Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(4): 4977 – 4994 (2025)
www.ejabf.journals.ekb.eg

Quantifying Carbon Storage and Sequestration in Mangrove Ecosystems of Remote Eastern Indonesian Islands: A Case Study of Akat and Parang Islands

Rahman Rahman[1*], Juliana W. Tuahatu[1], Fredinan Yulianda[2], Achmad R. Usemahu[1], Nurul F. Rumalas[1], Nessa H. Lasamahu[1], Giansiva Pattimukay[1], Cahyo Widodo[3]

[1]Department of Marine Science, Faculty of Fisheries and Marine Science, Pattimura University, Ambon 97233, Indonesia

[2]Department of Aquatic Resources Management, Faculty of Fisheries and Marine Science, IPB University, Bogor, 16680, Indonesia

[3]Baileo Maluku, Indonesia

***Corresponding Author: rahmanrajaali@gmail.com**

ARTICLE INFO

Article History:
Received: July 29, 2025
Accepted: Aug. 8, 2025
Online: Aug. 10, 2025

Keywords:
Carbon stock,
Climate change,
Mangrove,
Small island,
East Seram Regency

ABSTRACT

Mangrove ecosystems are significant carbon sinks and play a vital role in climate change mitigation. This study quantified carbon stock and sequestration potential in mangrove stands on two small islands—Akat Island and Parang Island—in East Seram Regency, Maluku Province. Field data were collected using the quadrat transect method to measure tree density and diameter, with biomass estimated through species-specific allometric equations. Results showed that Akat Island had the highest total carbon stock (255.75 Mg C/ha), primarily contributed by *Sonneratia alba* and *Rhizophora stylosa*. Parang Island recorded a carbon stock of 219.85 Mg C/ha but exhibited greater species diversity. The estimated carbon sequestration potential, expressed as CO_2 equivalent, was 518.14 Mg CO_2e/ha for Akat Island and 439.04 Mg CO_2e/ha for Parang Island. These variations likely reflect differences in ecological conditions, stand structure, and anthropogenic pressures. The findings underscore the strategic role of small-island mangroves as nature-based climate solutions, with strong potential for integration into green economy mechanisms such as carbon trading and REDD+ programs. This study is among the first to provide empirical estimates of mangrove carbon stock in Maluku's small islands, helping fill a critical data gap to inform conservation policy and sustainable coastal management.

INTRODUCTION

Global climate change, marked by increasing concentrations of greenhouse gases (GHGs) in the atmosphere—particularly carbon dioxide (CO_2)—has emerged as a major environmental issue over recent decades **(Rahman *et al.*, 2025)**. Anthropogenic activities such as deforestation, land conversion, and fossil fuel combustion significantly contribute to GHG accumulation, disrupting the global climate system **(Rahman *et al.*, 2024a)**. GHGs, such as methane (CH_4), are also naturally produced through the decomposition of organic matter **(Tubalawony *et al.*, 2024)**. In response, nature-based mitigation approaches have gained attraction as long-term strategies to stabilize atmospheric GHG concentrations **(Berhitu *et al.*, 2025)**.

Coastal ecosystems, particularly mangroves, have been identified as highly effective carbon sinks within the climate change mitigation framework **(Friess, 2023)**. Mangroves possess a high capacity for carbon sequestration and storage, especially in their living biomass components—both aboveground and belowground **(Murdiyarso *et al.*, 2015; Rahman *et al.*, 2024b)**. Empirical studies have shown that mangrove ecosystems store more carbon per unit area than most tropical upland forests, making them among the most efficient coastal carbon sinks in the tropics **(Donato *et al.*, 2011; Alongi, 2014; Adame *et al.*, 2015)**.

Indonesia, as an archipelagic nation with the world's second-longest coastline and the largest extent of mangroves globally, plays a critical role in climate change mitigation **(Rahman *et al.*, 2024a)** and contributes to biodiversity conservation **(Rahman *et al.*, 2024c)**. However, most mangrove carbon stock studies in Indonesia remain concentrated in major coastal zones, with limited attention to small island ecosystems in eastern Indonesia, such as those in Maluku Province. These regions, despite hosting extensive mangrove stands and experiencing relatively low anthropogenic pressures, remain underrepresented in the scientific literature **(Rahman *et al.*, 2024d)**.

