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Research Article

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Mangrove Health in Muara Gembong District, Bekasi Regency: Carbon Stock to Support Indonesia's FOLU Net Sink 2030

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ABSTRACT
Mangrove ecosystems are among the world's most effective natural carbon sinks and play a strategic role in climate change mitigation. Indonesia, home to approximately one-quarter of the world's total mangroves, has positioned mangrove conservation and rehabilitation as a key pillar of its FOLU Net Sink 2030 policy. This study aims to assess mangrove health and estimate carbon stocks in Muara Gembong District, Bekasi Regency, West Java, a peri-urban coastal area with high anthropogenic pressure. Mangrove health assessments were conducted using Sentinel-2 imagery processed through Google Earth Engine using the NDVI approach, while carbon stock estimates were calibrated using field measurements of aboveground biomass. The analysis results indicate a decline in healthy mangroves in the 2020–2025 period, followed by a net carbon stock decline of approximately 412 tons. This decline was primarily due to the degradation of medium-density mangroves, which play a crucial role in maintaining ecosystem resilience. These findings propose the FMJ-IM³ Model as an integrated mangrove management framework that integrates ecosystem health monitoring, carbon-based rehabilitation, and community empowerment. Mangrove management models based on ecosystem health and carbon stock data at the local scale can make a significant contribution to achieving national climate change mitigation targets.

Keywords: Mangrove Health, Blue Carbon, FOLU Net Sink 2030, Community Empowerment

Introduction

Mangrove forests are coastal ecosystems with extraordinary long-term carbon absorption and storage capabilities [1,2]. From a materials science and environmental engineering perspective, mangrove biomass and its anaerobic sediments function as highly efficient natural carbon storage materials, with a carbon storage capacity three to five times greater than that of tropical terrestrial forests [3]. Therefore, mangroves play a strategic role as nature-based solutions for climate change mitigation.

Indonesia has the largest mangrove area in the world, encompassing approximately 20–25% of the global total [4,5]. This strategic position makes Indonesia a key player in controlling global carbon emissions from the coastal sector [6]. In line with its national commitment to the Paris Agreement, the Indonesian government has established the Forestry and Other Land Uses (FOLU) Net Sink 2030 policy, which targets the forestry and other land use sectors to become net sinks of greenhouse gas emissions by 2030 [7,8]. This policy prioritizes mangrove ecosystems due to their high carbon sequestration efficiency and their additional benefits for coastal resilience and community well-being.

Muara Gembong District in Bekasi Regency, Indonesia, is a prime example of a peri-urban mangrove area experiencing significant

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degradation due to land conversion to fishponds, coastal erosion, and coastal development pressures. This degradation not only reduces environmental quality and coastal resilience but also reduces carbon storage capacity. Nevertheless, this area still holds significant potential for mangrove rehabilitation and carbon stock enhancement if managed appropriately.

Most mangrove research in Indonesia still focuses on relatively natural or rural areas, while studies of mangroves in degraded peri-urban areas are limited, particularly those linking mangrove health to carbon stock dynamics in the context of the 2030 FOLU Net Sink policy. Therefore, this study aims to: (1) assess mangrove health in Muara Gembong using satellite imagery-based NDVI analysis, (2) estimate changes in mangrove carbon stocks during the 2020–2025 period, and (3) formulate an integrated mangrove management model that supports the achievement of the 2030 FOLU Net Sink target.

Mangroves as Natural Carbon Storage Material

Mangroves are complex biocomposite systems consisting of aboveground biomass, subsurface root systems, and organic-rich sediments [9]. The anaerobic conditions of these sediments cause carbon decomposition to be very slow, allowing carbon to be stored for hundreds to thousands of years. Various studies indicate that the total carbon stock of mangrove ecosystems in tropical regions ranges from 800 to over 1,200 Mg C ha^{-1}, making them one of the most effective carbon storage ecosystems in the world [10].

Blue Carbon and Climate Change Mitigation Policies

The blue carbon concept emphasizes the role of coastal and marine ecosystems, particularly mangroves, seagrasses, and salt marshes, in mitigating climate change [11]. In Indonesia, blue carbon has been integrated into national climate policy, particularly through the 2030 FOLU Net Sink [12]. The successful implementation of this policy depends heavily on the availability of accurate spatial and temporal data on ecosystem health and carbon stocks.

