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RESEARCH ARTICLE

Assessment of Mangrove Species Composition, Biomass, and Carbon Stock Potential for Climate Change Mitigation in Pekalongan, Indonesia

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ABSTRACT

Mangrove forests are vital coastal ecosystems that support biodiversity and deliver key ecological services, particularly in tropical regions. In Pekalongan, Central Java, rapid coastal development and land-use change threaten their ecological integrity, particularly their role in carbon sequestration. This study assessed mangrove species richness, biomass, and carbon stock in both conservation and non-conservation areas to evaluate their ecological status and contribution to climate change mitigation. Six sampling sites, comprising protected and unprotected areas, were surveyed using 60 nested square plots to record tree and sapling populations. Biomass estimates, including above and below ground components, were calculated through specific allometric models. Results showed that conservation areas stored higher carbon (248.82 tC ha^{-1}) than non-conservation sites, though Degayu which an unprotected area had the second-highest carbon stock (159.66 tC ha^{-1}). Among species, *Sonneratia alba* contributed the most carbon, while dense saplings of *Rhizophora apiculata* and *Bruguiera gymnorhiza* suggest potential shifts in species dominance. The mean carbon stock (125.02 tC ha^{-1}, equivalent to 495.07 t CO_2e ha^{-1}) indicates substantial emission risks if degradation occurs. These findings underscore the critical role of both conservation and non-conservation mangroves in climate regulation and align with Indonesia's current policy focus on blue carbon ecosystems, coastal resilience, and community-based conservation.

Introduction

Mangrove forests are globally acknowledged as essential ecosystems that deliver numerous critical ecological and socioeconomic services, collectively defined as ecosystem services (ESs) [1,2]. These services encompass provisioning roles, including functioning as nurseries, spawning, and feeding habitats for diverse coastal species and fisheries [3], as well as crucial regulatory services [4]. Particularly in carbon and climate regulation, mangroves are recognized as highly efficient carbon sinks within tropical regions [5]. They rank among the most carbon-rich forests worldwide and can store up to three times more carbon per hectare than other tropical forests [6].

Indonesian mangrove ecosystems notably exhibit higher carbon storage and faster sequestration rates than terrestrial tropical forests [7,8]. The function of the mangrove ecosystem as a carbon reducer makes it a crucial factor for the future of the Earth [7]. Indonesia, a tropical country in Southeast Asia, has emerged as a potential carbon reduction zone in recent decades [8]. Indonesia currently harbors the world's largest mangrove expanse, estimated at approximately 3 to 3.3 million hectares [9], with a national carbon sequestration potential reaching 3.0 gigatons (Gt C) [10]. These attributes underscore the pivotal role of mangroves in national and global climate mitigation strategies [11]. However, ongoing deforestation and degradation threaten these vital ecosystems [12].

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The mangrove forest ecosystem in Indonesia, as an archipelagic state structure, has an extraordinary potential capacity for carbon absorption process on earth [5]. In contrast, the conservation and sustainable management of mangroves provide a cost-effective approach for reducing greenhouse gas emissions and mitigating the impacts of climate change [6]. As fluctuations in mangrove carbon stocks directly affect atmospheric CO_2 concentrations [13,14], continuous monitoring and accurate quantification of these stocks are imperative to inform effective conservation efforts and carbon management.

Along the Pekalongan coastline, mangrove forests exist as fragmented patches distributed across various coastal features, such as bays, deltas, and estuarine riverbanks, spanning both conservation and non-conservation areas. Previous research estimated mangrove biomass carbon at 18.53 tC ha^{-1} in Indonesia but lacked a detailed spatial analysis of carbon stocks within fragmented zones [15]. Moreover, recent land-use changes and rehabilitation efforts in the region may have substantially altered mangrove biomass and carbon dynamics; however, updated empirical data remain scarce. This study urgently fills critical knowledge gaps by producing up-to-date, spatially detailed data on mangrove biomass and carbon stock distribution in Pekalongan. The evidence generated is essential for shaping effective local conservation strategies and strengthening climate-change mitigation policies.

Materials and Methods

Study Area

This study was conducted in Pekalongan, located on the island of Java, Indonesia (Figure 1). The mangrove ecosystem in the area extends from the estuarine zones to the riverine environments. Six sampling sites were selected, each comprising two sampling stations. These included Krapyak and Wonokerto, classified as local conservation areas, and Jeruksari, Degayu, Siwalan, and Mulyorejo, representing non-conservation zones. All locations are spread across the coastal areas of Pekalongan Regency and City in an integrated manner. Fieldwork will be conducted between April and May 2025.

