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Research Article

Landsat-Based Monitoring of Mangrove Blue Carbon Supporting Industry 5.0 in Gresik Coastal Area

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ABSTRACT

Mangrove ecosystems play a crucial role as blue carbon reservoirs while providing ecological services that support the sustainability of coastal environments. However, rapid industrial development in coastal areas has increased pressure on mangrove ecosystems, highlighting the need for efficient and data-driven environmental monitoring. This study aimed to estimate mangrove blue carbon potential using Landsat 8/9 satellite imagery and the Normalized Difference Vegetation Index (NDVI) to support the implementation of Industry 5.0 in coastal industrial areas of Gresik Regency, Indonesia. Spatial analysis was conducted using QGIS through NDVI calculation, land cover classification, and above-ground biomass (AGB) estimation based on an NDVI-derived allometric equation. Three industrial zones (Industry A, Industry B, and Industry C) were analyzed as representative study areas. The results showed that Industry C had the largest mangrove cover (26.30%), followed by Industry B (14.10%) and Industry A (8.77%). Nevertheless, Industry A exhibited the highest NDVI value (0.41) and the greatest estimated blue carbon stock (60.31 tC), followed by Industry C (54.21 tC) and Industry B (33.08 tC). These findings indicate that blue carbon storage is influenced not only by mangrove extent but also by vegetation quality, including canopy density, stand structure, and habitat fragmentation. The integration of remote sensing and Geographic Information Systems (GIS) provides an effective, low-cost, and repeatable approach for periodic mangrove monitoring. Furthermore, the resulting spatial information has significant potential to support environmental management, mangrove rehabilitation, Environmental, Social, and Governance (ESG) reporting, Corporate Social Responsibility (CSR) evaluation, and digital environmental monitoring systems aligned with the principles of Industry 5.0. This study provides an important baseline for sustainable mangrove management in industrial coastal landscapes while demonstrating the potential of satellite-based monitoring for data-driven decision-making.

Keywords: *Blue carbon, Mangrove, NDVI, Remote Sensing, Industry 5.0*

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Introduction

Mangrove ecosystems are among the world's most productive blue carbon sinks, with a carbon sequestration capacity 5 to 10 times higher than that of terrestrial tropical forests (Alongi, 2014; Donato et al., 2011). Their existence not only plays a strategic role in mitigating global climate change through carbon dioxide sequestration but also serves as a natural barrier protecting coastal areas from erosion and as a vital habitat for marine biodiversity (Murdiyarso et al., 2015). However, the rate of global mangrove degradation continues to increase significantly due to anthropogenic pressures, particularly in coastal areas that are centers of industrial growth and land-use conversion (Giri et al., 2011).

Gresik Regency, East Java, exemplifies the irony between accelerated industrialization and environmental sustainability. As the largest industrial area in the region, Gresik contributes significantly to economic growth, yet simultaneously fuels the accumulation of pollution including greenhouse gas emissions and heavy metal waste (Cu, Zn, Fe) in coastal waters (Werdianti, 2018; Fitriani et al., 2025). Although various corporate social responsibil-ity (CSR) programs have been promoted, the effectiveness of mangrove conservation and rehabilitation efforts is often not scientifically measurable. This is due to limitations in sustainable monitoring systems, resulting in policies that tend to be reactive and not data-driven (Maulidiyyah and Setiadi, 2023).

Conventional mangrove monitoring practices that rely on periodic field surveys face various challenges, ranging from high costs and limited spatial coverage to an inability to provide real-time data for strategic decision-making (Pham et al., 2019). As a result, the potential for carbon trading which should serve as an incentive for industry to preserve coastal ecosystems is difficult to realize due to the lack of accurate, verified carbon stock da-ta (Choudhary, Dhar, and Pawase, 2024). This situation creates a critical gap between the availability of technology and the need for sustainable environmental governance in coastal areas.

