Journal of Sustainability Science and Management
Volume 20 Number 3, March 2025: 506-527
eISSN: 2672-7226

ANALYSIS OF CARBON STOCK POTENTIAL IN MANGROVE ECOSYSTEMS, ECONOMIC VALUATION, AND ITS CONTRIBUTION TO EMISSION REDUCTION IN DEMAK DISTRICT

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http://doi.org/10.46754/jssm.2025.03.006
Received: 16 July 2024 Revised: 18 September 2024 Accepted: 7 October 2024 Published: 15 March 2025

Abstract: Mangrove ecosystems are vital for mitigating climate change due to their ability to sequester carbon. This study evaluates the carbon sequestration potential of mangroves in Demak District, Central Java, Indonesia and explores its implications for climate action and environmental policy. The research highlights that mangrove species such as *Rhizophora mucronata* and *Avicennia marina* are particularly effective at capturing carbon, with the former demonstrating the highest capacity among the species studied. The economic valuation of carbon sequestration underscores the significant financial benefits, particularly when integrating mangrove conservation into voluntary and regulated carbon markets. Despite the benefits of carbon sequestration, the district faces challenges in balancing its carbon emissions with sequestration, as current emissions exceed the sequestration capacity, hindering the achievement of net-zero emissions. However, the ongoing expansion of mangrove areas in the district offers a promising avenue to enhance carbon sequestration and improve the district's overall carbon balance. Accordingly, the findings underscore the need for strengthened mangrove restoration programs, legal protections, and integration of these efforts into broader climate policies, contributing to Indonesia's national and global sustainability goals.

Keywords: Mangrove structure, carbon stock, carbon economic value, carbon offset.

Introduction

Indonesia is an archipelago with a wealth of natural resources, one of which is the existence of mangrove forests. Within the mangrove ecosystem is a wealth of biodiversity consisting of flora and fauna. The flora in the mangrove ecosystem consists of trees (at least 47 species), shrubs (5 species), bamboo and grass (9 species), and parasites (2 species). In comparison, the fauna in the mangrove ecosystem consists of Gastropods (50 species), Bivalves (6 species), and Crustaceans (34 species) (Kusmana, 2011).

Mangrove forests are one of the three crucial ecosystems in coastal areas, in addition to coral reefs and seagrasses (Herr D, 2016). It is located in coastal areas consisting of groups of trees that can live in an environment with high salt content (Md Isa & Suratman, 2021). Various types of woody plants grow along sheltered tropical and subtropical coastlines with coastal landforms of anaerobic soil types. Notably, about 3 million hectares of mangrove forests grow along Indonesia's 95,000 km coastline. This represents

23% of the world's total mangrove ecosystems (Giri *et al*., 2011). In particular, Indonesia is home to the largest mangrove area in the world (18% to 23%), surpassing Brazil (1.3 million ha), and Nigeria (1.1 million ha). Mangroves can generally be found throughout the Indonesian archipelago. The largest mangroves are found in Indonesia's Papua, which has an area of about 1,350,600 ha (38%) (Wetlands International, 1999).

Mangroves are one of the potential parameters to be assessed from blue carbon ecosystems (Ali *et al*., 2022; Malik *et al.*, 2023). The role of mangroves in relation to blue carbon is more emphasised in the efforts of mangroves to utilise Carbon Dioxide (CO_2) for the photosynthesis process and store it in the form of biomass and sediment stocks as an effort to mitigate climate change (Taillardat *et al*., 2018). The existence of mangrove ecosystems provides physical, biological, and socio-economic benefits that contribute to the welfare of the surrounding community (Getzner & Islam, 2020; T.T., 2021). This includes protecting coastal areas (Nur & Hilmi, 2021) for feeding, spawning, and rearing various biota of coastal ecosystems and ecotourism (Nugroho *et al*., 2018).

The existence of global warming followed by climate change impacts rising sea levels, which causes the land area to decrease and the coastline to regress, often called Sea Level Rise (SLR) (Wacano *et al*., 2013). As a dynamic coastal ecosystem, mangroves have the adaptive capacity to respond to environmental changes from the impact of coastal hazards caused by SLR, such as erosion and waves (Marois & Mitsch, 2015). One form of mangrove adaptation is its ability to bind sediments from upstream and those carried by tides (Sidik, 2018). Furthermore, the mangrove ecosystem structure configuration creates an attractive force that can reduce wave energy and height (Spalding *et al*., 2014). Accordingly, this affects hydrodynamics and sediment deposition within the mangrove ecosystem, which can slow erosion and increase soil cohesion (Spalding *et al*., 2014).

Mangrove ecosystems are critical for carbon sequestration and provide significant economic and ecological benefits. However, they face severe underutilisation and global degradation, particularly in Southeast Asia, Brazil, and Nigeria. This response synthesises current knowledge on the carbon sequestration potential of mangroves, their economic valuation, and the challenges and solutions being implemented in various countries. In addition, mangroves are recognised for their exceptional ability to sequester carbon, with healthy mangrove forests storing significantly more carbon than degraded ones. For instance, healthy mangrove ecosystems can sequester up to 26.50 tonnes of carbon per hectare while damaged areas may only sequester around 4.37 tonnes per hectare (Sinaga *et al.*, 2023). This stark contrast highlights the significance of maintaining healthy mangrove ecosystems for carbon storage and mitigating climate change impacts. Globally, mangrove ecosystems can store between 79 MgC/ha and over 2,208 MgC/ha, depending on their health and environmental conditions (Kauffman & Bhomia, 2017).

The economic value of these carbon stocks is increasingly recognised, particularly with the emergence of carbon markets, which incentivise the conservation of these vital ecosystems (Indrayani *et al.*, 2021). In Southeast Asia, mangrove degradation is driven primarily by aquaculture expansion, urbanisation, and coastal development. Between 2000 and 2012, aquaculture was responsible for a significant portion of mangrove deforestation, although the conversion rate has decreased compared to previous decades (Richards & Friess, 2015). This region has the highest diversity of mangrove species and the greatest extent of global mangrove forests. Nonetheless, it also experiences the highest deforestation rates (Bryan-Brown *et al.*, 2020).