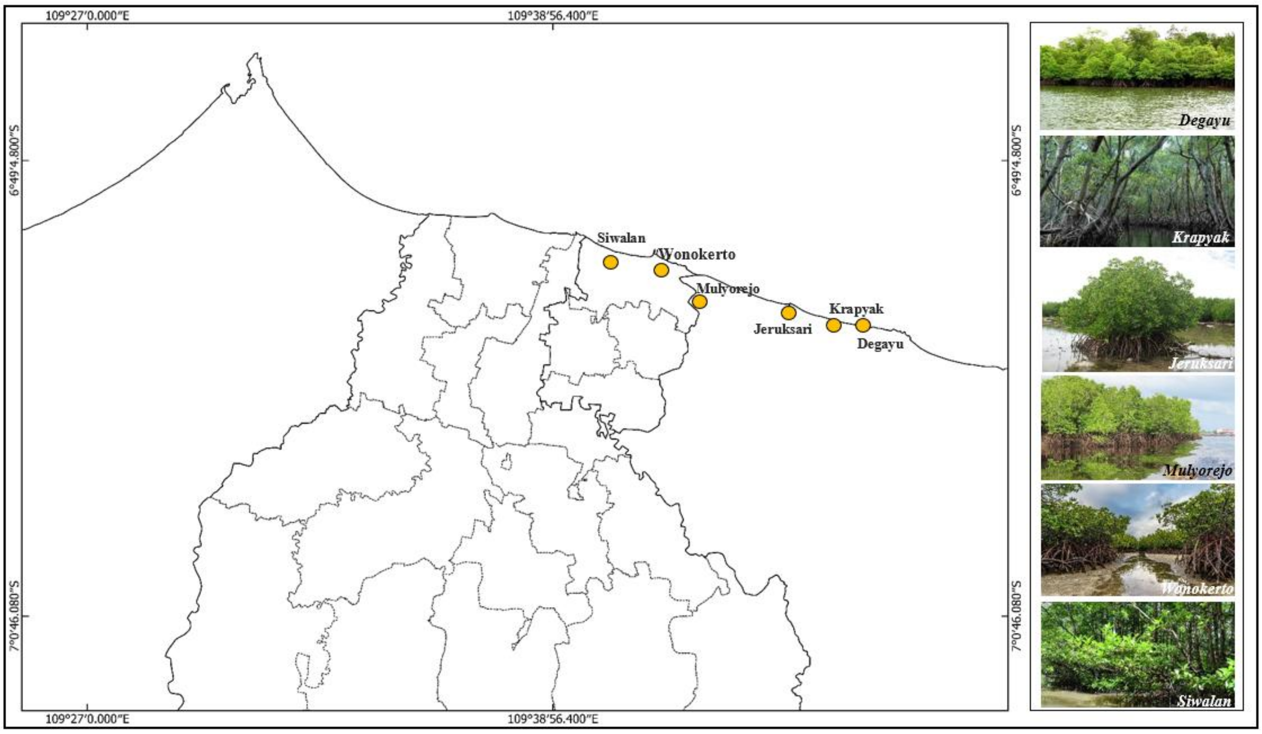


Figure 1. Research location map in coastal areas of Pekalongan Regency and City, Indonesia. Sampling was carried out in the areas of Degayu, Krapyak, Wonokerto, Jeruksari, Siwalan, and Mulyorejo.

Methods and Sampling Design

Sampling followed the carbon measurement protocol for mangroves [16]. Ideally, the number of plots should be calculated to achieve a precision of 10% for optimal accuracy. However, preliminary estimates showed that reaching this level of precision would require a very large number of plots around a hundred which was beyond the available resources. Consequently, a 20% precision level at a 95% confidence interval was adopted in accordance with the Standar Nasional Indonesia (SNI) 7724:2011 [17]. The number of plots was determined using equation (1) [16].

$$n = \left(\frac{txS}{E}\right)^2 \quad (1)$$

where n is the number of sampling plots, t is the t-statistic for the 95% confidence interval, S is the standard deviation (estimated or based on prior data), and E is the allowable error, calculated by multiplying the mean carbon stock by the desired level of precision.

Data Collection

Based on the above formula, approximately 60 sampling plots were deemed necessary. These were structured using a nested quadrat design with five plots established in each pair of stations per location. The plot sizes were 10 × 10 m^2 for trees with a diameter at breast height (DBH) greater than 10 cm and 5 × 5 m^2 for saplings with DBH less than 10 cm [18]. The plots were positioned perpendicular to the shoreline or riverbanks and aligned in a linear transect to capture the proximal, medial, and distal zones. In areas where mangrove cover was sparse, plot placement was adjusted according to mangrove sampling guidelines [19]. Species identification was conducted using a mangrove identification guide [20].

Estimation of Biomass and Carbon Stock

Biomass and carbon stock assessments were conducted using a non-destructive direct method through species-specific allometric equations. As noted, the direct method is more accurate for estimating biomass and carbon than indirect approaches that rely on volume, form factors, or biomass expansion factors [21]. Allometric models used to estimate above-ground biomass (Wtop) and below-ground biomass (WR) for each species are listed in Table 1. In cases where specific allometric equations were unavailable, generalized models were applied [22]. These models incorporate species wood density values, as detailed by Kangkuso et al. and Kesuma et al. [22,23] in Table 2.

At this stage, an estimate of the mangrove carbon stock will be conducted. This was done to determine the efficiency of carbon absorption by mangrove trees per unit time and area. Carbon stock (expressed in tC ha^{-1}) was calculated by multiplying the biomass by its corresponding carbon fraction (CF). Common practice uses default CF values from sources such as SNI 7724:2011 [17]. It is recognized that below-ground biomass (WR) typically has a lower carbon concentration than above-ground biomass (Wtop) [16]. Accordingly, CF values of 0.47 for Wtop and 0.39 for WR were applied [22] which expressed in equation (2).

$$Cstock = (Wtop \times CF\ Wtop) + (Wr \times CF\ Wr) \quad (2)$$

where *CF Wtop* is the carbon fraction of *Wtop* (0.47) [17] and *CF Wr* is the carbon fraction of *Wr* (0.39) [22].

Table 1. Selected specific and general-purpose allometric formulas. This formula is used to estimate the allometric length of mangrove plants in natural ecosystems.

Species	Allometric (Wtop)	r^2	References
Avicennia marina	$0.1718\ D^{2.45}$	0.98	[23]
Bruguiera gymnorrhiza	$0.177\ D^{2.21}$	0.97	[23]
Ceriops tagal	$0.518\ D^{2.01}$	0.99	[23]
Lumnitzera racemosa	$0.122\ D^{2.14}$	0.98	[23]
Rhizophora apiculata	$0.231\ D^{2.37}$	0.99	[22]
Rhizophora spp.	$0.115\ D^{2.58}$	0.98	[22]
Xylocarpus granatum	$0.1621\ D^{2.21}$	0.98	[22]
Common equation	$0.245\ \rho\ D^{2.31}$	0.95	[22]
Common equation	$0.188\ \rho^{0.899}\ D^{2.01}$	0.99	[22]

Table 2. The wood density of various mangrove species (mg cm^3). This formula is used to estimate the wood density of various mangrove species in natural ecosystems.

