducing greenhouse gas emissions [5]. The protection and restoration of mangrove forests can enhance climate resilience for coastal communities, reduce the impacts of coastal erosion, and help sustain fisheries and local livelihoods. However, to fully realize their potential in addressing climate change, it is essential to quantify the carbon capture capacity of mangroves, assess their long-term storage potential, and understand the mechanisms that underlie their ability to sequester carbon.

Mangrove forests are among the most carbon-dense ecosystems on Earth, sequestering large amounts of carbon both in their living biomass and in the sediments beneath them [6]. Their high productivity, coupled with the unique environmental conditions in which they grow, enables mangroves to capture and store carbon at rates significantly higher than terrestrial forests [7]. Mangroves sequester carbon through photosynthesis, in which they convert atmospheric carbon dioxide into organic carbon, which is then stored in their tissues [8]. The carbon in mangrove biomass is stored in the form of cellulose, lignin, and other organic compounds in the leaves, stems, and roots of mangrove trees.

Mangroves have the ability to trap organic matter brought in by tidal flows, which includes detritus, plant material, and carbon-rich particles [9]. These sediments accumulate around the roots and the surrounding substrate, creating a carbon-rich environment. In particular, the waterlogged and anoxic conditions of mangrove soils slow the process of microbial decomposition, which is typically accelerated in oxygen-rich environments. As a result, organic carbon in the sediment can be stored for long periods, often hundreds or even thousands of years [10]. The combination of high biomass productivity, sediment accretion, and slow decomposition rates makes mangrove ecosystems highly efficient carbon sinks.

Avicennia marina and *Rhizophora mucronata* are the two most abundant mangrove species. Both species are known for their high carbon sequestration potential due to their significant biomass production and efficient root systems, which contribute to carbon storage in both above-ground and below-ground components. *Avicennia marina* is particularly well-suited to areas with high salinity and tidal inundation, thriving in coastal environments where other mangrove species may struggle [11]. This species has an extensive network of fine roots and pneumatophores that facilitate gas exchange in anoxic sediments, helping it survive in waterlogged conditions [12]. The above-ground biomass of *Avicennia marina* consists of a dense canopy of leaves and branches, which captures carbon through photosynthesis. In addition to that, its root system traps organic matter and sediments, further contributing to carbon burial in the soil.

Rhizophora mucronata, on the other hand, is a dominant species in mangrove forests along tropical and subtropical coasts. It is characterized by its stilt roots, which grow above the soil surface and anchor the tree in soft sediments [13]. These roots not only help stabilize the sediment but also facilitate the accumulation of organic material, which is eventually buried in the soil. *Rhizophora mucronata* is particularly effective at trapping carbon in the sediments due to its high root biomass, which accelerates sediment accretion. This species also has a high rate of biomass production, which contributes to both above-ground and below-ground carbon storage.

Together, these two species play a crucial role in carbon capture in the Randuboto Mangrove Conservation Area. The ability of *Avicennia marina* and *Rhizophora mucronata* to sequester carbon both in their living biomass and in the surrounding sediments makes them important contributors to the overall carbon storage capacity of the mangrove ecosystem. Quantifying the carbon storage of these species is essential for understanding their potential to mitigate climate change and support climate resilience in coastal regions.

The Randuboto Mangrove Conservation Area is located in Gresik Regency, East Java, Indonesia. This area is particularly valuable for studying carbon capture potential because of its relatively undisturbed condition, which allows for a more accurate assessment of the natural carbon storage capacity of mangrove ecosystems. Preliminary data suggests that the total carbon storage potential of the mangrove ecosystem in Randuboto may be substantial. Carbon sequestration is expected to occur not only in the living biomass of the trees but also in the sediment below, where organic carbon is trapped and stored over time. By quantifying the above ground biomass of *Avicennia marina* and *Rhizophora mucronata*, this study will provide an initial calculation to estimate the carbon storage capacity of the Randuboto Mangrove Conservation Area.