Remote Sensing for Mangrove Health Assessment

Remote sensing technology has been widely used to monitor mangrove conditions efficiently and sustainably [13]. The Normalized Difference Vegetation Index (NDVI) is the most commonly used vegetation index to assess greenness, canopy density, and vegetation productivity [14,15]. The strong relationship between NDVI values and mangrove biomass makes this index a reliable proxy for assessing mangrove health and estimating carbon stocks, especially when combined with field data.

Research Methodology

This research was conducted in Muara Gembong District, Bekasi Regency, West Java, focusing on several coastal villages with significant mangrove cover and varying levels of degradation. Field data were collected through vegetation measurements in several sample plots representing different mangrove density classes. Parameters measured included mangrove species, stand density, and tree diameter at breast height (DBH) [16]. Remote sensing data were obtained from Sentinel-2 imagery from 2020 and 2025, processed using Google Earth Engine. Mangrove health was classified based on NDVI values into three classes: unhealthy, moderately healthy, and very healthy. Spatial analysis was conducted to compare changes in health classes over time. Aboveground biomass was estimated using an NDVI-based model calibrated with field data. Biomass values were then converted to carbon stocks using a conversion factor of 0.47.

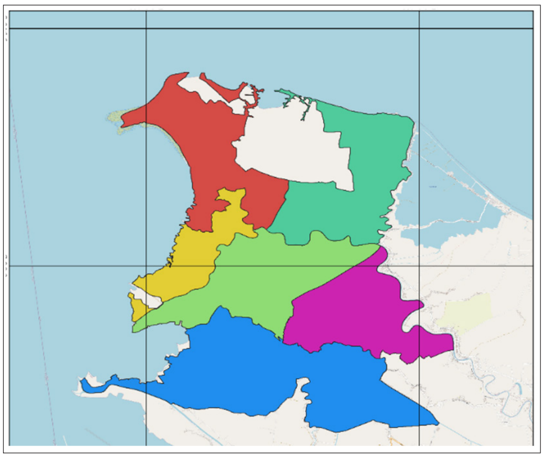

Figure 1: Administrative map of Bekasi Regency showing the location of Muara Gembong District and the distribution of mangrove areas in coastal areas

Results and Discussion

Classification of Mangrove Vegetation Health Based on NDVI Values

NDVI classification map showing the distribution of unhealthy, moderately healthy, and very healthy mangroves in 2020 and 2025. A significant decrease in the healthy class is seen around the pond area and the abrasion zone. Mangrove Composition and Structure Field observations indicate that Avicennia marina and Rhizophora apiculata are the dominant species in the study area. The dominance of Avicennia marina indicates stressed environmental conditions, especially related to high salinity and unstable substrates.

Table 1: Changes in Mangrove Health Class Area in Muara Gembong District (2020–2025)

Mangrove Health Class	Area in 2020 (ha)	Area in 2025 (ha)	Change (ha)
Unhealthy (Red)	215	268	+53
Moderately Healthy (Yellow)	342	291	-51
Very Healthy (Green)	198	176	-22
Total	**755**	**735**	**-20**

Based on Sentinel 2A satellite image analysis in 2020, the total area of mangroves in the coastal area of Muara Gembong was 1,550.12 ha. Of this total area, 426.86 ha were mangrove areas in unhealthy (damaged) conditions, 322.23 ha were mangrove areas in healthy (good) conditions, 87.11 ha were mangrove areas with normal health conditions, while the mangrove area with very good health conditions was 1,036.15 ha. In 2025, these conditions changed, namely the area increased by 15.13 ha (3.54%) for the unhealthy mangrove classification; the area decreased by 29.78 ha (34.19%) for the healthy mangrove classification; and the area increased by 14.65 ha (1.41%) for the very healthy mangrove classification. The percentage value of changes in the area of mangrove health shows a positive direction, namely 67.79% (very healthy) and 3.70% (healthy), while 28.51% (unhealthy) is an indication of the vulnerability of the Muara Gembong coastal area which requires special attention.

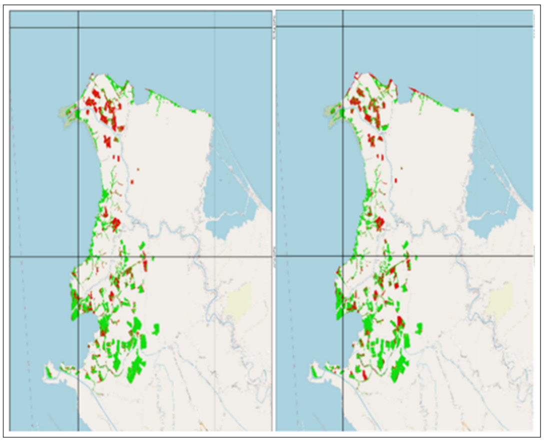

Figure 2: Changes in area from mangrove health classification in 2020 (left) and 2025 (right)

Carbon Stock Dynamics

Table 2 shows a decrease in mangrove biomass and carbon stocks which is correlated with a decrease in ecosystem health.