Countries like Indonesia and Myanmar have been identified as critical areas for further research and conservation due to their ongoing mangrove loss (Giri *et al.*, 2010; Hamiltonne & Casey, 2016). Brazil and Nigeria also face similar challenges. In Brazil, mangrove loss is exacerbated by industrial activities and urban expansion, particularly along the Amazon River (Goldberg *et al.*, 2020). Meanwhile, Nigeria's mangroves are threatened by oil spills, deforestation, and coastal erosion, which undermine their ecological functions and carbon storage capabilities (Dutta & Hossain, 2020). The socio-economic impacts of mangrove degradation in these regions are profound, affecting local fisheries, tourism, and the livelihoods of coastal communities (Feller *et al.*, 2017). Note that various carbon offset initiatives and coastal protection measures have been implemented to address these challenges. For instance, in Southeast Asia, community-based management approaches have been advocated to enhance mangrove conservation and restoration efforts (Friess *et al.*, 2016). These initiatives often involve local communities in decision-making, ensuring conservation strategies align with their socio-economic needs. In Brazil, the establishment of protected areas and restoration projects aims to recover lost mangrove habitats and enhance their carbon sequestration potential (Goldberg *et al.*, 2020).

Similarly, Nigeria has initiated programs to restore degraded mangrove ecosystems, sequestering carbon and providing critical coastal protection against storms and erosion (Feller *et al*., 2017; Dutta & Hossain, 2020). The socio-economic impacts of mangrove conservation are significant. Moreover, healthy mangrove ecosystems provide numerous services, including coastal protection, fisheries support, and tourism opportunities, with an estimated economic value exceeding USD900,000 per square km (Estrada & Soares, 2017). Conversely, the degradation of these ecosystems leads to increased vulnerability of coastal communities to climate change impacts. This includes flooding and erosion, exacerbating poverty, and reducing food security (Polidoro *et al*., 2010; Abino *et al*., 2013).

The largest contribution to global warming today is CO_2 and methane produced from various human activities that cause CO_2 gas to accumulate (IPCC, 2007). CO_2 gas is estimated to account for as much as ¾ of the greenhouse effect (Nwankwo *et al*., 2023). Reducing the release of CO_2 into the air is one of the efforts to reduce Greenhouse Gas (GHG) concentrations (emissions) in the atmosphere (Amru *et al*., 2023). In an effort to mitigate climate change, a forest ecosystem is needed as vegetation that can absorb CO_2 gas before it is released into the atmosphere, including mangrove ecosystems (Adame *et al*., 2021). Mangrove ecosystems have an essential role in reducing the GHG effect since they are able to reduce CO_2 through a sequestration mechanism, namely the absorption of carbon from the atmosphere and its storage in the form of biomass for a long time (Alongi, 2020; Rovai *et al*., 2021; Islam *et al*., 2023). Although it only covers 0.7% of the total area of tropical rainforest ecosystems, mangrove ecosystems have the highest carbon stocks of all existing forest ecosystems (Nyanga, 2020 & Aljenaid *et al*., 2022), with carbon stocks estimated at 69.8 ± 23.1 MgC/ha^{-1} (Alongi, 2020).

Due to their high carbon sequestration efficiency and long storage capacity, mangrove ecosystems are considered in international carbon stock accounting mechanisms (Rovai *et al*., 2021). The function of mangroves as carbon storage is closely related to efforts to fulfil Indonesia's GHG emission reduction target of 31.89% with its capabilities and 43.20% with foreign assistance (Enhanced Nationally Determined Contribution Republic of Indonesia, 2022).

Evaluation of the achievement of GHG emission reduction targets has been conducted by calculating Net Zero Emission (NZE) with a cluster approach both nationally and regionally. Mawardi *et al*. (2023) conducted a national evaluation of NZE, demonstrating that four out of 34 provinces in Indonesia (11.76%) had not yet reached the NZE condition. A more detailed evaluation was conducted by (Amru *et al*., 2023) with a research locus in Central Java Province. Research results (Amru *et al*., 2023) revealed that although Central Java Province has achieved NZE nationally, 10 cities or districts (28.57%) still have not achieved NZE. These incudes Tegal City, Pekalongan City, Magelang City, Salatiga City, Semarang City, Demak District, Kudus Regency, Klaten Regency, Sukoharjo Regency, and Surakarta Regency.

Indonesia, as one of the coastal countries, is projected to be able to organise carbon trading based on blue carbon. The potential for implementing carbon trading by utilising blue carbon is enormous at 3.4 giga tonnes, equivalent to 17% of global blue carbon reserves (Wetlands International, 2017). Notably, mangroves have an economic potential of more than USD90,000 per ha (ICCTF, 2023). The Economic Value of Carbon (NEK) is the value given to each unit of carbon emissions. NEK information is vital in addition to encouraging green investment, addressing climate change financing gaps, and promoting sustainable growth. It also contributes to mitigation and the need to increase climate resilience due to climate change.

Sayung Village and Wedung Village are coastal villages in Demak District. Both Sayung and Wedung villages have mangrove potential, which is gradually being damaged. One of them is caused by excessive mangrove logging (Ristianti, 2016) to be converted into housing, industry, tourism, fish ponds, and firewood (Soeprobowati P S & Sudarno, 2020).

Based on data from the Demak District Marine and Fisheries Service in 2011, 8% of the mangrove ecosystem in Demak District was damaged and further increased to 13.86% in 2012. The damage impacts land subsidence at a rate of 2 cm to 3 cm per year, resulting in coastal erosion and the expansion of tidal flooding areas inland, called rob flooding (Yuwono *et al*., 2018 & Handoko *et al*., 2020). As a result, the affected coastline retreated by 1 km to 1.5 km from its original location (Damastuti *et al*., 2022). At the same time, shoreline change plays an essential role in the deterioration of the surrounding environment and the loss of environmental and socio-economic aspects, coastal damage, loss of residential areas, and infrastructure damage (Muskananfola *et al*., 2020).