East Seram Regency, an administrative region within Maluku Province, comprises numerous small islands with relatively intact mangrove ecosystems. Akat Island and Parang Island are two such islands, characterized by substantial mangrove coverage. However, their carbon stock potential remains poorly documented. The absence of scientific data on mangrove carbon stock in these islands hinders the integration of this information into evidence-based conservation planning and climate mitigation policies.

Despite minimal human disturbance, these islands are ideal pilot sites for blue carbon initiatives due to their intact mangrove ecosystems and manageable spatial scale for monitoring and reporting. Their geographical position and ecological integrity offer strategic advantages for long-term blue carbon demonstration projects and climate finance readiness.

Estimating carbon stock in mangrove stands is critically important for advancing sustainable development agendas, particularly within the framework of Indonesia's Nationally Determined Contributions (NDCs) and the development of environmental service-based economic instruments **(Nurhati & Murdiyarso, 2022)**. Furthermore, empirical data on carbon stock can serve as a basis for accessing carbon trading mechanisms, result-based payment schemes, and both national and global climate finance **(Karpowicz *et al.*, 2024)**.

This study specifically aimed to estimate carbon stocks in mangrove stands on Akat and Parang Islands by measuring the aboveground and belowground biomass of mangrove trees. Data collection employed a quantitative field-based approach involving direct measurements of stand structure, which were analyzed using scientifically validated allometric models in accordance with guidelines from the Intergovernmental Panel on Climate Change (IPCC) and Indonesia's Ministry of Environment and Forestry (MoEF).

The scope of the study focuses solely on living biomass components, as these can be measured relatively quickly and accurately, aligning with carbon accounting schemes used in land-based management. This approach is also methodologically efficient and practically applicable in supporting carbon inventory efforts in remote coastal areas with limited access and research resources.

The findings of this study are expected to contribute to strengthening the coastal ecosystem carbon database in eastern Indonesia, particularly in small island mangrove ecosystems. The information is not only scientifically valuable but also strategically relevant for supporting the formulation of local policies on climate change adaptation and mitigation. Moreover, this research may enhance regional capacity to secure conservation-based incentives and foster the integration of coastal ecosystem management into green economy and low-carbon development frameworks **(Formuli *et al.*, 2023)**.

Accordingly, this study positions small island mangrove ecosystems as strategic elements in national carbon emission reduction efforts. The assessment of mangrove carbon stocks on Akat and Parang Islands is ecologically relevant and holds broad economic and policy implications, especially in supporting the transition toward sustainable development and ecosystem-based climate responses in Indonesia's coastal regions.

MATERIALS AND METHODS

Description of the study sites

This study was conducted in July 2025 within the mangrove ecosystems of Akat and Parang Island, located in East Seram Regency. Sampling stations were selected based on mangrove vegetation characteristics and site accessibility.

Akat Island is an uninhabited small island surrounded entirely by mangrove ecosystems. It is characterized by white sandy beaches and clear waters, making it a popular marine tourism destination for residents of West Seram Regency. In contrast, Parang Island is an inhabited small island situated in the waters of Waru Bay. Ecologically, it is fringed by mangrove forests distributed across two administrative areas: the Nama Andan and Nama Lena Villages (Fig. 1).

Sampling of mangrove density

Mangrove density data were collected using the quadrat transect method with a plot size of 10 × 10 meters **(Bengen *et al*., 2022)**. At each study site, plots were proportionally distributed across different vegetation strata using a stratified proportional sampling technique. A total of 30 plots were established on Akat Island and 30 on Parang

Island to ensure representative coverage. Stratification was based on vegetation density, categorized as high, medium, or low.

Plot placement was adapted to local field conditions, with transect lines oriented either from land to sea or vice versa, depending on coastal morphology and mangrove zonation patterns at the site. This approach was employed to ensure that the full variability in mangrove vegetation structure was proportionally represented. An illustration of plot placement is provided in Fig. (2).