The industry 5.0 paradigm emerges as a revolutionary solution that bridges digital technological advancements with humanistic values and ecological sustainability (Nahavandi, 2019; Xu et al., 2021). In this context, satellite-based remote sensing technology and Geographic Information Systems (GIS) offer significant opportunities to map the distribution, density, and biomass of mangroves quickly, accurately, and cost-effectively (Bunting et al., 2018; Zhao et al., 2024). However, the use of these technologies in coastal indus-trial areas such as Gresik remains very limited and has not yet been integrated with smart monitoring systems oriented toward adaptive decision-making (Hammad et al., 2025). To date, there remains a research gap regarding the integration of vegetation index-based spa-tial analysis of mangroves with the industry 5.0 implementation framework in regions dominated by heavy industrial activities (Kur-niawan et al., 2025; Hadi et al., 2019).

Based on the above discussion, there remains a research gap regarding the utilization of remote sensing data not only for mapping mangrove cover but also for integrating it as a decision support system in the implementation of Industry 5.0 in coastal industrial areas. Most previous studies have focused on estimating biomass or mapping mangroves separately, whereas this study develops a spatial approach that integrates NDVI analysis, blue carbon stock estimation, and the industry 5.0 implementation framework as the basis for formulating strategies for environmental monitoring, mangrove rehabilitation, and the evaluation of data-driven Corporate Social and Environmental Responsibility (CSR) pro-grams. Thus, this study not only generates spatial information on blue carbon but also offers an adaptive conceptual monitoring model to support sustainable industrial area management.

Materials and Methods

Location and Instruments

The study was conducted in three industrial zones in Gresik Regency, classified as Industrial Zone A (located around the PT. Petrokimia area), Industrial Zone B (located around the PT. Maspion area), and Industrial Zone C (located in the JIPPE industrial area). The results from each of these selected locations are used solely as examples for estimation and do not directly represent the mangrove profile of a specific company. This study utilizes Geographic

Information System (GIS) technology to spatially analyze the blue carbon content of mangroves in these three industrial zones. The imagery data used is the latest from the USGS for the years 2025–2026. This method serves as a baseline for measuring blue carbon potential in support of Industry 5.0 implementation (Pham et al., 2019; Xu et al., 2021; Zhao et al., 2024). The analysis tool used was the QGIS application, with primary data consisting of Landsat 8/9 satellite imagery obtained from USGS Earth Explorer and Google Earth, as well as Administrative Boundary Vector (RBI) data from the Indonesian Geospatial Information Agency (BIG).