Mangrove ecosystems in the coastal Demak District can increase resilience to coastal disasters and climate change if managed properly (Damastuti *et al*., 2023). To anticipate the condition of damaged and reduced mangrove areas on the coast of Demak District, efforts need to be made to provide awareness to the community about the benefits and potential of mangrove ecosystems. One of the efforts made is to estimate the value of carbon stocks and the carbon economy of mangrove ecosystems (Hadiyanto *et al*., 2021). It is hoped that by knowing this information, the preservation of mangrove ecosystems can continue to be pursued in order to mitigate climate change (Chow, 2018). Various studies related to the assessment of mangrove carbon stocks have been conducted on the coast of Demak District such as in the Village of Timbulsloko (Lestariningsih *et al*., 2018), in Sayung Village (Prakoso *et al*., 2018 & Azzahra, 2020), and Tambak Bulusan Village (Susilowati *et al*., 2020). However, these studies have not considered the changes in mangrove land that occur and the potential carbon economy that will be obtained from carbon stocks in existing mangrove ecosystems.

In this research, we used the Automatic Mangrove and Map Index (AMMI) method, which marks a new approach in mangrove cover mapping studies. This mapping method is more specific, as it can provide a clearer picture of the mangrove landscape through a comprehensive RGB NIR-SWIR1-RED channel combination (Suyarso, 2022). Furthermore, applying the AMMI method contributes to overcoming the challenges inherent in traditional mapping techniques, especially when dealing with non-mangrove plants, Nipah, and invasive alien species. As such, the method improved the accuracy of mangrove mapping and proved to be a time- and cost-effective solution, eliminating the need for manual digitisation and streamlining the entire process for end users (Suyarso & Avianto, 2022).

This study aims to determine the standing carbon stock in mangrove ecosystems in Demak District. Consequently, carbon stocks at the research site will be calculated to determine its contribution and economic valuation of carbon in Demak District. This research can be utilised to evaluate the achievement of Indonesia's NZE target at a more detailed scope, namely up to the village or subdistrict level.

Materials and Methods

Study Site

The research was conducted in Sayung and Wedung, Demak District, Central Java, Indonesia (Figure 1). This is located at 6^0 74' 05.30" S to 6^0 74' 31.79" S and 110^0 58'16.36" E to 110^0 58' 29.69" E. Mangrove area (37.4 ha) located along the northern coast of Java (6.4 km length). The study site at Mangrove Demak, particularly in the Wedung and Sayung areas, experiences a tropical climate with average temperatures ranging between 25°C and 30°C throughout the year. The region is influenced by semi-diurnal tides, resulting in two high tides and two low tides each day, with a tidal range that can reach up to 1.5 m. Additionally, the coastal currents in this area are primarily driven by monsoonal winds, which significantly affect sediment transport and mangrove dynamics.

Methods

The research employs a structured methodology starting with Geographic Information System (GIS) and remote sensing, where geometric and atmospheric corrections are applied to Landsat satellite imagery to ensure accurate data collection (Figure 2). Following this, a detailed vegetation survey involves field plot analysis to assess various vegetation characteristics such as species, density, and health. Concurrently, socio-economic data is gathered, focusing on population demographics and CO_2 per capita emissions to understand human environmental impact. Comprehensive data analysis is then performed, including determining the mangrove area using satellite imagery and field data, performing carbon stock analysis to assess the amount of carbon stored in vegetation and soil, and developing an AMMI to facilitate mapping. Moreover, further analysis evaluates the carbon offset potential of the mangrove areas, estimating their capacity to mitigate CO_2

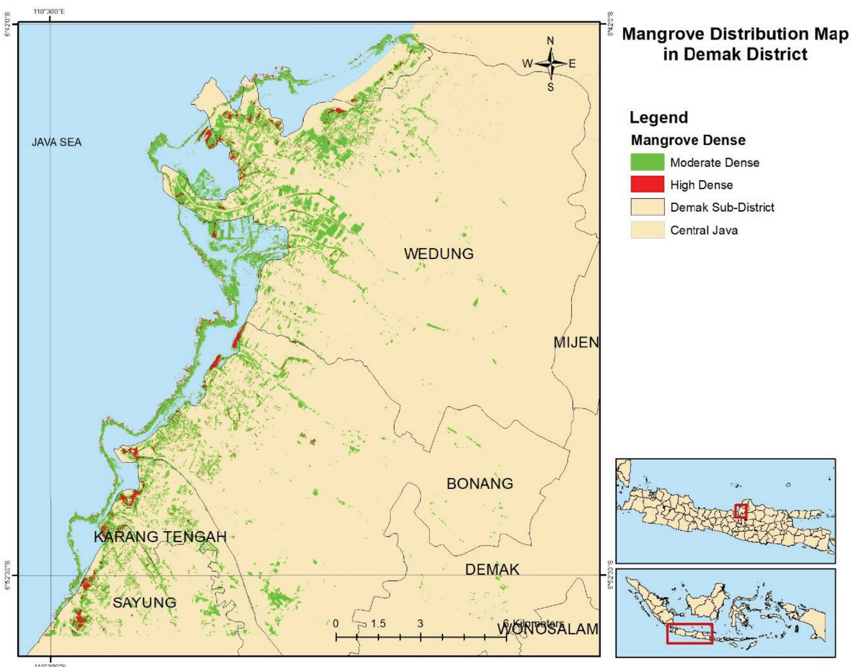

Figure 1: Map of research location in Sayung Village Mangrove Forest

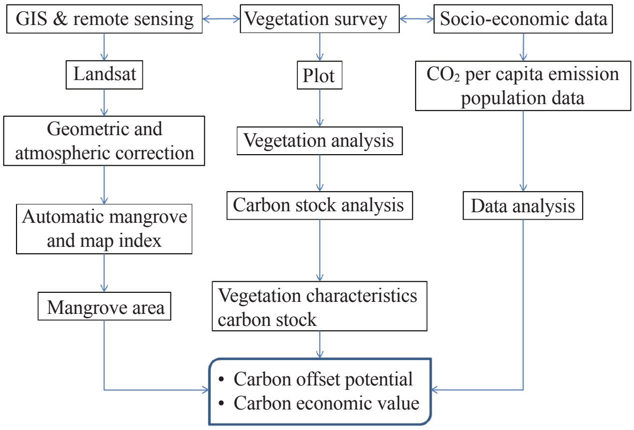

Figure 2: Flowchart of methods

emissions, and assesses the economic value of this carbon storage. Thus, by integrating these diverse datasets and analyses, the research aims to provide a holistic assessment of environmental and socio-economic factors, achieving its objectives of understanding and managing mangrove ecosystems and their contributions to carbon sequestration and climate change mitigation.