Within each established plot, all mangrove trees were identified and counted. Species identification was based on morphological characteristics of roots, leaves, flowers, and fruits, following the guidelines of **Noor *et al*. (2006)**. Tree stands were categorized based on stem diameter, with individuals classified as trees if they had a diameter (D) greater than 5cm, following the criteria outlined by **Rahman *et al*. (2024e)**.

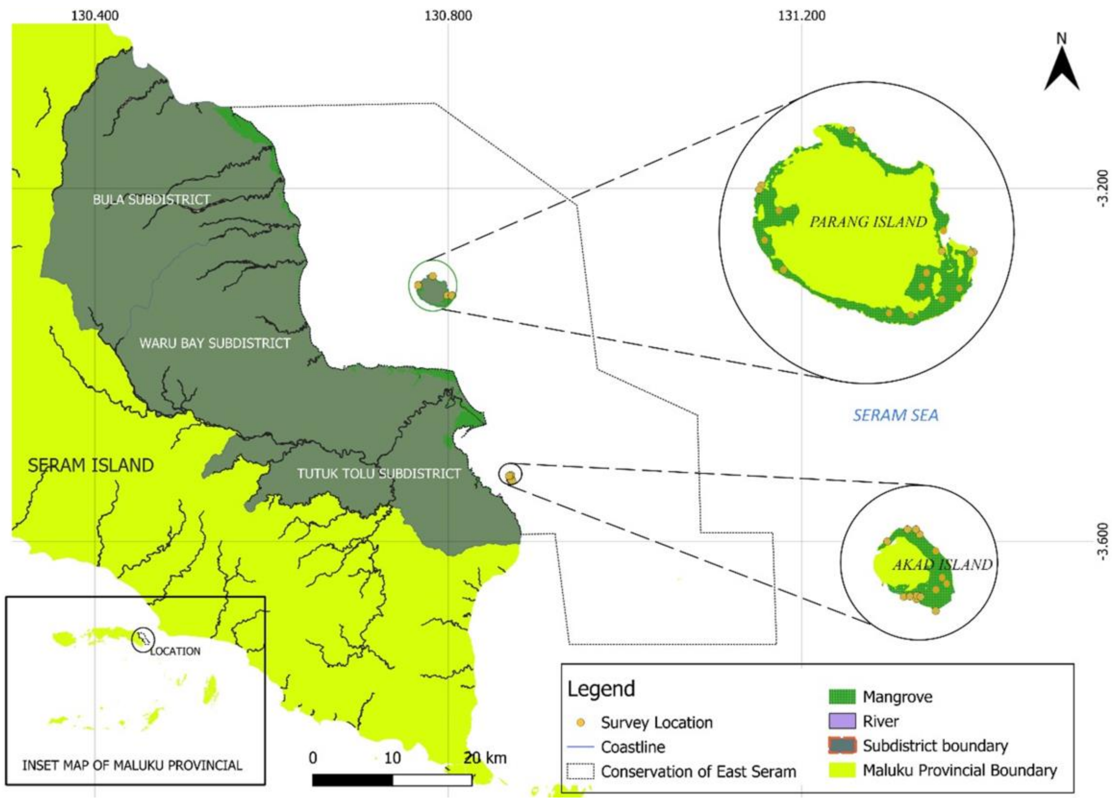

Fig. 1. Map of the study sites

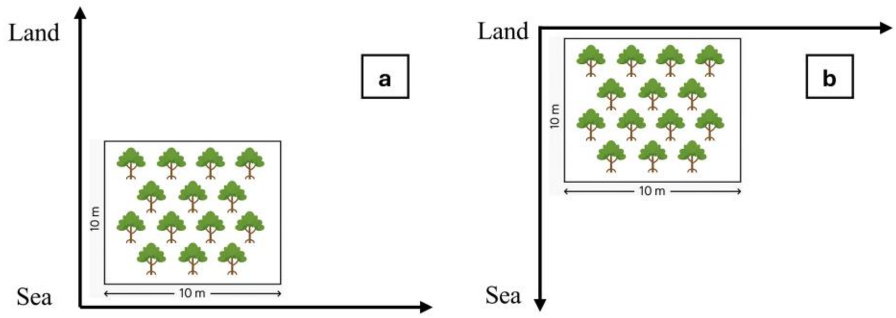

Fig. 2. Illustration of mangrove sampling plot placement: (a) Sampling from sea to land; (b) Sampling from land to sea

Measurement of mangrove diameter

Diameter measurements were conducted for each mangrove tree within the quadrat plots. The measurement method followed the protocols outlined by **Komiyama *et al*. (2005)** and **Bengen *et al*. (2022)**. For trees taller than two meters (H > 2 m), diameter at breast height (DBH = 130 cm) was measured, with specific measurement procedures illustrated in Fig. (3). For trees shorter than two meters (H < 2 m), trunk diameter (TD = 50 cm) was measured instead.