Species	Allometric	References
Avicennia marina	0.44	[23]
Bruguiera gymnorrhiza	0.57	[22]
Ceriops tagal	0.68	[22]
Lumnitzera racemosa	0.60	[23]
Rhizophora apiculata	0.62	[22]
Rhizophora stylosa	0.81	[23]
Xylocarpus granatum	0.58	[22]
Lumnitzera littorea	0.64	[23]
Sonneratia alba	0.48	[22]

Uncertainty Estimation

Estimating carbon stocks in mangrove biomass inevitably yields uncertain values. This can occur due to large deviations in the calculated values and imprecise sampling techniques (Equation 3). To assess the level of uncertainty in carbon stock estimation, the standard deviation (SD) and sampling error (SE) were calculated at the stand level. Additionally, to support climate change mitigation assessments, carbon stocks were converted into CO_2 equivalents (CO_2e). The equations for these calculations were based on the methodology outlined in a previous study [16].

$$Uncertainty\ (\%) = \sqrt{([95\%\ CIcwtop]^2 + [95\%\ CIcwr]^2)} \quad (3)$$

Where, 95% CI half-width = 2 × SE; CO_2e = (Mw.CO_2 / Aw.C) × Cstock; Mw.CO_2 – molecular weight of CO_2 (44); Aw.C – atomic weight of C (12); and C stock – carbon stock (ton C ha^{-1}).

Environmental Parameters

The environmental parameters observed in this study included salinity, soil pH, temperature, dissolved oxygen, total nitrogen, and total phosphorus content. All parameters were analyzed at the Soil and Water Quality Laboratory of the Pekalongan University. Furthermore, to determine the relationship patterns among these parameters, a cluster analysis was performed using PAST 4.03.

Results and Discussion

Results

Mangrove Species Richness

Nine mangrove species from five different families were identified across six sampling locations (Table 3). Among these, *Avicennia marina* and *Rhizophora apiculata* were consistently present at all sites, whereas *R. cf. stylosa* and *Lumnitzera racemosa* appeared only at a single location. This study shares notable similarities with the findings of Farahisah et al. [15], who also reported nine mangrove species in Pekalongan City. However, several new species recorded in this research, namely *A. marina*, *R. cf. stylosa*, and *L. racemosa* had not been previously documented.

The widespread presence of *A. marina*, *R. apiculata*, and *Sonneratia alba* is likely due to their strong ecological tolerance. According to Istomo et al. [20], species of the *Avicennia* genus are highly adaptable to varying salinity levels, and *A. marina* can thrive in both saline and freshwater conditions. *R. apiculata* typically inhabits muddy substrates frequently inundated by tides [20,24], whereas *S. alba* prefers mixed mud-sandy substrates, which are common in the study areas [25]. These ecological traits explain their high occurrence at the sampling sites. In contrast, the limited presence of *R. stylosa* and *L. racemosa* could be attributed to anthropogenic pressures such as wood harvesting, land conversion, and specific substrate preferences. *L. racemosa* typically favors solid muddy substrates, while the observed sites primarily feature light mud-sandy substrates, less suitable for this species [20].

The mangroves along the Pekalongan coast are extremely diverse and unique in their composition. This analysis was based on the varying species rich at each location within the Pekalongan coastal area. Based on Table 3, further indicates that Wonokerto hosted the highest species richness. This site is in a riverine environment, away from the estuary but connected to Siwalan via a man-made tidal channel, creating a gradient of salinity favorable to various species of fish. In contrast, Krapyak and Jeruksari had the fewest number of species. Krapyak is directly situated in the estuary, and Jeruksari is in close proximity to the Pekalongan estuary, which likely subjects it to high salinity conditions, limiting species diversity to salt-tolerant types [20].

Table 3. Presence and distribution of mangrove species at study sites. There are nine mangrove species identified at the research site spread across six different locations.

No.	Species		Locations					
	Scientific name	Local name	Krapyak	Jeruksari	Wonokerto	Degayu	Siwalan	Mulyorejo
1	*Avicennia marina*	Api-api	+	+	+	+	+	+
2	*Rhizophora apiculata*	Bakau minyak	+	+	+	+	+	+
3	*Sonneratia alba*	Pidada	+	+	+	+		+
4	*Bruguiera gymnorrhiza*	Mangi-mangi	+	+	+		+	
5	*Ceriops tagal*	Soga	+					+
6	*Lumnitzera littorea*	Teruntum merah			+		+	
7	*Xylocarpus granatum*	Nyirih			+	+		
8	*Lumnitzera racemosa*	Teruntum putih						+
9	*Rhizophora stylosa*	Bakau pasir					+	

Biomass and Carbon Stock

The study estimated that the average total mangrove biomass (Wtot) and carbon stock (C-stock) across all sampling locations were 231.52 ton ha^{-1} and 28.93 tC ha^{-1}, respectively (Table 4). These figures are considered relatively high, especially since carbon stock values exceeding 100 tC ha^{-1} are generally classified as high. For reference, the High Carbon Stock (HCS) approach designates areas with more than 50 tC ha^{-1} as high carbon stock zones; values below often indicate degraded land or sparse vegetation, despite being in forested or agricultural areas [26]. Table 4 also includes average values for above-ground (Wtop), below-ground biomass (WR), and total uncertainty in the carbon estimates.