Sentinel 2 satellite images of 2019 and 2023 were downloaded from https://earthexplorer.usgs.gov/. GIS and remote sensing with the AMMI method (Suyarso, 2022) were applied to generate a land cover map, especially for mangroves. AMMI is a specific index for mangrove classification and mapping using an RGB NIR-SWIR1-RED channel combination (Suyarso, 2022). Land cover in the study area was classified as moderate mangrove and sparse mangrove. Ground truth was conducted in December 2023 using Global Positioning System (GPS) and field observations to validate the spatial data and maps. The images were radiometrically and geometrically corrected using Global ErMapper 21.0 software. The identification of mangrove land refers to the composite of the red band, Near-Infrared (NIR) band, and Short-Wave Infrared (SWIR) band (4, 8A, 11) in order to illustrate mangroves clearly and separate from non-mangrove vegetation. The band composite process is done using Quantum Geographic Information System (QGIS) software through the Semi-Automatic Classification Plugin, which is calculated by the following formula:

$$\frac{(NIR-RED)}{(Red+SWIR)}\ x\ \frac{(NIR-SWIR)}{(SWIR-0{,}65*Red)} \qquad (1)$$

A combination of stratified and purposeful random sampling was applied to determine the location of vegetation plots (point sampling). Field measurements were conducted in the Wedung and Sayung areas. A total of 10 plots (10 m x 10 m) were placed throughout the study site to represent all variations of mangrove vegetation. Note that plots were placed at various locations representing mangroves from the landward edge to the seaward edge. The plots covered various mangrove vegetation and different hydrodynamic conditions (from upstream to coastal). Trees were defined as counted individuals.

Several mangrove tree parameters such as diameter, crown height, stem density, and crown cover were collected from 10 plots across the study area. Consequently, tree diameters were measured at 130 cm above ground level (at breast height) using a sewing meter. Tree height was measured using a clinometer.

Socio-economic data on CO_2 per capita emission in Indonesia were downloaded from https://edgar.jrc.ec.europa.eu/report_2023?v is=co2pop#emissions_table. Population data of Demak District (2018) was provided by the Central Statistics Agency (BPS).

Data Analysis

Vegetation characteristics were analysed using a method developed by Mueller-Dombois and Ellenberg (1974) to determine tree density, relative density, basal area, relative dominance, and important value index. Shannon-Wienner Diversity index was calculated, following Kusmana (2018), the Index of Uniformity (Saputro *et al*., 2013), and the Dominance Index (D) (Febriansyah *et al*., 2018).

Tree biomass was calculated using species-specific allometric equations: *Avicennia marina* $B = 0.1848 D^2$,3624 (Siregar & Dharmawan, 2009), *Rhizophora apiculata* $B = 0.043 D^2$,63 (Amira, 2008), and *Rhizophora mucronata* $B = 0.128 D^2$,60 (Fromard *et al*., 1998). Subsequently, the biomass was converted into carbon using the Intergovernmental Panel on Climate Change (IPCC) standard of 0.47 (IPCC, 2007). Root biomass values were calculated using root biomass density values from previous studies (Adame *et al*., 2017; Ardhani *et al*., 2020; Ramadhanti *et al*., 2022). Root carbon and belowground biomass analysis were derived using allometric equations (Komiyama *et al*., 2008).

Carbon emissions in Demak District are calculated indirectly through the Individual Carbon Footprint (ICF) approach. The ICF approach considers various activities and behaviours of individuals such as energy consumption, transportation choices, and waste production to estimate their personal contribution to overall carbon emissions. Thus, by aggregating these individual contributions, researchers can comprehensively understand the district's total emissions. This method effectively highlights specific areas where individuals can make changes to reduce their carbon footprint, making it a powerful tool for raising awareness and promoting sustainable practices (Mulrow *et al*., 2019). Carbon emissions in the district were calculated by the following equation:

$$\sum \textit{Emissions Demak District} = \textit{Emissions per Capita} \times \sum \textit{Residents of Demak} \quad (2)$$

The data collected on mangrove carbon emissions and stocks are analysed to assess the extent of carbon emission reductions attributable to the Demak District mangrove ecosystem. Briefly, it can be formulated with the following equation:

$$\textit{Net Zero Emissions} = \textit{Carbon emissions} - \sum \textit{Carbon Stock} \quad (3)$$

Total carbon stock is obtained from the accumulation of carbon in the stand and in the sediment. It can be briefly explained using the following equation:

$$\sum \textit{Carbon Stock} = \textit{Stand's Carbon Stock} + \textit{Root Biomass Carbon Stock} \quad (4)$$

The economic value of aboveground carbon stock was evaluated following the economic valuation procedure described in Jerath *et al*. (2016). The economic value of aboveground carbon was calculated using carbon sequestration in mangrove forests and carbon selling values as described in the formula:

$$\textit{Total Economic Valuation of Carbon} = \sum \textit{Total Carbon Sequestration of Mangrove Ecosystems} \times \textit{Carbon Selling Value} \quad (5)$$

Carbon Selling Value is the international carbon market by the World Bank Group. The value of carbon is based on the average price of carbon in the voluntary market as well as the regulated market. Economic Valuation Carbon offset was calculated using the total carbon offset of mangrove and Carbon Selling Value following the described formula below:

$$\textit{Economic Valuation Carbon Offset} = \sum \textit{Total Carbon Offset of Mangrove Ecosystems} \times \textit{Carbon Selling Value} \quad (6)$$

Results and Discussion

Vegetation Conditions and Characteristics

The density of mangrove trees in the study area of Demak District is 3,241 ind ha^{-1}. Mangrove tree density in the Wedung site is 3,522 ind ha^{-1}, higher than in the Sayung sites (2,800 ind ha^{-1}).

Following the Indonesian regulation Ministry of Environment No. 201 year 2004, mangrove conditions in the study area are good. This finding aligns with a previous study that showed that mangrove in Demak was categorised as dense mangroves (Kusmana *et al*., 2016). The density of saplings in Demak was relatively high, with sapling density in Wedung was 1,511 ind ha^{-1} and in Sayung was 444 ind ha^{-1}. This suggests that potential mangrove regeneration in the study area was good.