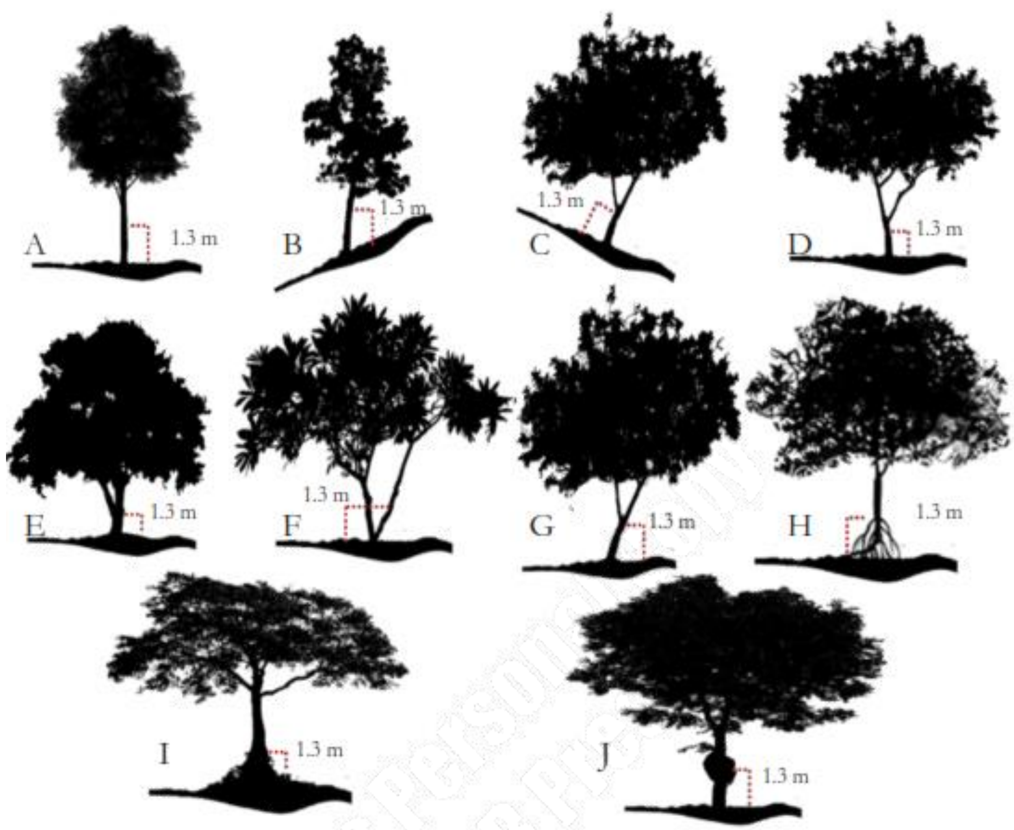

Fig. 3. Method for measuring mangrove diameter **(Bengen *et al*., 2022)**

Data analysis

Mangrove density

The analysis of total mangrove density (D) and species-specific density (Di) was carried out based on the formulas provided by **Bengen *et al*. (2022)**, as follows:

$$D = \frac{N}{A}; \text{ and } Di = \frac{\Sigma ni}{A}$$

Where, D = total tree density (individuals/ha), Di = density of species i (individuals/ha), N = total number of mangrove trees in the quadrat plots, ni = number of individuals of species I, and A = total area of the quadrat plots (in hectares).

The classification of mangrove density followed the criteria proposed by **Rahman *et al*. (2019)**, as shown in Table (1).