Table 4. The average biomass and carbon stock at the study site. This data presents data on carbon biomass absorption by the mangrove ecosystem in the coastal area of Pekalongan.

Value	Wtop	WR	Wtot	Cwtop	CWR	Cstock
Average (ton/ha)	185.05	65.11	231.52	87.44	28.93	113.18
Standard error	13.25	5.30	19.23	6.32	2.41	15.42
CI half-width	*	*	*	18.26	6.85	19.37
Total uncertainty (%)	*	*	*	*	*	15.33

Compared with earlier studies, the biomass and carbon stock in this study were significantly higher. Mangrove biomass and carbon stock values of 37.06 ton ha^{-1} and 18.53 tC ha^{-1}, respectively [15]. In another study, 32.9 ton ha^{-1} of biomass was recorded, which is approximately seven times lower than our findings [25]. This substantial disparity may be attributed to factors such as natural growth, shifts in mangrove coverage, and differences in sampling methodologies. While natural growth may have contributed marginally, it is unlikely to be the main reason. Trunk diameter growth rates for the identified mangrove species typically range from 0.4–1.8 cm year^{-1} [27,28], and the mean annual increment (MAI) for secondary mangrove carbon stock is approximately 2.8 tC ha^{-1} year^{-1} [29]. Based on previous stock estimates, this would result in a current projection of 30–40 tC ha^{-1}.

Changes in mangrove coverage in the region are also an unlikely explanation. While research estimated the current mangrove area in Bengkulu City at 242.35 ha [30], slightly more than the 214.62 ha reported by another study [15], the increase does not sufficiently account for the massive carbon stock difference. Thus, variations in research design and methodology, such as the number of plots, plot placement, data analysis techniques, and potential sampling errors, are likely the main contributors to this discrepancy [31].

This reinforces the importance of reporting sampling errors in carbon stock studies, as highlighted [16]. The uncertainty in this study was 13.41% at a 95% confidence interval (Table 4) slightly above the ideal level (<10%) but still within the acceptable 20% threshold [17]. This places the estimated carbon stock between 116–153 tC ha^{-1}. Such a high estimate can also be attributed to the large tree diameters and high stem density recorded at the site, which is consistent with previous findings [32]. As shown in Table 5, the average large tree density was moderate (553 ind ha^{-1}), whereas the sapling density was high (2,885 ind ha^{-1}), resulting in a combined density of 3,437 ind ha^{-1}. The mean tree diameter was also relatively large at approximately 20 cm. This correlation between tree size, density, and biomass/carbon stock has been supported by previous studies [18,32,33].

Table 5. Average diameter and density between study site locations. This formula is used to estimate the average diameter and density of mangrove trees sampled at different study locations. This is done to determine the resistance of the mangrove trees to differences in physical size.

Location (n = 60)	Mean diameter (cm)		Individuals counted			Density (ind ha^{-1})		
	Sapling	Tree	Sapling	Tree	Total	Sapling	Tree	Total
Krapyak	3.75	21.88	110	65	175	4,512	650	5,162
Jeruksari	5.18	18.23	105	60	165	1,080	600	1,680
Wonokerto	3.77	18.32	107	45	152	4,265	475	4,740
Degayu	5.67	13.47	87	40	127	3,525	400	3,925
Siwalan	5.42	24.57	69	61	130	2,600	630	3,230
Mulyorejo	5.61	21.16	32	57	89	1,325	560	1,885
Average	4.90	19.61	85	55	140	2,885	553	3,437

Biomass estimates for the tree and sapling categories across the sites are illustrated in Figure 2. Overall, tree biomass (W-tree) exceeded 154 t ha^{-1} in most areas, except for Siwalan, where sapling biomass (W-sapling) was higher than tree biomass. Typically, tree-level biomass (DBH > 10 cm) exceeded that of saplings (DBH < 10 cm), except in Mulyorejo, where saplings had higher biomass and carbon stocks. This anomaly may be due to the higher sapling density and larger average diameters in that category, as shown in Table 5. Consequently, the carbon derived from saplings surpassed that of mature trees at this location (Figure 2).

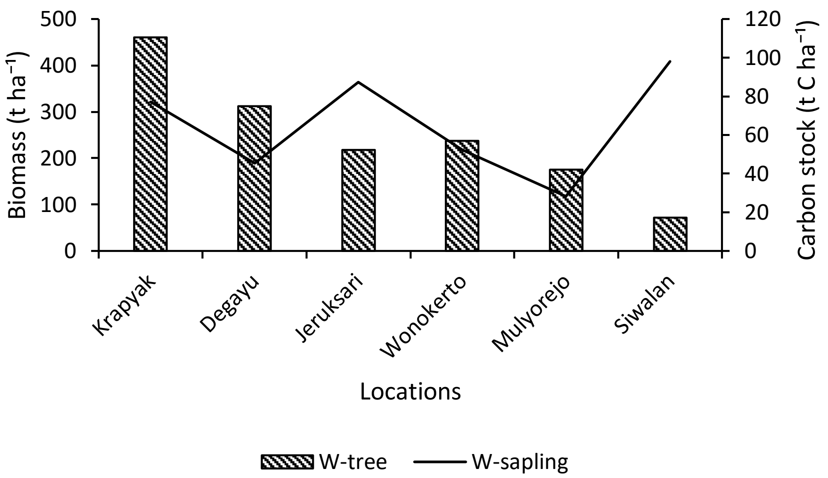


Figure 2. Biomass estimates for tree and sapling categories at the research site. Results of the calculation of estimates of active mangrove saplings in the coastal area of Pekalongan.