Year	Aboveground Biomass (tons)	Carbon Stock (tons C)
2020	23,650	11,115
2025	22,775	10,703
Change	-875	-412

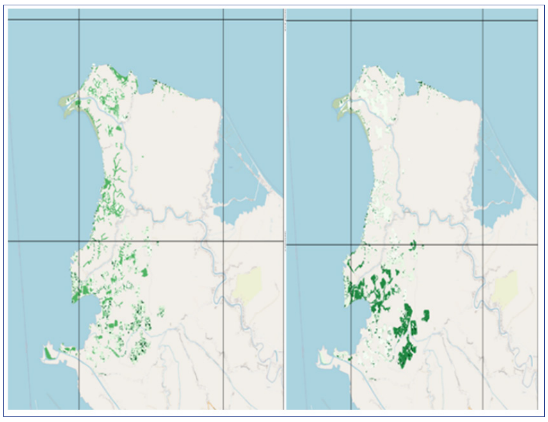

Figure 3: Comparison of Mangrove Carbon Stocks in 2020 and 2025

Figure 3 shows the decline in mangrove carbon stocks between 2020 and 2025.) The total mangrove carbon stock in Muara Gembong decreased from approximately 11,115 tons in 2020 to 10,703 tons in 2025. The net decrease of approximately 412 tons of carbon indicates the significant impact of mangrove degradation on carbon storage capacity.

The decline in mangrove health and carbon stocks in Muara Gembong reflects the vulnerability of peri-urban mangrove ecosystems to human pressures. The loss of moderate-density mangroves significantly impacts ecosystem stability and carbon sequestration capacity. From a climate policy perspective, this degradation has the potential to increase carbon emissions if not addressed promptly.

Carbon Reduction in Muara Gembong

The decline in total carbon in Muaragembong, from 11,115 tons in 2020 to 10,703 tons in 2025, indicates a carbon stock degradation of 412 tons in five years. This indicates that the mangrove ecosystem is losing its ability to absorb and store carbon. This decline may be influenced by land conversion, vegetation degradation, and a reduction in the area of medium-density vegetation, which, according to previous data, decreased by approximately 29.78 hectares. Carbon stocks in mangroves are generally closely related to stand structure, area size, and ecosystem health.

The correlation between density and carbon is clear, with decreases in areas in the medium density class implying reduced biomass and photosynthetic productivity. Mangrove vegetation with high density tends to be able to sequester more carbon because the greater number of stems, leaves, and roots contribute to increased biomass. However, although the high density and "very healthy" health classes showed a slight increase (approximately 14.65 ha), this was not enough to compensate for the significant losses in the medium density class. Studies have shown that differences in canopy density and vegetation distribution directly influence variations in carbon storage [17].

Mangrove ecosystem health also plays a crucial role in supporting carbon storage capacity. Healthy and very healthy mangroves have more developed root systems, allowing them to store carbon not only in aboveground biomass but also belowground biomass. However, the relatively small increase in the very healthy area did not completely mitigate the impact of the 29.78 hectare decrease in the healthy class. This is consistent with the findings of Donato et al., who explained that even small-scale mangrove loss can lead to significant declines in ecosystem carbon stocks [18].

From an ecosystem dynamics perspective, carbon decline in Muara Gembong confirms the close relationship between habitat degradation and the ecosystem's blue carbon absorption function. Carbon decline not only reflects a reduced capacity to mitigate climate change but also indicates the ecosystem's vulnerability to anthropogenic pressures. If this trend continues, the ecological function of mangroves as a natural buffer against global climate change will further decline, increasing the risk of carbon emissions being released into the atmosphere [19].

Thus, the analysis results indicate that the 412-ton decrease in carbon stock during the 2020–2025 period is closely related to the dynamics of mangrove density and health in Muaragembong. Significant reductions in the medium density and moderate health categories led to a decrease in total carbon, despite a slight increase in the high density and very healthy classes. Therefore, mangrove conservation and rehabilitation efforts, focusing on increasing the density from medium to high density and maintaining vegetation health, are crucial steps to ensure the sustainability of the ecosystem's carbon storage function [20].