Table 1. Mangrove density criteria according to **Rahman *et al*. (2019)**

Density (stand/ha)	Criterion
< 500	Very rare
> 500 - 1.000	Rare
> 1.000 - 1.500	Moderate
> 1.500 - 2.000	Dense
> 2.000	Very dense

Biomass, carbon stock, and CO_2 sequestration

Mangrove biomass was estimated to be using species-specific allometric equations developed by previous researchers (Table 2). For each species, the selected allometric equation was the one with the highest correlation coefficient (r) among the available equations referenced in the literature, applied to both above-ground biomass (AGB) and below-ground biomass (BGB).

Table 2. Allometric equations for mangrove biomass estimation

No.	Species	*Above-ground Biomass*	*Below-ground Biomass*
1	*S. alba*	$B = 0.258D^{2.287}$ **Kusmana *et al*. (2018)**	$B = 0.230\,\rho\,(D^2H)^{0.74}$ **Kusmana *et al*. (2018)**
2	*R. apiculata*	$B = 0.235D^{2.42}$ **Ong *et al*. (2004)**	$B = 0.0689D^{2.61}$ **Ong *et al*. (2004)**
3	*R. stylosa*	$B = 0.178D^{2.59}$ **Gevana and IM. (2016)**	$B = 0.261D^{1.86}$ **Comley and McGuinness (2005)**
4	*X. granatum*	$B = 0.0823D^{2.59}$ **Clough and Scott (1989)**	$B = 0.145D^{2.55}$ **Poungparn *et al*. (2002)**
5	Common equation*	$B = 0.251\,\rho\,(D)^{2.46}$ **Komiyama *et al*. (2005)**	$B = 0.199\,\rho^{0.899}\,D^{2.22}$ **Komiyama *et al*. (2005)**

The amount of mangrove carbon stock was calculated by multiplying the biomass value by the carbon fraction. The carbon fraction was set at 46.82% for mangrove species of *Bruguiera*, *Rhizophora*, and *Sonneratia* **(Rahman *et al.*, 2023)**. Thus, the equation for estimating carbon stock is as follows:

$$\text{Tree Carbon Stock (kg C/tree)} = \text{Tree Biomass} \times 0.4682$$

Carbon sequestration was then derived by converting the carbon stock into CO_2 equivalents, based on the molecular weight ratio between carbon and carbon dioxide, expressed as:

$$\text{Carbon Sequestration} = \text{Carbon Stock} \times 3.67$$

Where, 3.67 is the ratio obtained from dividing the molecular weight of CO_2 (44) by the atomic weight of carbon (12).

RESULTS AND DISCUSSION

1. Mangrove density

Mangrove species density data recorded on Akat and Parang Islands, East Seram Regency, revealed structural and compositional variations that reflect the ecological conditions of each site. Akat Island exhibited a total tree density of 1,026 individuals per hectare, higher than Parang Island’s 791 individuals per hectare (Table 3). Based on the classification by **Rahman *et al.* (2019)**, this density level is categorized as moderate for Akat and low for Parang. This difference indicates environmental heterogeneity influencing mangrove growth, such as substrate characteristics, tidal frequency, and the degree of anthropogenic disturbance.

Akat Island is uninhabited and mainly utilized for ecotourism, resulting in minimal human impact. In contrast, Parang Island is inhabited and experiences anthropogenic pressures, including timber extraction and land conversion for settlements. The dominant species on both islands were *Rhizophora stylosa* and *Rhizophora apiculata*, two true mangrove species commonly found in the middle zone of mangrove forests **(Noor *et al.*, 2006; Rahman *et al.*, 2020a; Bengen *et al.*, 2022)**. On Akat Island, *R. stylosa* reached 545 individuals/ha, followed by *R. apiculata* with 345 individuals/ha. On Parang Island, these species were recorded at 273 and 82 individuals/ha, respectively. This indicates that the genus *Rhizophora* forms the main structural component of vegetation at both sites, reflecting favorable hydrological conditions for its regeneration and growth.

Interestingly, several species were absent on Akat Island but present on Parang Island, including *Aegialitis annulata*, *Aegiceras corniculatum*, *Ceriops decandra*, and *Xylocarpus granatum*, indicating a relatively higher species richness on Parang Island despite its lower total tree density. This may be attributed to the diversity of microhabitats in Parang, including variations in substrate types such as sandy mud, pure mud, and muddy sand, allowing a broader range of species to establish and thrive.