The results of this research are important for understanding the role of mangrove ecosystems in climate change mitigation, as well as for guiding conservation and restoration efforts. If the carbon storage capacity of the Randuboto mangroves is confirmed to be significant, it could serve as a model for other mangrove conservation initiatives in Indonesia and beyond. Furthermore, this research will help inform climate policy by providing data on the carbon sequestration potential of mangroves, which could be integrated into national and international carbon accounting frameworks.

This research was conducted to investigate the carbon capture potential of the mangrove ecosystem in Randuboto, Gresik Regency, and to examine its role in addressing climate change. The focus of this study is placed on the assessment of the carbon storage capacity of two dominant mangrove species—*Avicennia marina* and *Rhizophora mucronata*—through the quantification of their biomass. By evaluating the carbon storage potential of these mangrove species in this specific region, insights are intended to be provided into the contribution of mangroves to global carbon reduction efforts, and the importance of mangrove conservation and restoration as part of climate adaptation strategies is intended to be highlighted.

2. Methodology

2.1 Data Collection

Data collection was conducted in September-October 2024 within the range of Randuboto Mangrove Conservation Area, Gresik. Determination of vegetation observation locations was carried out randomly based on regional representation and land cover. The initial stage of determining sampling locations was to analyze satellite imagery to identify the area. The main information extracted from the satellite imagery is the type of land use cover, existence, location position, area, and density of vegetation. Based on the results of the satellite imagery analysis, the vegetation sampling location area was then determined. Sampling locations were also prioritized for lands that are potentially affected by disasters such as abrasion in Randuboto, Gresik. See Figure 1. Data collection was carried out using GPS (Global Positioning System), cameras, stationery, ropes, meters, measuring tapes, and flora data tallysheets. Collection of natural vegetation data was carried out by conducting field observations by recording the species found. It was done through the transect method in an area of 42.6 Ha. Plots were systematically established along the transect lines to record the presence, abundance, and characteristics of mangrove species within each plot [14].

T1	6°57'28.99"S	112°36'06.46"E
T2	6°57'28.69"S	112°36'07.06"E
T3	6°57'28.48"S	112°36'07.64"E
T4	6°57'28.19"S	112°36'08.24"E
T5	6°57'27.91"S	112°36'08.83"E
T6	6°57'27.62"S	112°36'09.42"E
T7	6°57'27.38"S	112°36'10.03"E
T8	6°57'27.10"S	112°36'1 0.62"E
T9	6°57'26.85"S	112°36'11.21"E
T10	6°57'26.59"S	112°36'11.82"E
T11	6°57'26.31"S	112°36'12.40"E
T12	6°57'26.06"S	112°36'13.00"E
T13	6°57'25.79"S	112°36'13.60"E
T14	6°57'25.52"S	112°36'14.19"E
T15	6°57'25.25"S	112°36'14.79"E
T16	6°57'25.00"S	112°36'15.38"E
T17	6°57'24.73"S	112°36'15.97"E

Figure 1. Map of the sampling location

2.2 Data Analysis

2.2.1 Biomass Calculation

The calculation of mangrove biomass in this study used the allometric equation method. The allometric equation is determined based on data from measuring the diameter of tree trunks at breast height (DBH). The DBH value is measured at a height of 1.3 meters from the ground surface. The allometric model formula of biomass for each species of mangrove in one hectare can be seen in Table 1.

Table 1. Biomass Allometric Model Formula

Species	Biomass Allometric Model
Avicennia marina	$B = 0.1848 \times K \times (DBH)^{2.3524}$ [15]
Rhizopora mucronate	$B = 0.1466 \times K \times (DBH)^{2.3136}$ [16]
Sonneratia alba	$B = 0.2064 \times K \times (DBH)^{2.34}$ [17]
Lumnitzera racemose	$B = 0.2064 \times K \times (DBH)^{2.34}$ [17]
Ceriops tagal	$B = 0.2064 \times K \times (DBH)^{2.34}$ [17]

Note:
B = Biomass (kg/Ha)
K = Density (individual/Ha)
DBH = Diameter at Breast Height (cm)