Vegetation data analysis revealed detailed characteristics of mangroves in the study area, as shown in Table 1. Data analysis presented that *A. marina* is the most dominant mangrove in Sayung while *R. mucronata* is more pronounced in Wedung. The important value index of *A. marina* in Sayung was 178.78, followed by *R. mucronata* (21.22). On the other hand, *R. mucronata* has a higher important value index (110) than *A. marina* (86). A high importance value index indicates that the mangrove is vital in the coastal environment (Kusuma, 2023). Furthermore, the ability to control the types of mangrove plants that are consistent in their communities is indicated by the order of the level of mastery of the types of other types in this mangrove forest community. Note that plants with high resistance and adaptation to a habitat usually play a vital role in forming communities (Akhmadi, 2022).

The study revealed that mangrove diversity in the study area was low. Only three species of mangrove, *R. mucronata*, *R. apiculata*, and *A. marina* were noted in the area. Diversity indices for tree species showed mixed results strongly influenced by the number of individuals and species. Species diversity in both Sayung and Wedung ranged from 0.18 to 0.34 (low) and the uniformity index ranged from 0.023 to 0.042 (low). The dominance value at Sayung station ranged from 0.75 (medium) and at Wedung station ranged from 0.48 (low). However, the species diversity index in the study area was much lower than that found in the mangrove forest area of Sampit Bay, Kotawaringin, ranging from 0.6404 (Akhmadi, 2022).

Table 1: Vegetation characteristics of the mangrove trees and sapling categories

Station	Type	Ni	D (ind/ha)	RD (%)	Do (cm)^2	RDo (%)	IVI
Trees category							
Sayung	*Avicennia marina*	215	2,389	85.32	12,232.06	93.46	178.78
	Rhizophora mucronata	37	411	14.68	855.88	6.53	21.22
	Total	**252**	**2,800**	**100**	**13,087.94**	**100**	**200**
Wedung	*Avicennia marina*	153	1,700	48.26	5,828.60	37.69	86
	Rhizophora mucronata	156	1,733	29.21	9,406.52	60.84	110
	Rhizophora apiculata	8	89	2.52	225.66	1.45	34
	Total	**317**	**3,522**	**100**	**15,460.78**	**100**	**200**
Sapling categories							
Sayung	*Avicennia marina*	10	444	100	66.69	100	200
Wedung	*Avicennia marina*	26	1,156	76.47	200.50	79.94	156.41
	Rhizophora mucronata	8	356	23.53	50.32	20.06	43.59
	Total	**34**	**1,511**	**100**	**250.82**	**100**	**200**

Note: RD: Relative Density; RDo: Relative Dominance; IVI: Important Value Index.

The uniformity index indicates the level of uniformity of individuals of each species in a particular community. The existence of an unequal or uneven distribution of individuals of each species can be influenced by a low level of uniformity (Natania *et al*., 2017). In addition, this study's overall uniformity index value is lower than that of mangroves in Bulaksetra, Pangandaran, and West Java, ranging from 0.46 to 0.87 (Kusmana & Chaniago, 2017). Note that a community's lower uniformity index value indicates that environmental conditions can become more unstable.

The dominance index value at the Demak District research site is higher compared to that of the mangrove area in Aceh Province, which is approximately 0.42 (Mandosir *et al*., 2017). On the other hand, the dominance index of mangroves in Sayung and Wedung is lower than that in Bengkulu City, which is 0.87 (Febriansyah *et al*., 2018). It is essential to note that a lower dominance index suggests a more stable ecosystem with less pressure. Moreover, it is critical to understand that the dominance index does not solely indicate the prevalence of a single species.

Carbon Stock

The biomass potential of the three mangrove species is proportional to the total carbon sequestration potential and can be observed in Table 2. Carbon sequestration is the ability of mangrove stands to absorb CO_2 from the atmosphere (Easteria *et al*., 2022 & Ahmed *et al*., 2023). The highest ratio of carbon sequestration potential was obtained in *A. marina* species with a total of 5,055.78 tonnes CO_2 eq (58.54%), followed by *R. mucronata* species with a total of 3,561.39 tonnes CO_2 eq (41.24%). Following the amount, *R. apiculata* species provides the least carbon sequestration potential ratio of 19.32 tonnes CO_2 eq or equivalent to 0.22%. However, when viewed from the average, the *R. mucronata* species has the highest carbon sequestration potential of 18.45 tonnes CO_2 eq for each stand. Meanwhile, *A. marina* species presented a carbon sequestration potential of 13.74 tonnes of CO_2 eq while *R. apiculata* has a much lower carbon sequestration potential of 2.42 tonnes of CO_2 eq for each stand. The study by Uthbah *et al.* (2017) focused on the biomass and carbon stock of *Agathis dammara* in Banyumas Timur, Indonesia, evaluating different stand ages to assess their carbon sequestration potential.

This research aligns with the study on mangroves in the Demak District by emphasising the significance of understanding carbon stock variations across different ecosystems and ages of vegetation. Both studies highlight the significant role of forested ecosystems, whether mangrove or *A. dammara,* in carbon sequestration and climate change mitigation. Additionally, the comparison between mangroves and Agathis dammara highlights the diversity in carbon storage potential across different vegetation types. This underscores the critical need for targeted conservation and management strategies in various forest

Table 2: Calculation results of potential carbon sequestration in stands

Species	**Ni**	**Number of Diameter (cm)**				**Potential Biomass (kg)**	**Carbon Sequestration (Tonnes CO_2 eq)**
		4.0-8.0	**8.1-12.0**	**12.1-16.0**	**16.1-20.0**		
Avicennia marina	368	243	96	22	7	10,111.56	5,055.78
Rhizophora mucronata	193	146	23	18	6	7,122.77	3,561.39
Rhizophora apiculata	8	8	0	0	0	38.64	19.32
Total						**17,272.97**	**8,636.48**

ecosystems to optimise carbon sequestration efforts. The greater the biomass in a stand, the higher the carbon storage potential (Ahmed *et al*., 2011 & Suryono *et al*., 2018).