One notable finding is the identical density of *Sonneratia alba* on both islands, at 118 individuals/ha. This species is known for its high salinity tolerance and pioneer role in the seaward edge of mangrove zones **(Noor *et al*., 2006; Bengen *et al*., 2022)**. This similarity suggests that tidal and hydrological conditions at both sites remain favorable for the optimal growth of *S. alba*.

The number of true mangrove species recorded in both locations is lower compared to the findings of **Rahman *et al*. (2020b)** on the coast of West Muna, documenting 10 species. Nationally, Indonesia is home to 48 true mangrove species **(Rahman *et al*., 2024c)**, thus Akat Island and Parang Island, respectively, contribute 8.33 and 16.67% of the national diversity. The composition of the eight species identified on Akat and Parang Islands suggests that, although these islands do not yet reflect the full richness of Indonesia's true mangrove flora, key ecologically and economically important species are already represented.

Table 3. Mangrove density on Akat and Parang islands, East Seram Regency

Species	**Density (individuals/ha)**	
	Akat Island	**Parang Island**
Aegialitis annulata	0	9
Aegiceras corniculatum	0	64
Bruguiera gymnorrhiza	18	27
Ceriops decandra	0	173
Rhizophora apiculata	345	82
Rhizophora stylosa	545	273
Sonneratia alba	118	118
Xylocarpus granatum	0	45
Total	**1026**	**791**

At the regional level, for example in other areas in Maluku Province such as Ambon Bay, Tual, and West Seram, the number of true mangrove species ranges from 10 to 13 **(Suyadi, 2009)**. This places Parang Island as a site with species diversity approaching the regional average, while Akat Island appears more homogeneous in terms of species composition.

From an ecosystem function perspective, a vegetation structure dominated by only one or two species—as observed on Akat Island—may reduce resilience to environmental disturbances such as salinity changes, coastal erosion, or rising temperatures **(Rahman *et al*., 2024e)**. In contrast, higher species diversity such as that found on Parang Island can enhance the stability and long-term sustainability of the ecosystem.

The structural and compositional differences between the two islands are also significant in determining appropriate management strategies. Parang Island, with its higher diversity, should be prioritized for biodiversity conservation and the protection of rare habitats. Meanwhile, Akat Island can be directed toward mangrove conservation and restoration efforts integrated with ecotourism, as has already been initiated. These two strategies not only support conservation goals but also serve as a foundation for community-based initiatives such as ecotourism and environmental education.

Overall, these data provide an initial overview of the ecological significance of both islands within the context of mangrove conservation in Maluku Province. Although each island possesses distinct strengths, they complement each other in supporting national targets for coastal ecosystem protection and restoration.

2. Mangrove biomass

Mangrove biomass estimates reveal significant variation across species and locations. On Akat Island, the highest total biomass was recorded for *Sonneratia alba*, with 226.67 tons/ha for above-ground biomass (AGB) and 75.15 tons/ha for below-ground biomass (BGB). This species also dominates on Parang Island, albeit with slightly lower values of 167.58 tons/ha AGB and 88.16 tons/ha BGB, indicating the crucial role of *S. alba* in biomass storage at both sites (Fig. 4). The dominance in biomass is consistent with previous density data, which showed a high number of *S. alba* stands on both islands.

Rhizophora stylosa also contributes substantially to the biomass, particularly on Akat Island, with 107.53 tons/ha AGB and 45.51 tons/ha BGB. This suggests that the dense stand structure of *R. stylosa* on Akat Island is directly correlated with significant biomass accumulation. In contrast, the biomass of this species on Parang Island decreases to 38.79 tons/ha AGB and 8.65 tons/ha BGB, likely due to differences in standing age or varying ecological pressures.

Rhizophora apiculata also shows a notable contribution to biomass on Akat Island, amounting to 67.04 tons/ha AGB and 20.91 tons/ha BGB, but its values are markedly lower on Parang Island, at only 6.47 tons/ha AGB and 2.93 tons/ha BGB. This reflects structural dominance differences between the two islands, with *R. apiculata* being more established on Akat. Conversely, *Xylocarpus granatum,* which was not recorded at all on Akat Island, shows a significant biomass contribution on Parang Island with 57.54 tons/ha AGB and 7.78 tons/ha BGB. This species is typically found in the back-mangrove zone with firmer substrates, which are likely more prevalent on Parang Island.