Biomass and Carbon Stock Distribution Across Locations

The dynamic conditions of the Pekalongan coastline and careful sampling of research data provided a picture of variations in biomass and carbon stocks across regions. This is understandable, given the differences in mangrove density and carbon absorption capacity at each site. This study found notable variations in biomass and carbon stock across the six research locations, with Krapyak and Siwalan showing the highest and lowest values at 212.33 tC ha^{-1} and 69.24 tC ha^{-1}, respectively. The remaining four sites exhibited intermediate values ranging from 93 to 147 tC ha^{-1}, as illustrated in Figure 3.

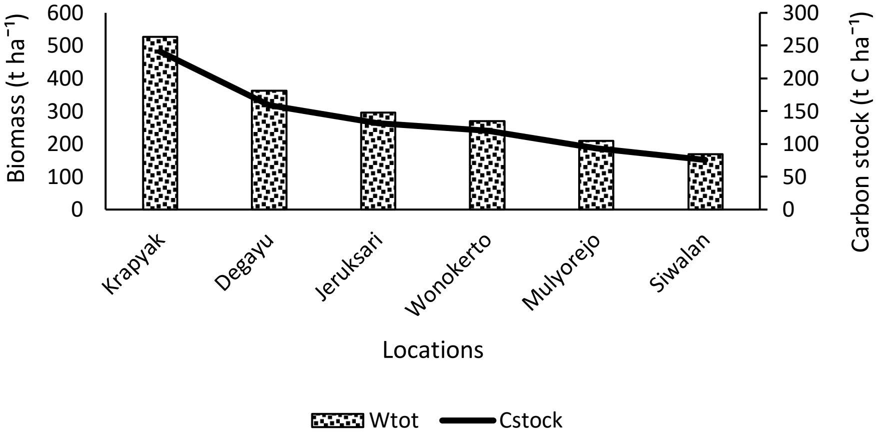


Figure 3. Biomass and carbon stock variation among different locations. The results of the calculation of the estimated variation in biomass and carbon stock of active mangrove trees in the coastal area of Pekalongan.

Interestingly, although Krapyak recorded the highest carbon stock, it ranked second lowest in overall mangrove density (Figure 2 and Table 5). This seemingly contradictory result could be attributed to the presence of numerous mature trees with large diameters at this location, which is reflected in its relatively high tree density (630 ind ha^{-1}) and the largest average tree diameter (24.57 cm) among all sites (Table 5). These findings reinforce the notion that biomass is not solely determined by tree density; rather, it is also strongly influenced by tree size, as indicated by the volume and basal area [18]. The conservation status of Krapyak, along with its proximity to the Krapyak and Wonokerto Local Nature Park management offices, likely contributes to limited anthropogenic disturbance, thereby preserving large mangrove trees.

The data show that areas within ecosystem protection areas tend to have higher habitat and carbon absorption capacities than non-conservation areas. This condition is illustrated in Figure 4. In Figure 4 presents a comparison of biomass and carbon stock between conservation and non-conservation areas. The conservation zones include Krapyak, Wonokerto, and Jeruksari, whereas the remaining locations fall under non-conservation jurisdictions.

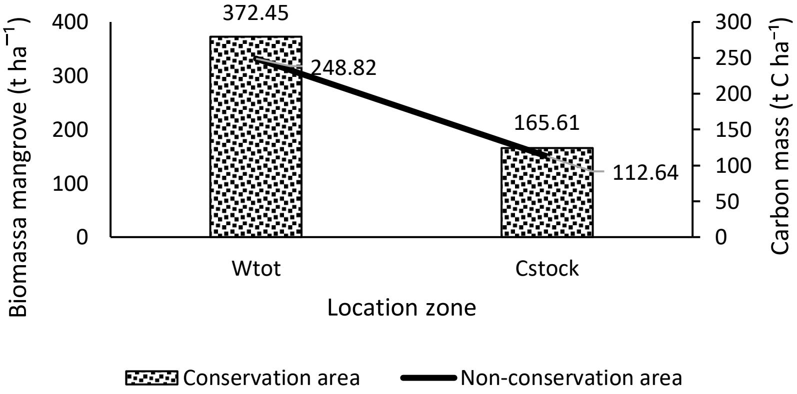


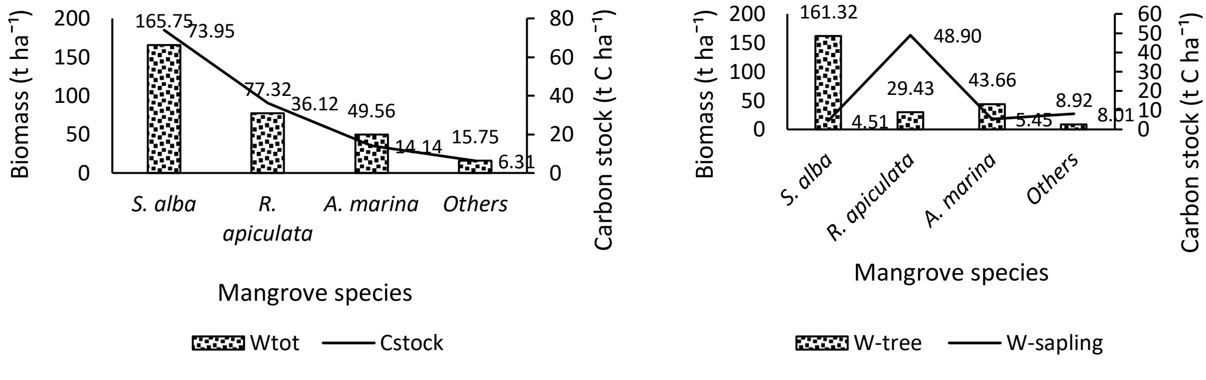
Figure 4. Biomass and carbon stock differences in conservation versus non-conservation zones. These results are comparative values of mangrove biomass and carbon stocks in conservation and non-conservation areas.