2.2.2 Carbon Storage Calculation

The calculation of carbon reserves was done by multiplying the biomass value by the carbon constant value of organic matter [18]. The National Standardization Agency in SNI 7724:2019 provides a carbon content percentage value of 47%. The formula for calculating mangrove carbon reserves is as follows.

$$Cb = B \times \%\ C\ Organik \quad (1)$$

$$Cb = B \times 0.47 \quad (2)$$

Note:
Cb : Carbon Storage (kg/Ha)
B : Biomass (kg/Ha)
% Organic C : Organic Carbon Percentage = 47% = 0.47

2.2.3 Carbon Capture Calculation

Calculation of carbon dioxide gas absorption was done using the formula referring to Amanda et al. (2021) [16] as follows.

$$CO_2\ Capture = Cb \times 3.67 \quad (3)$$

Note:
CO_2 Capture : CO_2 Gas Captured (kg/Ha)
Cb : Carbon Storage (kg/Ha)
3.67 : Equivalent Number of C to CO_2 (Atom Number: C = 12 and O = 16, $CO_2 = (1x12) + (2x16) = 44$; converted to Molecular Weight (Mr) of CO_2 divided by Atomic Weight (Ar) of C = 44 : 12 = 3.67)

3. Results

The results of biomass, carbon storage, and carbon capture calculations are shown in Table 2. The total biomass in the Randuboto Mangrove Conservation Area of 172.031 tons/ha can accommodate carbon storage of 80.855 tons/ha and capture CO_2 gas of 296.738 tons of CO_2/ha. Based on the stratum, mangroves in the sapling stratum as seen in **Figure 2** produce more biomass and accommodate a lot of carbon reserves and CO_2 absorption. This is because the density value of each type of mangrove in the sapling stratum is much greater than that of the mangrove tree stratum. *Avicennia marina* produces the highest biomass, carbon storage, and CO_2 capture values, accounting to 172.031 tons/ha, 80.855 tons/ha, and 296.738 tons/ha, respectively.

Table 2. Biomass, Carbon Storage, and Carbon Capture in Randuboto Mangrove Conservation Area

Stratum	Species	Density (individual/Ha)	Biomass (Ton/Ha)	Carbon Storage (Ton C/Ha)	CO_2 Capture (Ton CO_2/Ha)
Tree	*Avicennia marina*	319	57.423	26.989	99.050
Sapling	*Avicennia marina*	6,475	106.483	50.047	183.673
	Rhizophora mucronata	400	8.125	3.819	14.015
	Total		**172.031**	**80.855**	**296.738**


Figure 2. Mangrove saplings

4. Discussion

4.1 The Influence of Mangrove Biomass on Carbon Capture

Mangrove biomass refers to the total mass of living biological material within mangrove ecosystems, including the roots, trunks, branches, and leaves of mangrove trees, as well as the associated understorey vegetation [19]. Mangroves are uniquely adapted to saline and waterlogged environments, where they thrive in intertidal zones along coastlines and estuaries. The biomass in mangrove ecosystems is an essential indicator of their ecological productivity and carbon storage capacity. These forests, as seen in Figure 3, are among the most carbon-dense ecosystems globally, capable of sequestering significant amounts of carbon in both above-ground and below-ground biomass. This characteristic makes mangroves critical in mitigating climate change by acting as natural carbon sinks.

The distribution and amount of mangrove biomass vary based on species composition, environmental conditions, and hydrological factors [20]. The dense network of roots not only contributes to the biomass but also plays a vital role in stabilizing sediments, reducing coastal erosion, and providing habitats for various aquatic and terrestrial species. Mangrove biomass supports nutrient cycling and enhances the productivity of adjacent ecosystems, such as coral reefs and seagrass beds, by acting as a source of organic matter [21]. Understanding and quantifying mangrove biomass is essential for conservation efforts, as it helps evaluate the health of mangrove ecosystems and their capacity to provide ecosystem services.