FMJ-IM³ Model

The Faisal M. Jasin Integrated Mangrove Management Model (FMJ-IM³) is an adaptive and collaborative multi-stakeholder framework designed to support mangrove ecosystem health, increase blue carbon capacity, and coastal resilience in Indonesia. This model is applied in the Muara Gembong area, where mangrove vegetation is dominated by Avicennia marina (60%) and Rhizophora apiculata (40%). Vegetation conditions show an increase in the "very healthy" category of 1.41%, although there are still unhealthy areas due to the influence of acidic soil pH, muddy substrates, high salinity, and human activities such as fish ponds and settlements.

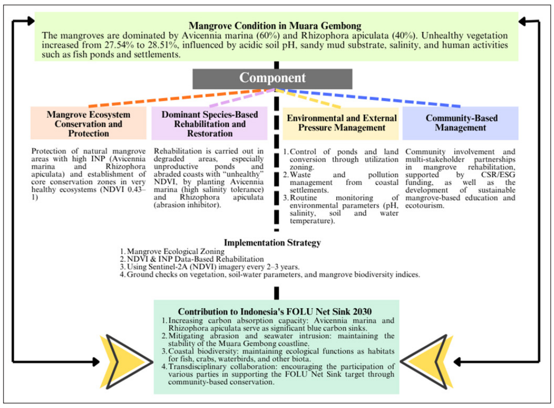

Figure 4: The Faisal M. Jasin Integrated Mangrove Management Model (FMJ-IM³): An Adaptive, Multi-stakeholder Framework for Mangrove Health, Blue Carbon, and Coastal Resilience in Indonesia

The FMJ-IM³ model has four main components: mangrove ecosystem conservation and protection, dominant species-based rehabilitation and restoration, environmental and external pressure management, and community-based management. Its implementation strategies include mangrove ecological zoning, NDVI and INP data-based rehabilitation, the use of Sentinel-2A imagery for six-year monitoring, and field inspections of vegetation, soil-water parameters, and biodiversity. The model's contribution to Indonesia's FOLU Net Sink 2030 target includes increasing carbon sequestration capacity through high-carbon-absorbing mangrove species, mitigating abrasion and seawater intrusion, enhancing coastal biodiversity, and a transdisciplinary approach involving various parties in supporting the sustainability goals of participatory and community-based mangrove rehabilitation.

Mangrove ecosystem management has become a critical issue in the context of sustainable development and climate change mitigation. Mangroves play a strategic role in maintaining coastal stability, absorbing blue carbon, and supporting biodiversity. However, pressures from land conversion, abrasion, and human activities are causing degradation that threatens their sustainability [21]. As awareness of the importance of conservation increases, various mangrove management models are being developed to integrate ecological, social, economic, and institutional aspects into a single, integrated system. Sarker, Gain, and Giupponi emphasize that mangrove management needs to be viewed as a complex socio-ecological system , where human and natural components influence each other. This approach encourages spatial data-based management, community participation, and adaptive models that can respond dynamically to environmental changes [22].

One proven effective model is Community-Based Mangrove Management (CBMM), which positions local communities as key actors in conservation [23]. According to Damastuti et al., community involvement in mangrove protection and rehabilitation not only improves ecosystem health but also strengthens their social and economic capacity. The success of such programs in various coastal areas of Indonesia demonstrates that local participation combined with education and traditional wisdom is key to sustainable mangrove management [24]. Furthermore, Arfan et al suggest that strengthening institutions and developing productive mangrove ecosystem-based businesses can be effective strategies for linking conservation with community economic well-being. For example, the development of ecotourism and mangrove-derived products such as processed food, crafts, and mangrove honey can create new economic value without damaging the environment [6].

In an institutional context, collaboration between stakeholders is a key success factor. Rumondang et al. explain that a co-management approach between the government, non-governmental organizations, the private sector, and coastal communities can create synergies that strengthen ecosystem sustainability [25]. This model emphasizes transparency, shared responsibility, and continuous evaluation so that decisions taken reflect ecological and social interests in a balanced manner. To strengthen policy effectiveness, various analytical tools such as the Driver–Pressure–State–Impact–Response (DPSIR) and the Analytic Network Process (ANP) are used to identify environmental pressures, ecosystem conditions, social impacts, and necessary policy responses.

Conclusion

The mangrove ecosystem in Muara Gembong District experienced a significant decline in health and carbon stocks during the 2020–2025 period. This condition has the potential to hinder the achievement of climate change mitigation targets if not accompanied by appropriate management interventions. An integrated approach combining mangrove health assessment, carbon stock estimation, and community-based management is an effective strategy to support Indonesia's 2030 Net Sink FOLU.

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