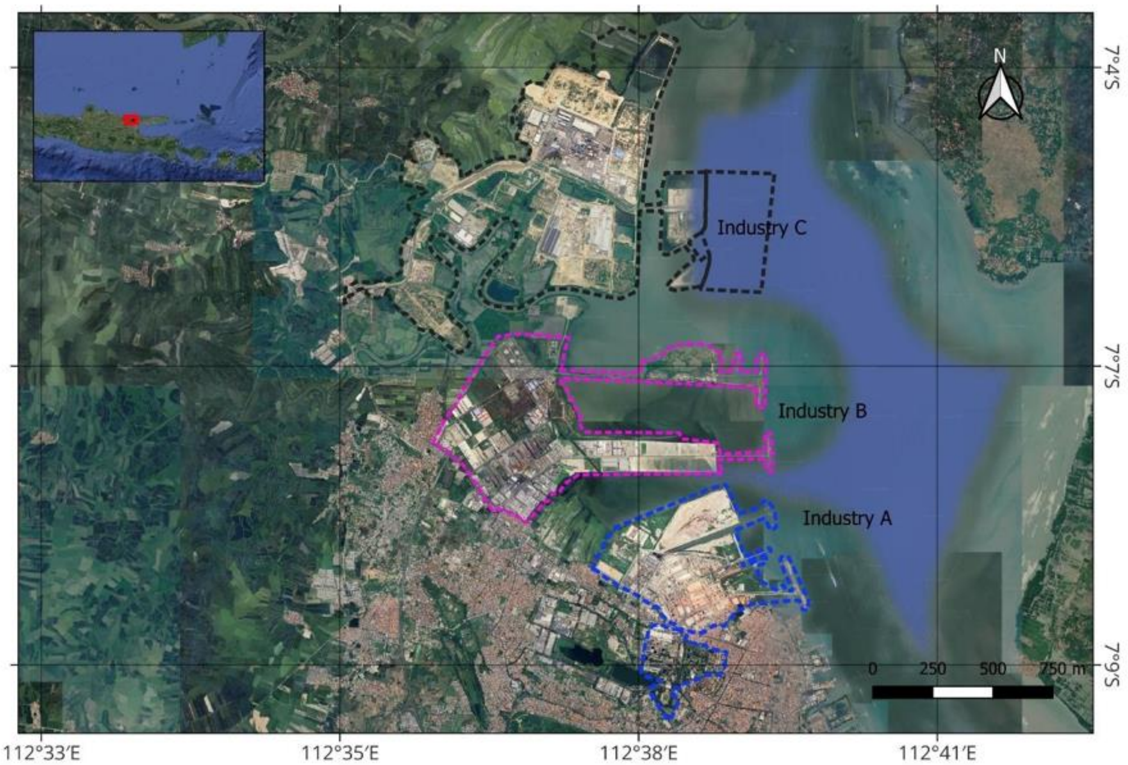

Figure 1. Location of the study areas for estimating mangrove blue carbon in several industrial zones in Gresik Regency

NDVI and Classification Analysis

The analysis process began by processing the Landsat 8/9 imagery by creating layers for bands 1 through 7. Level-2 Landsat 8 OLI/TIRS imagery was used because it had undergone radiometric and atmospheric corrections, allowing surface reflectance to be used directly in vegetation analysis. Images were selected with cloud cover levels below 10% to minimize interpretation errors. The entire process was carried out using the latest version of QGIS with the Semi-Automatic Classification Plugin (SCP). The data was then cropped (CLIP) according to the study area. The NDVI data was then analyzed using the formula from the study by Zhao et al. (2024):

NDVI = NIR Band 5-RED (Band 4)NIR Band 5+REDBand 4

where NIR corresponds to Band 5 and RED corresponds to Band 4 in Landsat 8/9 imagery. Next, land cover was classified us-ing the Semi-Automatic Classification (SCP) plugin in QGIS to distinguish three catego-ries: mangrove, non-mangrove, and areas without vegetation. The classification results were then used to calculate the area of each category.

Blue Carbon Estimation Analysis

Blue carbon estimation in this study was limited to indirect measurements (remote sensing-based estimation) using NDVI values. The NDVI results were then processed through the raster calculator using the equation from Hastuti et al. (2017):

AGB = 305.9 × NDVI4.9

where AGB represents above-ground biomass in units of metric tons per hectare. The obtained AGB values were then converted to total biomass per area by multiplying them by the effective area, defined as the number of pixels multiplied by the area per pixel (0.09 ha for 30-meter-resolution Landsat imagery). The total biomass is then converted into carbon stock using a conversion factor of 0.47, as per Hastuti et al. (2017), which assumes that 47% of the biomass consists of carbon. Supporting data on mangrove species for interpreting NDVI values and estimating carbon were obtained from various previous literature studies. Visual validation was conducted using high-resolution Google Earth imagery to ensure that the mangrove classification results matched actual conditions. Additionally, the estimation results were compared with several previous studies in Gresik Regency as a form of secondary validation.

Result and Discussion

Land Cover Classification and Non-Vegetation Area Dominance

The results of land cover classification using the Semi-Automatic Classification Plugin (SCP) method reveal variations in spatial structure across three industrial zones in Gresik Regency. Industrial Zone A has 8.77% mangrove cover, 21.50% non-mangrove vegetation, and 69.73% non-vegetation area. Industrial Zone B showed a mangrove coverage of 14.10%, non-mangrove vegetation of 15.31%, and non-vegetation areas of 70.59%. Meanwhile, Industrial Zone C had the highest mangrove coverage at 26.30%, with non-mangrove vegetation at 1.04% and non-vegetation areas at 72.65%. Although all three industrial zones still have mangrove coverage, all locations are dominated by non-vegetated areas— , accounting for more than 69%—which indicates a high intensity of land use for industrial activities. This situation aligns with the findings of Safitri (2022), who noted that some industrial zones in Gresik Regency have developed through land reclamation in coastal areas previously dominated by mangrove ecosystems. This process has led to a reduction in mangrove forest area due to land-use conversion for industrial development. The dominance of these non-vegetation areas has the potential to reduce blue carbon storage capacity; therefore, periodic monitoring of mangrove conditions using satellite imagery is crucial as a basis for environmental management and the implementation of the Industry 5.0 concept in coastal areas (Sidiq et al., 2025).