On average, conservation sites stored more carbon (248.82 tC ha^{-1}) than non-conservation sites (112.64 tC ha^{-1}). However, carbon levels in non-conservation areas remained substantial, exceeding 100 tC ha^{-1}, despite their private or community management status. Notably, Degayu, a non-conservation site situated adjacent to Wonokerto and separated only by a road, recorded the second-highest carbon stock at 159.66 tC ha^{-1} (Figure 3). Prior studies have also emphasized the carbon storage potential of mangroves outside protected zones [34,35], particularly because conservation areas represent only 22% of Indonesia's total mangrove coverage [36].

Nonetheless, mangroves in unprotected regions face a higher risk of degradation owing to land-use changes. Field surveys have observed several instances of mangrove clearing for aquaculture, residential expansion, and infrastructure development. Therefore, as argued for stakeholder involvement in managing protected mangroves, similar collaborative governance is crucial for non-conservation areas [36]. Sustainable initiatives, such as mangrove ecotourism and silvofishery (integrated aquaculture), can ensure both ecosystem preservation and community welfare.

Biomass and Carbon Distribution by Species and Growth Class

Species-level analysis revealed that *S. alba*, *R. apiculata*, and *A. marina* contributed the most to total biomass and carbon storage (Figure 5a). The other six species contributed relatively little to the total biomass. The combined biomass of the six minor species was lower than that of *A. marina* alone. Regarding the growth class, trees account for most of the biomass in most species, especially *S. alba* and *A. marina* (Figure 5b). However, *R. apiculata* was an exception, with saplings contributing more biomass than mature trees, likely because of its significantly higher sapling density.



(a) (b)

Figure 5. (a) Variation in biomass and carbon stock between species; (b) Tree and sapling biomass distribution among species within the study area (t ha^{-1}). These results describe the physical and biological diversity of the mangrove ecosystem in each research area.

Each mangrove species in this study has unique characteristics. This can be observed from the physical morphology of the mangrove plants and the estimated carbon stock absorption. As detailed in Table 6, *S. alba* had the highest carbon stock owing to its large trunk diameter, despite its moderate density. Most of these large individuals were found near the conservation office. Conversely, species such as *L. littorea*, *X. granatum*, *R. stylosa*, *L. racemosa*, and *C. tagal* had fewer individuals and smaller biomass contributions, even though their diameters were not substantially different.

Table 6. Mean tree diameter and stand density of mangrove species at the research location. These results describe the physical diversity of mangrove trees at each sampling location.

Species	Mean diameter (cm)		Density (ind ha^{-1})		
	Sapling	Tree	Sapling	Tree	Total
Rhizophora apiculata	5.15	13.12	2,000	164	2,164
Bruguiera gymnorhiza	3.12	12.25	738	15	753
Sonneratia alba	4.13	27.24	343	226	569
Avicennia marina	5.77	19.73	259	113	372
Lumnizera littora	6.13	13.26	78	14	92
Xylocarpus granatum	7.6	13.47	25	23	48
Rhizhophora stylosa	0.01	14.32	1	19	20
Lumnitzera racemosa	8.75	0.00	8	0	8
Ceriops tagal	5.14	0.00	7	2	9
Total number of individual (ind ha^{-1})			3,459	576	4,035

The total mangrove density was high at 4,035 ind ha^{-1}, meeting the Ministry of Environment's criteria for high-density mangrove stands (> 1,500 ind ha^{-1}) [37]. This is consistent with the findings of other studies, although minor discrepancies may arise from differences in plot size and diameter thresholds [25]. Moreover, the high sapling densities of *R. apiculata* and *B. gymnorhiza* suggest their potential to replace *S. alba* as the dominant species in the future.

Environmental Parameter Results

The environmental parameters observed at each research station are listed in Table 7. In general, the water and soil quality parameters at each observation station did not show any striking differences. The uniformity of these environmental parameters is since all sampling locations were situated within the same area, namely, the northern coastal zone of Pekalongan. The topographic conditions of the region also influence the water and soil quality profiles of coastal areas. These environmental factors affect the growth of mangrove ecosystems.

Table 7. Environmental quality profile (water and soil) at the sampling stations. This is a profile of environmental quality in the coastal area of Pekalongan in general, seen from the quality of the water and soil.

Location	Environmental parameters					
	Salinity	pH soil	temperature	Dissolved oxygen	N Total	P Total
Krapyak	25	7.1	28.75	4.11	2.05	0.44
Jeruksari	22	7.1	27.25	3.62	2.22	0.69
Wonokerto	22	7.5	28.25	4.52	1.95	0.51
Degayu	25	7.5	28.25	3.16	2.15	0.75
Siwalan	23	7.5	25.75	3.62	2.16	1.03
Mulyorejo	21	7.2	26.55	4.12	2.34	0.68

The growth of mangrove ecosystems at each observation station, particularly in Degayu, is influenced by the water salinity levels and soil pH of the mangrove substrate. Other parameters, such as total phosphate and water temperature, were only of minor significance. Water salinity affects the profile and solubility of mineral ions, which stimulates the growth of mangrove roots and stems. Normal soil pH provides an ideal medium for root development and the transfer of mineral ions.