Figure 3. Mangrove ecosystem at the sampling site

The biomass of *Avicennia marina*, commonly known as the grey or white mangrove, is a significant component of mangrove ecosystems due to its widespread distribution in tropical and subtropical coastal regions. This species thrives in saline and intertidal environments, often dominating areas with high salinity and limited freshwater input [22]. *Avicennia marina* has a relatively high biomass production, with its above-ground biomass comprising leaves, branches, and trunks, while the below-ground biomass includes an extensive network of cable roots, pneumatophores, and fine roots [12]. The biomass of *Avicennia marina* varies depending on environmental factors such as soil salinity, nutrient availability, hydrology, and climatic conditions. Studies estimate that the above-ground biomass of *Avicennia marina* can range from 50 to 300 tons per hectare, with below-ground biomass accounting for 20–50% of the total biomass [23]. Its high root biomass makes it particularly effective in stabilizing coastal zones and supporting soil accretion processes.

The substantial biomass of *Avicennia marina*, quantified at 163.906 tons per hectare, underscores its pivotal role in coastal ecosystem dynamics and global carbon cycles. This significant biomass density highlights the species' capacity as an effective carbon sink, sequestering large amounts of atmospheric carbon dioxide and contributing to climate change mitigation efforts. The extensive above-ground and below-ground biomass enhances sediment stabilization and coastal resilience, reducing erosion and buffering against storm surges and sea-level rise [24]. Later, the organic matter contributed by *Avicennia marina*'s biomass supports nutrient cycling and sustains adjacent ecosystems, such as seagrass beds and coral reefs, by enriching them with essential nutrients [21]. These ecological services not only protect biodiversity but also support local livelihoods reliant on fisheries and coastal resources.

Other than *Avicennia marina*, *Rhizophora mucronata*, commonly referred to as the red mangrove, exhibits exceptional biomass production, positioning it as a keystone species in tropical and subtropical mangrove ecosystems [25]. Renowned for its complex stilt root system, this species stabilizes sediment in dynamic intertidal environments, where it also facilitates nutrient cycling and organic matter deposition. The above-ground biomass includes a dense network of branches, leaves, and a robust trunk, while the below-ground biomass features an extensive root system crucial for structural integrity and biochemical functions [12]. This dual biomass system enhances the capacity of *Rhizophora mucronata* to thrive under extreme environmental conditions, such as fluctuating salinity, tidal inundation, and low oxygen levels.

Empirical studies have demonstrated that *Rhizophora mucronata* achieves extraordinary biomass densities. The above-ground biomass often exceeds 400 tons per hectare in mature stands and below-ground biomass contributes up to 60% of the total, depending on site-specific factors such as hydrology, soil properties, and stand age [26]. The species' biomass is a significant global carbon reservoir. It sequesters vast quantities of carbon in its living tissues and the surrounding sediment, where carbon storage persists over geological timescales.

With a total biomass of 8.125 tons per hectare, *Rhizophora mucronata* demonstrates a unique ecological contribution despite its comparatively moderate biomass density. This species plays a critical role in sediment stabilization through its intricate stilt root systems, which enhance soil accretion and mitigate coastal erosion [27]. Its biomass supports essential nutrient cycling processes, providing organic inputs that sustain detrital food webs and nourish surrounding ecosystems such as mudflats and estuarine waters. The biomass of *Rhizophora mucronata* also contributes to maintaining habitat complexity, offering refuge and breeding grounds for a variety of aquatic and terrestrial organisms [28]. While the overall biomass is modest compared to other mangroves, its strategic distribution in highly dynamic coastal zones amplifies its impact, underscoring its importance in maintaining ecological balance and providing ecosystem services for coastal resilience and community well-being.

4.2 Carbon Storage in Support of Climate Resilience

Carbon storage in mangrove ecosystems plays a vital role in supporting climate resilience by mitigating the impacts of climate change and enhancing the adaptive capacity of coastal communities and ecosystems. Mangrove species such as *Avicennia marina* and *Rhizophora mucronata* act as natural carbon sinks, sequestering significant amounts of carbon dioxide in their biomass and the surrounding sediment. This stored carbon, often referred to as "blue carbon," reduces greenhouse gas concentrations in the atmosphere, helping to stabilize global temperatures [1].