Table 1. SCP analysis results for land categorization

Location Name	Area (m^2)	Area (%)		
		Mangrove	Non-Mangrove	Non-Vegetation
Industry A	5,881,500	8.77%	21.5%	69.73%
Industry B	7,974,900	14.10%	15.31%	70.59%
Industry C	14,323,500	26.30%	1.04%	72.65%

According to Bunting et al. (2022), coastal areas in various regions are experiencing a relatively high rate of mangrove conversion due to anthropogenic activities, such as the development of industrial zones, settlements, and coastal infrastructure. This condition is also evident in the study area in Gresik Regency, which is still dominated by non-vegetated aeas. Industry C has the highest proportion of mangrove cover compared to Industry A and Industry B. This is likely due to the larger size of the study area, which still contains relatively extensive mangrove areas. However, the mapping results show that mangrove cover in Industry C is scattered across several separate fragments and does not form a continuous expanse. Bryan-Brown et al. (2020) state that mangrove habitat fragmentation can reduce its ecological function as a biological corridor, decrease the stands' resilience to environmental pressures, and increase the ecosystem's vulnerability to the accumulation of pollutants originating from industrial activities in coastal areas. Furthermore, Sasmito et al. (2020) emphasize that spatial connectivity among mangrove fragments is crucial for maintaining nutrient circulation, supporting fauna migration, and preserving the hydrological functions of coastal areas. Therefore, the information on mangrove cover percentage obtained in this study can serve as a baseline for the development of mangrove ecosystem monitoring and management programs by companies in Gresik Regency. This data can also be used as a basis for evaluating the effectiveness of mangrove rehabilitation programs and supporting the implementation of sustainable environmental management in line with the Industry 5.0 concept.

NDVI Analysis and Blue Carbon Potential

The Normalized Difference Vegetation Index (NDVI) values in the three industrial areas showed relatively small variations, ranging from 0.36 to 0.41. Industry A had the highest NDVI value at 0.41, followed by Industry C at 0.39 and Industry B at 0.36 (Figure 2). Based on these NDVI values, blue carbon stock estimates calculated using a vegetation index-based allometric approach yielded a total carbon stock of 60.31 tC in Industrial Area A, 54.21 tC in Industrial Area C, and 33.08 tC in Industrial Area B. Spatial mapping results show that areas with higher NDVI values generally have denser mangrove canopy cover, thereby contributing to higher estimated carbon stocks. Interestingly, Industry C, which has the largest proportion of mangrove cover (26.30%), does not exhibit the highest estimated carbon stock. Conversely, Industry A, with a smaller proportion of mangrove cover (8.77%), yielded a higher estimated carbon stock. This finding indicates that the magnitude of carbon stocks is influenced not only by the extent of mangrove cover but also by vegetation characteristics—such as canopy density, stand structure, and biomass—as reflected in the NDVI values. The high carbon estimate for Industry A, despite its smaller mangrove area, indicates that vegetation quality is more influential than the quantity of cover. NDVI represents the level of canopy greenness, which correlates with above-ground biomass. Therefore, areas with a smaller mangrove coverage but a denser canopy can yield higher carbon estimates compared to areas with a larger coverage but fragmented stands. This phenomenon was also reported by Kauffman and Bhomia (2021), who noted that stand structure is a dominant factor in determining mangrove carbon storage capacity.