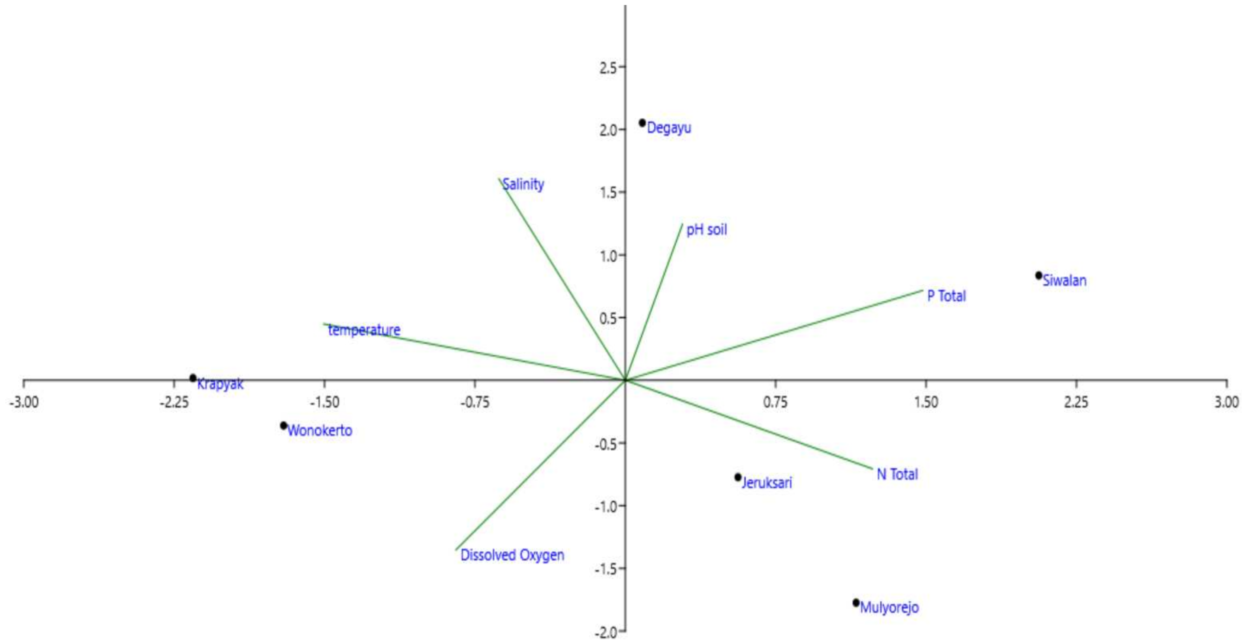


Figure 6. Results of the PCA Cluster analysis of environmental factors influencing mangrove growth at each observation station. These results are data identification related to external factors, namely environmental quality parameters that influence the life of the mangrove ecosystem on the observation station.

Environmental factors that play an important role in the growth of mangrove species, such as *Avicennia marina* and *Xylocarpus granatum*, include salinity, water temperature, and soil pH. Mangroves are aquatic plants that require stable environmental conditions and suitable substrate media. Environmental factors directly related to mangrove growth include water salinity and water temperature stability. A stable soil pH influences the threshold conditions of the substrate that supports mangrove root growth.

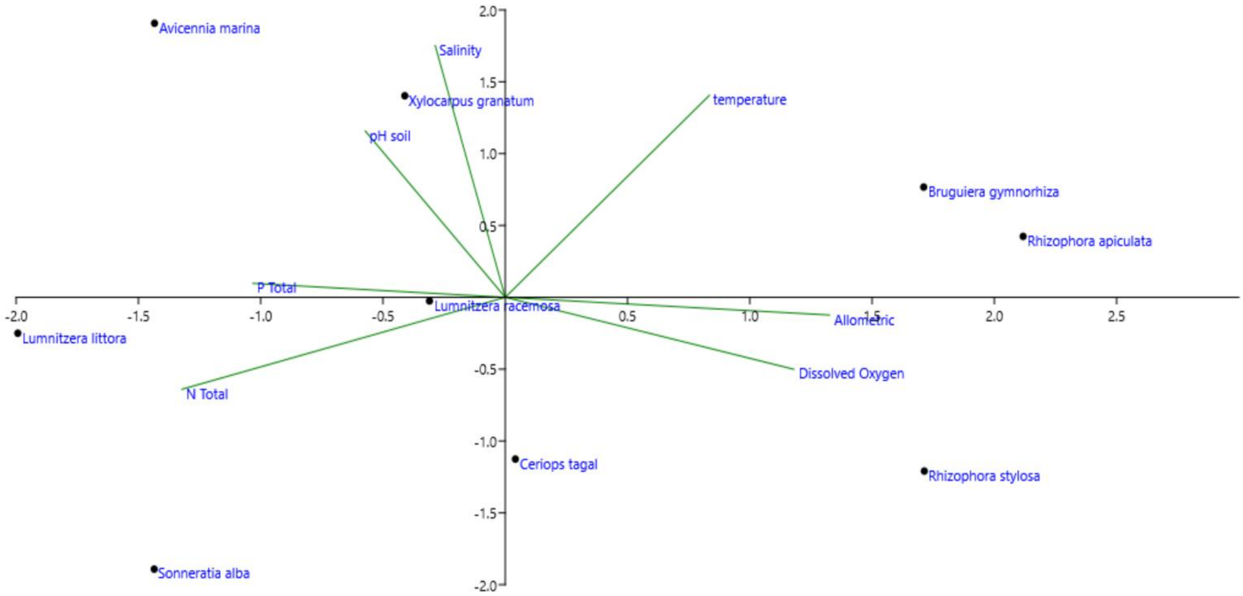


Figure 7. Results of the PCA Cluster analysis of environmental factors influencing mangrove growth. These results reflect the identification of external factors in the form of environmental quality parameters influencing mangrove ecosystem sustainability in the Pekalongan coastal area.

Discussion

Carbon Stock and Climate Change Mitigation in Pekalongan

The average carbon stock of 125.02 tC ha^{-1} found in the mangrove ecosystem of the study area demonstrates a significant contribution to climate change mitigation, equivalent to approximately 495.07 CO_2e ha^{-1}. Although this value indicates substantial carbon sequestration potential, it falls within the global average range and is relatively lower than that of other mangrove sites, such as Karimunjawa Island, which has an aboveground carbon stock of 216.4 tC ha^{-1} [38]. This variation is likely influenced by ecological factors such as species composition, stand age, and diameter at DBH, which have been proven to significantly determine biomass and carbon stock [13,39]. Therefore, the interpretation of these results must consider the local ecological and management contexts of the area.