The mechanism of carbon storage in mangroves is intricately linked to their unique ecological and physiological traits, which enable them to sequester and retain carbon effectively [29]. Above-ground biomass, including trunks, branches, and leaves, captures atmospheric carbon dioxide through photosynthesis, converting it into organic matter. Simultaneously, the extensive below-ground biomass, consisting of roots, pneumatophores, and fine root systems, plays a critical role in transferring carbon into the soil [12]. Mangroves excel in sediment trapping, where organic carbon from decomposed biomass and tidal inputs is buried and preserved in anoxic, waterlogged soils. These conditions slow down microbial decomposition, allowing carbon to remain stored for centuries, making mangroves some of the most efficient long-term carbon reservoirs [10].

This capacity to store carbon not only mitigates climate change but also supports climate resilience by enhancing ecosystem stability. The carbon-rich sediments and robust mangrove structure act as physical buffers, absorbing wave energy and reducing the impacts of storm surges and sea-level rise on coastal communities [24]. In line with the ability to provide physical buffers, by stabilizing sediments and maintaining water quality, mangroves indirectly support climate resilience in adjacent habitats such as coral reefs and seagrass meadows, which further protect coastlines and sustain marine biodiversity [30]. The dense root systems of mangroves stabilize shorelines, protect against storm surges, and reduce erosion [12], minimizing the vulnerability of human and ecological systems to extreme weather events.

Moreover, the organic matter provided by mangroves enriches adjacent ecosystems, sustaining biodiversity and enhancing fisheries productivity, which are crucial for local economies and food security. By integrating mangrove conservation and restoration into climate action plans, their carbon storage potential can be maximized, providing a nature-based solution to build resilience against climate change. Beyond carbon sequestration, mangroves' ability to store carbon for long periods—often centuries—buffers against climate variability and strengthens the resilience of coastal areas. Understanding and leveraging these mechanisms is critical for integrating mangrove ecosystems into broader strategies for climate adaptation and mitigation, ensuring their conservation delivers maximum ecological and socio-economic benefits [31].

The carbon storage capacity of the Randuboto Mangrove Conservation Area, quantified at an impressive 80.855 tons of carbon per hectare, exemplifies the critical role mangroves play in combating climate change and enhancing coastal resilience. This significant carbon reservoir highlights the value of conserving and restoring mangrove ecosystems as nature-based solutions to global environmental challenges. Preserving this carbon-rich habitat ensures the continued provision of essential ecosystem services, including biodiversity support, water quality improvement, and sustainable livelihoods for local communities [31]. The Randuboto Mangrove Conservation Area serves as a living model of how targeted conservation efforts can amplify the ecological and socio-economic benefits of mangrove ecosystems, reinforcing their indispensable role in fostering climate resilience.

4.3 Carbon Capture Mechanism in Mangrove Ecosystem

The carbon capture mechanism in mangrove and coastal areas is a multifaceted process that involves both biological and physical factors, allowing these ecosystems to store and sequester large amounts of carbon in a long-term, stable form [32]. Mangroves, with their dense root systems, play a critical role in trapping and storing carbon from the atmosphere and water. Through photosynthesis, mangrove trees convert atmospheric carbon dioxide (CO_2 gas) into organic carbon, which is then incorporated into their above-ground biomass (trunks, branches, and leaves) and below-ground biomass (roots and sediments) [8]. The ability of mangrove roots to grow in waterlogged, anoxic soils slows down the decomposition of organic matter, allowing carbon to be retained in the sediments for extended periods, often centuries. Coastal areas, including mudflats, seagrass meadows, and salt marshes, further enhance carbon capture through similar mechanisms, where the accumulation of organic matter in submerged sediments is protected from rapid decomposition due to low oxygen conditions [33]. Together, these ecosystems act as "blue carbon" systems, storing carbon in both living biomass and in sediments as seen in Figure 4, where it can remain locked away, mitigating climate change.