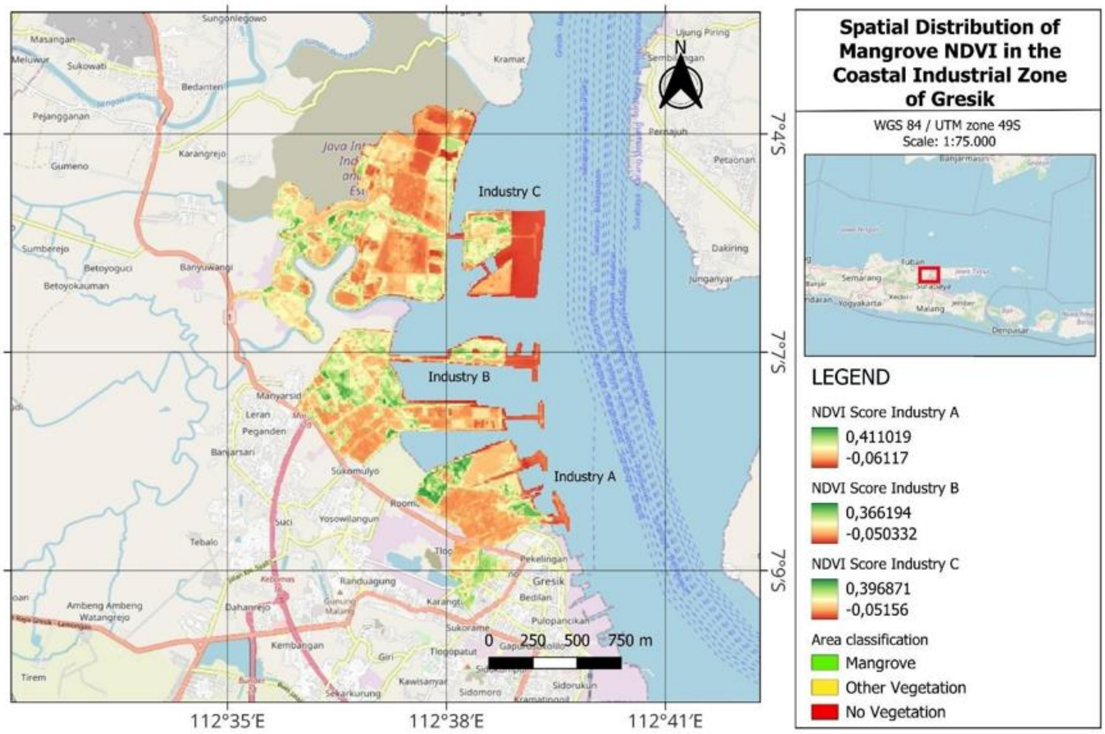

Figure 2. Spatial Distribution of Mangroves Based on NDVI Using Satellite Imager

Table 2. Results of NDVI Analysis and Total Blue Carbon

Location	NDVI	Total Blue Carbon (tC)
Industry A	0.41	60.31
Industry B	0.36	33.08
Industry C	0.39	54.21

The differences in mangrove cover area and estimated carbon stocks across the three industrial areas indicate that the magnitude of carbon stocks is not always directly proportional to the area of mangrove cover. In addition to area, the magnitude of carbon stocks is influenced by various vegetation characteristics, such as stand structure, tree age, species composition, and canopy density. Based on the results of a mangrove vegetation inventory in the coastal areas of Gresik Regency, the mangrove ecosystem is dominated by *Avicennia marina*, with *Rhizophora mucronata* as one of the primary constituent species of the mangrove community. The dominance of these two species has also been reported in the Ujung Pangkah and Tanjung Widoro areas of Gresik Regency, reflecting the general characteristics of mangrove vegetation along the northern coast of East Java (Mabruroh et al., 2025; Maharani et al., 2023).

Kauffman and Bhomia (2021) reported that healthy *Rhizophora* stands can store approximately 100–150 tC/ha of carbon, while mature *Avicennia* stands range from 40–70 tC/ha. In contrast, the estimates from this study indicate relatively lower carbon stocks. This discrepancy suggests that the condition of mangrove stands in the study area has likely not yet reached optimal carbon storage capacity. These findings align with the study by Hidayah et al. (2022) in the eastern coastal area of Surabaya, which showed that the magnitude of mangrove carbon stocks is significantly influenced by vegetation density and stand biomass, rather than solely by the area of mangrove cover.