The carbon stock findings from this research in the Demak District of Central Java align with broader patterns observed in other mangrove ecosystems in Indonesia, particularly those described in the South Sulawesi study. The Demak study reported a total carbon sequestration potential of 8,792.09 tonnes of CO_2 equivalent, with the vast majority (98.23%) coming from aboveground biomass and a smaller fraction (1.77%) from root biomass. This distribution reflects a common characteristic of mangrove ecosystems, where most carbon is typically stored in aboveground biomass and Soil Organic Carbon (SOC), as observed in the South Sulawesi study (Malik *et al.*, 2023) due to high levels of anthropogenic activities, mangroves rapidly disappear worldwide, resulting in a significant loss of carbon stocks. This study aims to quantify the biomass carbon stock of mangroves (standing live trees and roots.

Malik *et al*. (2023) study provided a comprehensive framework for understanding the distribution of carbon in mangrove ecosystems, highlighting the significant role of SOC, which accounted for 85% of the total carbon pool. This finding underscored the significance of soil as a primary carbon sink in mangrove ecosystems. In contrast, the Demak study focused more on aboveground and root biomass, with less emphasis on SOC. However, this does not diminish the relevance of SOC, especially considering that soil typically holds a substantial portion of the total carbon stock in mangrove ecosystems.

The research in Demak, with its emphasis on aboveground biomass, aligns with the theoretical understanding that it is a critical component of carbon storage in mangroves. The reported carbon stock values in the Demak study are comparable to those in other disturbed and undisturbed mangrove forests across Indonesia, as discussed in the South Sulawesi study. For example, the South Sulawesi study reported aboveground carbon stock values ranging from 100.66 ± 23.44 MgC/ha^{-1}, which are within the range observed in Demak. This highlights the consistency of these findings with national and regional data.

Root Biomass

The results of the calculation of carbon sequestration potential in the lower biomass (Table 3) reveal similar results to the carbon sequestration potential in stands where the highest ratio of carbon sequestration potential is reported in *A. marina* species with a total of 32.17 tonnes of CO_2 eq (81.55%). This is followed by *R. mucronata* species with a total of 6.17 tonnes of CO_2 eq (15.64%) and *R. apiculata* with a total of 1.11 tonnes of CO_2 eq (2.81%). In contrast to the carbon potential of the stand, the understory biomass of *R. apiculata* had the highest average

Table 3: Calculation results of carbon sequestration potential in lower biomass

Species	Ni	Number of Diameter (cm)			Density	Potential Biomass (kg)	Carbon Sequestration (Tonnes of CO_2 eq)
		1.0-2.0	2.1-3.0	3.1-4.0			
Avicennia marina	35	1	16	18	0.73	64.35	32.71
Rhizophora mucronata	8	0	5	3	0.74	12.35	6.71
Rhizophora apiculata	1	1	0	0	1.05	2.21	1.11
					Total	**78.91**	**39.45**

carbon sequestration potential (1.1 tonnes CO_2 eq), compared to *A. marina* (0.92 tonnes CO_2 eq) and *R. mucronata* (0.77 tonnes CO_2 eq) for each stand.

Mangrove forest structure significantly influences carbon stock accumulation while root biomass is positively correlated with stem diameter (Malik *et al*., 2020). Mangrove plants have developed this specific characteristic of root biomass to effectively anchor themselves and acquire nutrients in the sediment where they typically grow (Rahmattin & Hidayah, 2020 & Hidayah *et al*., 2022). Note that the amount of carbon in the form of lower biomass is influenced by soil type, tree species diversity, tree age, and litter production (A. Ahmed *et al*., 2011; Adame *et al*., 2017; Easteria *et al*., 2022; Albasit *et al*., 2022).

Carbon Footprint Emissions and Mangrove Cover Change

The study conducted in the Demak district showed that total carbon emissions in the region reached 2,580,023.04 tonnes of CO_2 equivalent, attributed to a human population of 1,151,796 in the district in 2018. This finding aligns with provincial-level carbon emissions calculations in Central Java, indicating a consistent methodology for estimating carbon emissions at various administrative levels (Arifanti *et al*., 2022; Lovelock *et al*., 2022).

Research on mangrove conservation and restoration has highlighted the significance of these ecosystems in climate change mitigation efforts (Mawardi *et al*., 2023; Amru *et al*., 2023). Studies have proven that mangroves play a significant role in sequestering carbon and reducing GHG emissions (Yancho *et al*., 2020). In addition, mangrove restoration has been identified as a strategy to increase carbon storage and mitigate climate change impacts.

GIS and remote sensing analysis using AMMI suggested that the total mangrove area in 201 was 1,246.87 ha, comprised of sparse mangrove (702.4 ha), moderate mangrove (430.14 ha), and dense mangrove (114.59 ha). The total mangrove area in 2023 was 2,423.76 ha, comprised of moderate (2,114.2 ha), and dense (309.56 ha). Thus, it is evident that the total mangrove area increased. However, vegetation shifting and mangrove conversion into other land use also occurred in the study area (Figure 3).

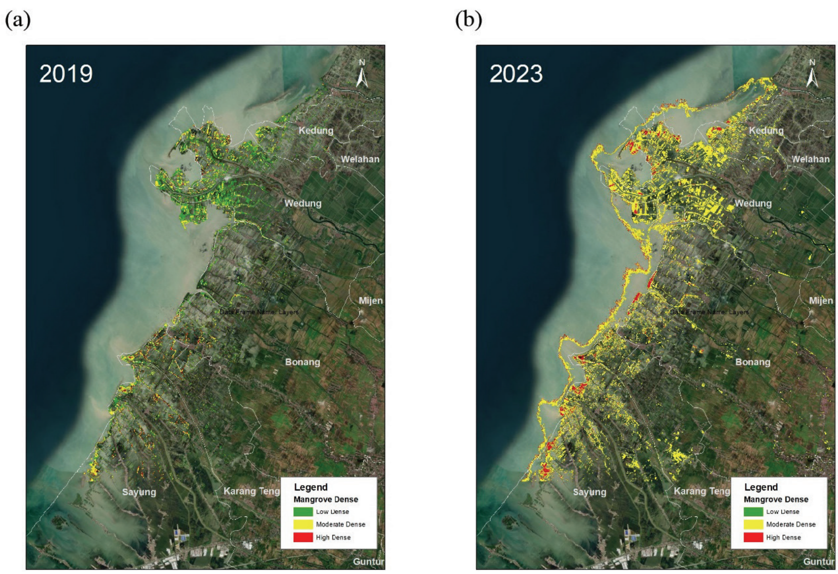

Figure 3: Changes in mangrove density level in Sayung Village: (a) year 2019 and (b) year 2023