Mangrove ecosystems interact with the ocean in several key ways that enhance their carbon capture capacity, making them crucial components of coastal carbon sequestration. One of the primary interactions is through tidal exchange, where ocean waters carry nutrients, sediments, and organic matter into the mangrove habitat [35]. These tidal influxes contribute to the accumulation of organic material in the form of plant detritus, which, combined with mangrove biomass, promotes the trapping and storage of carbon in sediments. The frequent tidal flooding and draining of mangrove forests facilitate the deposition of carbon-rich organic material from the ocean, which is then retained in the anoxic soils beneath the mangrove roots [36]. These conditions significantly slow down the decomposition process, allowing carbon to be stored for long periods, often over centuries.

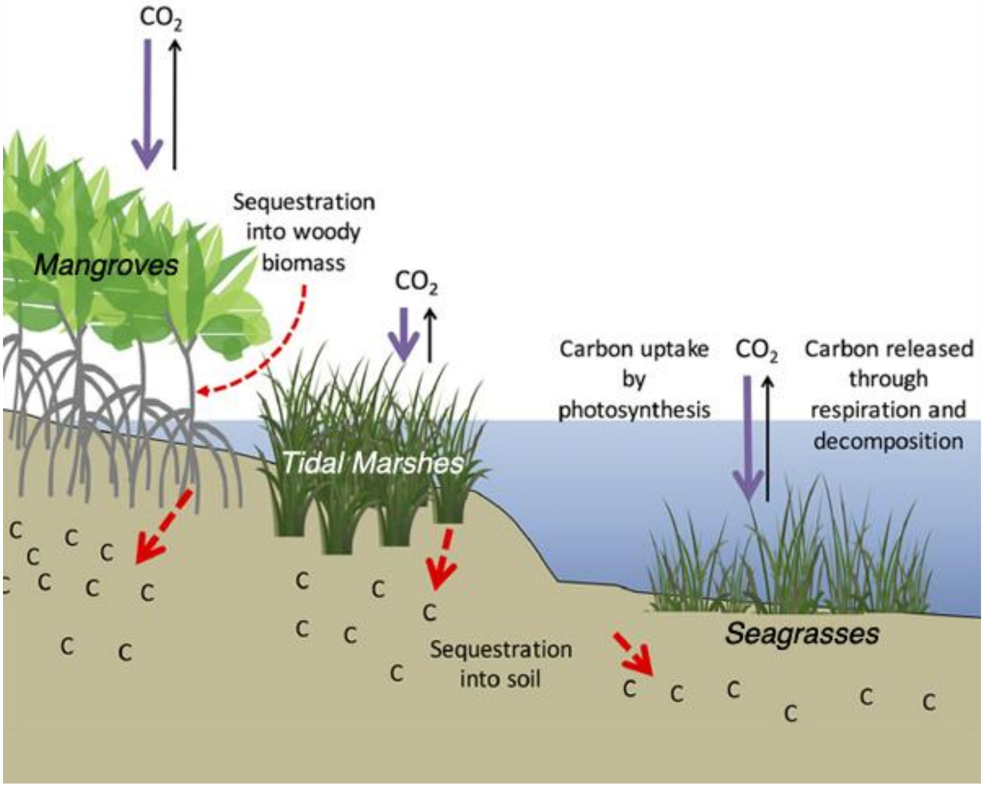

Figure 4. Pathways of carbon sequestration in mangrove ecosystem and its surroundings (Howard et al., 2017) [34]

Mangrove forests provide critical nursery habitats for a variety of marine species, fostering biodiversity and supporting oceanic food webs. As these species grow, they contribute organic matter back into the system, further enriching the carbon content of the mangrove sediments. The roots of mangroves, which are submerged during high tides, also interact directly with the marine environment by stabilizing the substrate, reducing erosion, and facilitating the growth of seagrasses and other coastal plants [27]. These interlinked habitats help create a continuous cycle of carbon capture by providing a complex ecosystem that supports both terrestrial and marine carbon storage mechanisms [37]. Through these interactions, mangroves not only act as a buffer between land and ocean but also as one of the most effective blue carbon ecosystems, enhancing global climate resilience.