When compared to other regions such as East Sumatra and Aceh, where biomass carbon stocks reach up to 356 Mg C ha^{-1} and sediment carbon exceeds tC ha^{-1} [40], the carbon storage potential in the study area appears to be relatively lower. This highlights the importance of including sediment components in total carbon stock estimations, as previous studies have shown that up to 62% of the carbon in mangrove ecosystems is stored in sediment layers [41]. The absence of sediment carbon data in this study may result in an underestimation of the total mitigation potential of the area, representing a key limitation that should be addressed in future studies. Thus, a comprehensive approach encompassing all ecosystem compartments is essential for obtaining more accurate and representative carbon-stock assessments.

In addition, non-conserved mangrove areas, such as those examined in this study, are particularly vulnerable to land-use changes. As noted by Duarte et al. [13], these areas are often subject to conversion into aquaculture, settlements, or coastal infrastructure, all of which can trigger significant carbon emissions. Global studies have shown that Indonesia holds one of the largest mangrove carbon stocks globally, and a 2% loss of mangrove cover between 2000 and 2012 could have released as much as 317 million tons of CO_2 [42]. These findings emphasize the urgent need to incorporate areas like Pekalongan, despite not being included in national rehabilitation programs, into strategic conservation policies so that their contribution to the national emission reduction target of 10–31% [32] can be fully realized.

Furthermore, comparative findings from other coastal regions, such as Kerala, India, show high variability in mangrove carbon stocks, with vegetation carbon ranging from 24 to 123 tC ha^{-1} and sediment carbon from 36 to 125 tC ha^{-1} [43]. This suggests that mangrove management cannot rely on a one-size-fits-all approach but rather requires location-specific strategies that consider local ecological dynamics, species characteristics, and socio-economic conditions [44–47]. Therefore, conservation and rehabilitation efforts should integrate ecological, biophysical, and community-based governance aspects to enhance the effectiveness of climate change mitigation strategies [48–51].

Considering these comparative analyses, it can be concluded that although the carbon stock in the study area is substantial, mangrove management must extend beyond conventional conservation approaches. Adaptive conservation strategies that consider local factors, such as stand structure, sediment conditions, and anthropogenic pressures, are needed while ensuring that non-conservation areas are also included in national protection and restoration schemes [52–55]. By doing so, the long-term carbon sink potential of mangrove ecosystems can be maximized, thereby strengthening their contribution to national and global climate change mitigation commitments [56–59].

The findings of this study reaffirm that mangrove ecosystems play a strategic role in sustaining coastal areas while simultaneously contributing to climate-change mitigation. Mangroves not only serve as natural barriers against coastal abrasion and seawater intrusion but also provide critical habitats for biodiversity and play a significant role in carbon sequestration and storage [60–62]. A noteworthy result of this study is the high carbon stock found in non-conservation areas, indicating that species diversity, particularly *Sonneratia alba*, along with relatively effective ecosystem management practices, can enhance carbon storage capacity even without an official protection status. This emphasizes that non-conservation areas should not be overlooked in conservation strategies [63]. Therefore, integrating non-conservation zones into coastal management policies is essential to support national emission reduction targets using mangrove-based ecosystem mitigation strategies [64,65].

The growth patterns of mangrove ecosystems along the coastal area of Pekalongan are influenced by biotic factors, such as salinity, soil pH, and water temperature. These biotic factors are essential for determining mangrove ecosystem abundance and species diversity [66]. The northern coast of Java, which consists largely of lowland areas with sandy clay soil textures, provides ideal conditions for the growth of several mangrove species, such as *Sonneratia alba, Rhizophora apiculata*, and *Avicennia marina*. This suitability is also influenced by calm and stable tidal conditions [67]. The high diversity of mangrove ecosystems along the northern coast of Java is often utilized for fishing activities, ecotourism, and coastal environmental protection [68,69].

Conclusions

This study identified nine mangrove tree species at the research site, with an average biomass and carbon stock of 231.52 ton ha^{-1} and 28.93 tC ha^{-1}, respectively, which are more than seven times higher than those reported in earlier studies. Further research is recommended to verify this significant discrepancy and support the development of effective conservation measures and greenhouse gas (GHG) emission reduction strategies. The findings also highlight the vital role of mangrove forests outside conservation areas in climate change mitigation, despite ongoing land-use changes. Therefore, it is crucial to design and implement appropriate strategies and programs to preserve existing mangrove ecosystems, both within and beyond protected zones, to sustain carbon storage. Additionally, more in-depth studies are necessary to explore how these efforts intersect with biodiversity conservation and local community livelihoods through initiatives such as silvofishery, sustainable aquaculture and ecotourism. From a policy perspective, these results underscore the urgency for Indonesia to strengthen its Nationally Determined Contribution (NDC) targets by incorporating non-conservation mangrove areas into coastal management frameworks. Future studies should adopt an integrated approach that combines ecological, social, and economic dimensions to formulate adaptive management models that maximize both climate mitigation benefits and community resilience.

Author Contributions

HA: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **AW:** Writing - Review & Editing, Supervision; **BDM:** Writing - Review & Editing; **MBS:** Writing - Review & Editing, Analysis; **LL:** Writing – Review & Editing, Sampling; and **TYM:** Methodology, Writing - Review & Editing.

AI Writing Statement

The authors did not use any artificial intelligence assisted technologies in the writing process.

Conflicts of interest

There are no conflicts to declare.

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