Both moderate and dense mangroves increased, with the rate of increase in mangrove area being 78% y^{-1} and 34% y^{-1}, respectively. In contrast, sparse mangroves decreased significantly (140.48 ha y^{-1} or 20% y^{-1}). The spatial analysis indicated vegetation shifting (Figure 2) from sparse to moderate mangroves due to mangrove rehabilitation (mangrove planting). Meanwhile, field observation and informal interviews confirmed that local Non-Gorvernmental Organisations (NGOs), local governments, and local communities conducted mangrove planting. This finding is in line with vegetation analysis, which indicated that species diversity in the study area is low and is dominated by *R. mucronata and R. apiculata*. This is due to most mangrove planting programs planting *R. mucronata and R. apiculata.* Note that grey mangrove (*A. marina*) is the most common mangrove in the northern part of Java. In some areas, the density of moderate mangroves in 2019 increased and then shifted into dense mangroves in 2023. However, mangrove loss or conversion into other land use also occurred in the study area due to coastal abrasion and converted into shrimp ponds.

The introduction of the AMMI method in this research represents a significant advancement in the field of mangrove ecosystem management, particularly in the accuracy of mangrove cover mapping. Despite that, traditional mapping techniques often struggle with the complexity of coastal ecosystems, where distinguishing between mangrove species and other vegetation types such as non-mangrove plants and invasive species, presents a considerable challenge. The AMMI method addresses this challenge by utilising a specific combination of spectral bands RGB, NIR, and SWIR1 to enhance the differentiation between mangroves and other vegetation. This approach improves the precision of mangrove mapping and offers a more detailed understanding of the spatial distribution and health of these critical ecosystems.

Critically, the AMMI method's ability to accurately distinguish between mangrove species and other vegetation types is critical in regions like Demak District, where human activities and environmental changes constantly threaten mangrove ecosystems. Hence, accurate mapping is essential for effective conservation and restoration efforts, as it identifies areas that are most at risk and those with the highest potential for successful rehabilitation. Moreover, the method's utility in distinguishing between healthy and degraded mangrove areas also provides valuable data for assessing the effectiveness of ongoing restoration projects and planning future interventions.

The Potential of Carbon Offset and Carbon Economic Value

The total carbon sequestration potential in the Demak district derived from mangrove ecosystems can be observed in Table 4. The total carbon sequestration potential of mangroves in Demak district reached 8,792.09 tonnes of CO_2 eq with a ratio of 98.23% (8,636.48 tonnes of CO_2 eq) derived from stands and 1.77% (155.61 tonnes of CO_2 eq) derived from bottom biomass. This total sequestration potential was then compared with the total emissions generated in the same year, according to Table 5 to obtain the *carbon offset* value. Based on the calculation results, it was reported that Demak District has a negative *carbon offset* value of 2,571,230.95 tonnes CO_2 eq/year. This suggests that Demak District has not yet reached a NZE condition.

Table 4: Total carbon uptake

Variables	Values
Per stand carbon uptake (tonnes CO_2 eq/person/year)	8,636.48
Total lower biomass carbon uptake (tonnes CO_2 eq/year)	155.61
Total carbon sequestration (tonnes of CO_2 eq/year)	8,792.09

Table 5: Carbon offset evaluation

Variables	Values
Total emission (tonnes CO_2 eq/year)	2,580,023.04
Total carbon sequestration (tonnes CO_2 eq/year)	8,792.09
Total carbon offset (tonnes CO_2 eq/year)	-2,571,230.95

Similar results were reported in Amru *et al.*'s (2024) research, which stated that although Central Java Province had achieved NZE, 10 cities or districts had not yet reached the NZE target, including Demak District.

In addition to the total *carbon offset*, Table 5 also provides information on the contribution of mangrove ecosystems to carbon emissions in the Demak District. The small contribution of mangroves is due to the limited area of mangrove areas with a small number of stands. Therefore, an increase in mangrove areas accompanied by additional vegetation stands is needed to contribute mangroves more significant.

Potential Valuation of Carbon Economic Value in Demak District

The analysis of determining the economic valuation value in this study is based on two approaches, namely the approach with the value of carbon trading in the voluntary market system and also the agreed carbon value in the regulated market, in this case, the value of carbon trading agreed by the European Union Emissions Trading System (EUETS). The United Nations Development Programme (2022) states that the average carbon trading price in the voluntary market is 5.38 USD/tonnes CO_2 while the average price of carbon trading in the regulated market, in this case, the EUTS is 88.76 EUR/tonnes CO_2. Based on the value of carbon trading, the potential value of carbon sequestration and carbon offset in this study (Table 6).

Table 6 presents that the total potential valuation of carbon sequestration in this study is 47,301.44 USD/tonnes CO_2 eq/year (based on the average price in the voluntary market system) and also 780,385.90 EUR/tonnes CO_2 eq/year (based on the average price in the regulated market) while the potential value of total carbon offset valuation is - 13,831 USD/tonnes CO_2 eq/year (based on the average price in the voluntary market system) and - 228,286.28 EUR/tonnes CO_2 eq/year (based on the average price in the regulated market system). Based on these results, it is known that the value of the potential economic valuation of carbon offsets demonstrates a negative value in both the voluntary market and regulated market systems. This is due to the fact that the total carbon offset in this study has a negative value.