The combined carbon capture capacity of *Avicennia marina* and *Rhizophora mucronate* in Randuboto Mangrove Conservation Area, totaling 296.738 tons of CO2 per hectare, underscores the critical role these mangrove species play in mitigating climate change. Through their extensive root systems, biomass production, and sediment stabilization, these mangroves effectively sequester carbon both in their living tissues and in the sediment beneath them, where it remains stored for extended periods [8]. This significant carbon capture capacity not only helps reduce atmospheric CO2 levels but also contributes to the resilience of coastal ecosystems, buffering against storm surges, sea-level rise, and coastal erosion.

By conserving and restoring habitats of *Avicennia marina* and *Rhizophora mucronata*, the potential of these ecosystems can be enhanced to continue providing vital ecosystem services, including carbon sequestration, coastal protection, and habitat support for biodiversity [31]. Their ability to store vast amounts of carbon makes them essential to both global climate change mitigation and local community resilience, particularly in coastal regions vulnerable to the impacts of climate change. The impressive carbon capture capacity of these mangrove species highlights the importance of integrating their conservation into broader climate action strategies.

4.4 Mangrove Conservation Strategies

Mangrove ecosystems play an essential role in carbon sequestration, coastal protection, and biodiversity preservation. Given their remarkable ability to capture and store carbon, they are crucial for mitigating climate change. The conservation of mangroves, particularly in areas like the Randuboto Mangrove Conservation Area, is critical to enhancing their ecosystem services and ensuring their sustainability. Several strategies for mangrove conservation can be outlined, focusing on enhancing their carbon capture capacity, protecting biodiversity, and supporting local resilience against climate change.

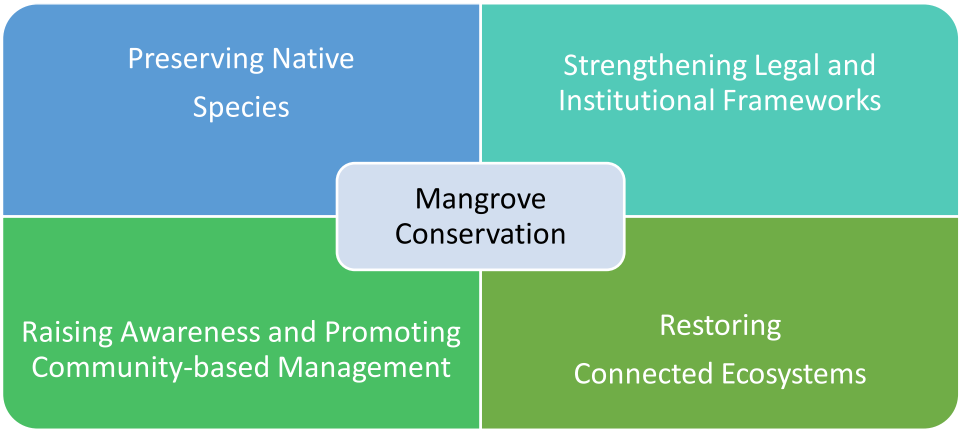

Figure 5. Feasible strategies in support of mangrove ecosystem conservation

The conservation of mangrove species, especially *Avicennia marina* and *Rhizophora mucronata*, is crucial because these species contribute significantly to carbon storage and carbon dioxide (CO_2) capture in coastal areas. In the Randuboto Mangrove Conservation Area, *Avicennia marina* was found to produce the highest biomass, with substantial carbon storage and CO_2 absorption rates. Therefore, conservation efforts should focus on preserving these species, ensuring their growth and regeneration, and maintaining their role in sequestering large amounts of carbon. Restoration efforts should be directed at degraded mangrove areas where these species have been diminished or lost. By replanting native mangrove species in suitable coastal zones, the natural balance of the ecosystem can be restored, enhancing its capacity for carbon sequestration and providing long-term stability to the area's biodiversity [31]. These restoration activities should involve local communities to ensure long-term stewardship and enhance the social acceptance of the projects.