Furthermore, changes in the extent and distribution of mangroves along the coast of Gresik Regency during the 2012–2023 period were also reported to affect blue carbon storage capacity, as changes in vegetation cover density correlate with biomass and stored carbon stocks (Muryani & Ni'matussyahara, 2024). Therefore, the low estimated carbon stock in this study is suspected to be influenced not only by the extent of mangrove cover but also by the ecological conditions of the coastal area, which are affected by industrial activities. Handayanto et al. (2017) noted that industrial activities can release heavy metals—such as copper (Cu) and zinc (Zn)—which are believed to inhibit mangrove growth by hindering stem development. Consequently, increasing mangrove coverage through rehabilitation must be accompanied by efforts to improve coastal environmental quality so that blue carbon storage capacity can be optimally enhanced.

Implications for Industry 5.0

This study demonstrates that the use of spatial data enables companies to conduct periodic monitoring of blue carbon without the need for costly field surveys. The integration of remote sensing data with Internet of Things (IoT) technology, Artificial Intelligence (AI), and Geographic Information System (GIS)-based dashboards has the potential to create a real-time environmental monitoring system aligned with the industry 5.0 paradigm. In addition to enhancing the effectiveness of mangrove rehabilitation, this system can serve as the foundation for preparing Environmental, Social, and Governance (ESG) reports, conducting TJSL assessments, and developing carbon trading schemes in coastal industrial areas. This study integrates this spatial information as the basis for implementing the industry 5.0 concept, which emphasizes a balance between technological advancement, environmental sustainability, and data-driven decision-making (Wahyuni et al., 2024). The resulting NDVI distribution map (Figure 2) and carbon stock estimates (Table 2) provide spatial information on mangrove vegetation conditions, which can be utilized as a basis for developing Corporate Social Responsibility (CSR) programs, mangrove rehabilitation, and the evaluation of coastal zone management in Gresik Regency.

Furthermore, the resulting spatial database has the potential to be integrated with monitoring systems based on the Internet of Things (IoT), machine learning, and remote sensing to support periodic monitoring of mangrove conditions, early detection of changes in vegetation cover, and the evaluation of the effectiveness of sustainable rehabilitation efforts (Oktavian, 2025). Thus, this study not only provides information on the distribution of mangrove cover and blue carbon stocks but also lays a scientific foundation for the development of an adaptive, data-driven coastal ecosystem monitoring system in line with Industry 5.0 principles. This study still employs an NDVI-based estimation approach; therefore, it does not account for below-ground carbon or sediment carbon, which are key components of blue carbon. Furthermore, no field biomass measurements have been conducted; therefore, the results of this study are more appropriately used as a baseline for monitoring rather than as absolute values of carbon stocks. From a plant ecology perspective, changes in the structure and density of mangrove vegetation due to anthropogenic pressures are important indicators reflecting changes in coastal ecosystem functions. A decrease in canopy density not only reduces the vegetation's ability to absorb carbon but also affects primary productivity, habitat stability, and the sustainability of coastal biota communities. Therefore, spatial monitoring of mangrove vegetation conditions is a crucial component of coastal landscape ecology studies.

Conclusion

This study shows that analysis of *the Normalized Difference Vegetation Index* (NDVI) using Landsat imagery can characterize variations in mangrove vegetation structure while estimating the potential blue carbon stock in the coastal industrial area of Gresik Regency. Differences in carbon values obtained at each location indicate that carbon storage capacity is influenced not only by the extent of mangrove cover but also by the ecological conditions of the vegetation, such as canopy density, stand structure, and the degree of habitat fragmentation. These findings suggest that changes in vegetation structure resulting from industrial pressures have the potential to affect the ecological functions of mangroves as carbon sinks, coastal protectors, and habitat providers for various organisms. Therefore, remote sensing-based vegetation monitoring can serve as an effective approach for periodically evaluating mangrove ecosystem dynamics and supporting the development of data-driven strategies for coastal conservation and management. Future research is recommended to integrate field biomass measurements, subsurface carbon analysis, and high-resolution imagery to improve the accuracy of estimates and deepen our understanding of the ecological response of mangrove vegetation to environmental pressures. In addition to providing information on the ecological condition of mangroves, the spatial data generated also has the potential to serve as the basis for developing a digital-based environmental monitoring system to support the implementation of Industry 5.0 in the management of coastal industrial areas.

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