The negative number in the potential economic valuation of carbon offsets means that this value is an opportunity for the economic potential that should be utilised from the mangrove forest area of Sayung Village, Sayung District, and Demak District in the carbon trading mechanism. It can be concluded that the increase in the total potential NEK offsets is in line with the increase in total carbon

Table 6: Estimated values of total economic valuation of carbon sequestration and total carbon offset

Variables	Voluntary Market: 5.38 USD (USD/tonnes CO_2 eq/year)	Regulated Market (EUTS): 88.76 (EUR/tonnes CO_2 eq/year)
Total carbon uptake (tonnes CO_2 eq/year): 8,792.09	47,031.44	780,385.90
Total carbon offset (tonnes CO_2 eq/year): - 2,571,230.95	-13.831	228,286.28

sequestration and a decrease in total emissions in the Sayung Village mangrove forest area, Sayung District, Demak District, in the carbon trading mechanism.

The mangrove ecosystems of Demak District annually sequester a total of 8,792.09 tonnes of CO_2 equivalent. This significant sequestration is predominantly attributed to two species, *A. marina* and *R. mucronata*. Such robust carbon sequestration presents substantial economic opportunities, particularly within carbon trading markets. To monetise this carbon sequestration, we applied the prevailing carbon prices from the voluntary market and the EUETS. The average prices are USD5.38 per tonne of CO_2 in the voluntary market and EUR88.76 per tonne in the EUETS. Accordingly, the annual economic value of the carbon sequestered by Demak's mangroves amounts to USD47,301.44 in the voluntary market and EUR780,385.90 in the regulated market.

This valuation offers vital insights for stakeholders and policymakers, highlighting the financial benefits of conserving and restoring mangrove forests. The monetary values underscore mangroves' critical role in carbon offset projects, bolstering support for sustainable management practices in coastal areas. Furthermore, the economic benefits derived from these ecosystems extend beyond carbon sequestration. They contribute long-term advantages in coastal protection, biodiversity preservation, and supporting community livelihood benefits, which are particularly crucial in regions susceptible to climate change and SLR. As the global demand for carbon offsets grows, the potential for mangroves to support Indonesia's emission reduction strategies, especially in meeting its NZE targets, becomes increasingly significant.

Aligning Mangrove Conservation with Sustainable Development Goals

To effectively enhance mangrove conservation efforts in Demak District and support Indonesia's broader net-zero emission targets, it is essential to integrate several key policy recommendations based on existing regulatory frameworks and initiatives. First, the expansion of the national mangrove restoration program, which aims to rehabilitate 600,000 hectares of mangroves by 2024 should be prioritised and integrated into both local and national development plans. This will ensure restoration projects are aligned with Indonesia's Enhanced Nationally Determined Contributions (NDCs) under the Paris Agreement, emphasising the importance of species with high carbon sequestration potential such as *R. mucronata* and *A. marina*.

Moreover, including mangroves in carbon trading schemes presents a significant economic opportunity. Developing policies that facilitate the integration of mangrove carbon credits into voluntary and regulated markets can leverage the NEK sequestration. This includes establishing a national framework that standardises the measurement and reporting of carbon in mangrove ecosystems, enabling more stakeholders to participate in carbon trading. Additionally, providing incentives for private sector investments in mangrove restoration as a carbon offset strategy will further bolster these efforts.

Strengthening legal protections is also critical. This involves revising land use regulations to designate more protected zones and enforcing stricter penalties against illegal activities that threaten mangrove ecosystems. These legal measures are essential for maintaining these forests' ecological integrity and carbon storage capacity, which are vital to achieve Indonesia's environmental and climate objectives. Note that engaging and empowering local communities in mangrove management is another crucial aspect. Hence, policies should be designed to provide financial incentives, technical support, and education to local communities, encouraging sustainable management practices.

By formalising and expanding community-based management approaches, these initiatives will contribute significantly to achieve net-zero emissions at the local level and enhancing community resilience to climate change.

Furthermore, the government should invest in a national mangrove monitoring system that integrates satellite data, field observations, and community inputs. Such a system would be invaluable for tracking restoration progress, assessing policy effectiveness, and guiding future conservation decisions.

Aligning these policy recommendations with the Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land) will reinforce Indonesia's commitment to global sustainability efforts. This alignment can attract international support and funding, which is critical for scaling up conservation activities and ensuring that mangroves continue to play a vital role in climate change mitigation and the sustainable development of coastal communities.

Conclusions

The mangrove ecosystems in Demak District exhibit remarkable carbon sequestration potential, primarily driven by *A. marina* and *R. mucronata*. These species play a vital role in contributing to aboveground and belowground carbon stocks, with *R. mucronata* showing the highest carbon storage capacity in individual stands and *R. apiculata* in lower biomass stands. Despite this significant sequestration, these mangroves' current carbon absorption capacity falls short of offsetting the district's high carbon emissions. This emphasises the urgent need for expanded restoration and protection efforts to increase carbon sequestration. Moreover, the findings of this study underscore the dual ecological and economic significance of mangroves in the Demak District. In addition to their role in mitigating climate change through carbon sequestration, the monetary value of this carbon storage is substantial. When valued in the voluntary and regulated carbon markets, the total carbon sequestration potential of Demak's mangroves amounts to USD47,301.44 per year and EUR780,385.90 per year, respectively.

This economic valuation highlights the critical role that mangroves can play in both climate action and sustainable development. By incorporating the financial value of carbon stocks into climate policy and economic decision-making, stakeholders can leverage natural capital to support long-term environmental and economic resilience. The potential for carbon trading offers a compelling financial incentive to scale up mangrove restoration efforts, protect existing forests, and integrate these ecosystems into Indonesia's broader sustainability goals. Effective management and restoration of mangrove ecosystems are essential for maximising their potential in climate change mitigation. By expanding the extent and health of mangrove forests, Demak District can significantly enhance its carbon stocks, contributing to both local environmental health and global climate targets. Therefore, combining ecological benefits and economic opportunities presents a powerful argument for prioritising mangrove conservation as part of a holistic approach to sustainable development.

Acknowledgements

The authors thank Muhammad Faisal and the Central Java Provincial Office for their discussions, suggestions, and support in realising this automated mangrove map. The authors would also like to thank those who provided funding, namely the Space Flight Programme House and the Clean Technology and Environmental Pollution Control Prototype Programme House, as well as all colleagues at the Center for Oceanographic Research, Indonesian Institute of Sciences, who assisted in the preparation of this article: Oceanography Research Center, National Research and Innovation Agency for helping in the preparation of this article.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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