Mangroves face significant threats from land-use changes, urban development, agriculture, and pollution. To protect these vital ecosystems, effective legal frameworks and institutional support must be established and enforced. Governments should implement policies that designate mangrove areas as protected zones, restricting activities that lead to their destruction, such as deforestation and land reclamation. This protection should also extend to buffer zones that can further safeguard mangrove forests from external threats.

In addition to legal protection, it is essential to raise awareness at both local and national levels about the importance of mangroves for climate change mitigation, coastal protection, and biodiversity. Public education campaigns and community-based management programs can empower local communities to actively participate in conservation efforts and act as guardians of these ecosystems [38]. Collaborative efforts between local authorities, environmental non-governmental organizations, and research institutions will be essential for effective mangrove conservation [39].

Mangroves provide numerous benefits, including resources like timber, firewood, and medicinal plants, which support the livelihoods of coastal communities. However, overexploitation of these resources can lead to the degradation of mangrove ecosystems. Sustainable management practices are crucial for balancing human needs with ecological health. One strategy is to implement community-based resource management programs, where local communities are involved in decision-making processes about the sustainable use of mangrove resources [40]. These programs can focus on promoting alternative livelihoods, such as eco-tourism, that provide economic benefits without compromising the health of mangrove ecosystems [41]. Moreover, the collection of resources should be regulated to prevent overharvesting, ensuring that mangrove forests can continue to provide ecosystem services, including carbon sequestration, water filtration, and habitat for biodiversity.

Mangroves do not function in isolation but are part of a larger coastal ecosystem that includes mudflats, seagrass meadows, and salt marshes [33]. These ecosystems, like mangroves, are important for carbon sequestration. The passage emphasizes how tidal exchange contributes to the carbon capture capacity of mangroves by bringing nutrients, sediments, and organic matter from the ocean into the mangrove habitat. This interaction helps accumulate carbon-rich organic material in the mangrove sediments, where it can be stored for centuries [33].

To maximize carbon capture, conservation strategies should include efforts to protect and restore other coastal ecosystems that complement mangroves. For instance, the restoration of seagrass beds and salt marshes can further enhance the carbon storage potential of coastal areas [42]. These ecosystems provide additional habitat for marine species, contribute organic matter, and enhance the overall biodiversity of the region. Furthermore, protecting the hydrological connectivity between mangrove forests and the ocean is essential. Proper management of riverine and coastal water systems, such as regulating freshwater flows and controlling pollution, ensures that mangroves continue to receive the necessary nutrients and sediment inputs from tidal exchanges [32].

Ongoing monitoring and research are crucial for understanding the dynamics of mangrove ecosystems and the effectiveness of conservation strategies. Regular assessments of mangrove biomass, carbon storage, and CO_2 absorption will help quantify the role of mangroves in mitigating climate change and provide valuable data for refining conservation approaches [42]. Research into the ecological functions of mangroves, their response to climate change, and the impacts of human activities on their health will further inform adaptive management strategies. It is also important to evaluate the long-term outcomes of restoration efforts to ensure that mangrove ecosystems continue to thrive and provide essential services over time.

5. Conclusion

The Randuboto Mangrove Conservation Area significantly contributes to carbon sequestration, storing 80.855 tons of carbon and capturing 296.738 tons of CO_2 per hectare. Sapling strata, particularly *Avicennia marina*, show the highest carbon storage potential. Mangroves retain carbon through slow decomposition in anoxic soils and tidal deposition of organic matter, while also supporting biodiversity and shielding coasts from erosion, storm surges, and sea-level rise. Conserving key species like *A. marina* and *Rhizophora mucronata* is vital for climate mitigation and coastal resilience. Effective protection strategies include preserving native species, strengthening legal and institutional frameworks, raising awareness, promoting community-based management, and restoring connected ecosystems such as seagrass beds and salt marshes.

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