Bruguiera gymnorrhiza, *Aegiceras corniculatum*, and *Ceriops decandra* exhibited higher biomass values on Parang Island compared to Akat Island. For instance, *B. gymnorrhiza* contributed 25.55 tons/ha and 9.08 tons/ha for above-ground and below-ground biomass, respectively, on Parang Island, whereas on Akat Island, the values were only 2.62 and 0.81 tons/ha. This suggests that habitat conditions on Parang Island are more favorable for the growth of these species, which typically require muddy substrates rich in organic matter and moderate salinity fluctuations.

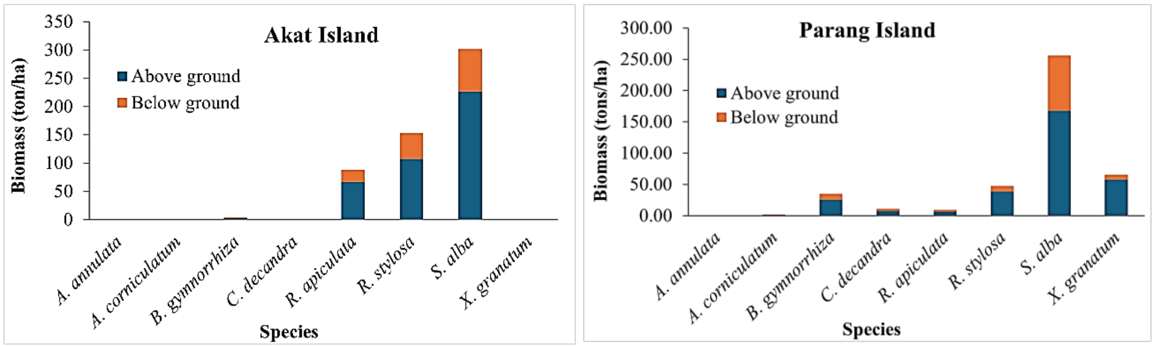

Fig. 4. Comparison of mangrove biomass (tons/ha) between Akat Island and Parang Island, East Seram Regency

Meanwhile, *Aegiceras corniculatum* and *Aegialitis annulata* were not recorded on Akat Island but made minor contributions to biomass on Parang Island. This further supports the notion that Parang Island hosts greater diversity of species, even though its total accumulated biomass is slightly lower than that of Akat Island. The presence of species with relatively small biomass contributions remains ecologically important, as it reflects structural and functional diversity within the ecosystem.

Comparison of biomass compartments also revealed that below-ground biomass (BGB) accounted for approximately 25–40% of the total biomass across most species, consistent with the general allometric assumption that BGB stores around 30–40% of total mangrove biomass.

Overall, total biomass was higher on Akat Island than on Parang Island, aligning with previously reported tree density values. However, species diversity and biomass distribution on Parang Island indicate a more complex and heterogeneous ecosystem structure. These findings suggest that conservation and management strategies should be tailored to the specific characteristics of each island—Akat serving as a key carbon stock reservoir and Parang as a center of species diversity.

3. Mangrove carbon stock

Carbon stock estimates at the two study sites revealed marked differences, both in total amounts and in species-specific contributions. On Akat Island, the total carbon stock reached 255.75 MgC/ha, with the largest share contributed by *Sonneratia alba* at 141.31 MgC/ha, accounting for approximately 55.25% of the total. The aboveground carbon (AGC) component of this species was 106.13 MgC/ha, while belowground carbon (BGC) was 35.19 MgC/ha (Fig. 5). The dominance of *S. alba* highlights its substantial potential as a carbon sink, aligning with its previously reported high biomass values.

In addition to *S. alba*, *Rhizophora stylosa* also made a significant contribution, with a total carbon stock of 71.65 MgC/ha (AGC 50.35 MgC/ha; BGC 21.31 MgC/ha), followed by *R. apiculata* at 41.18 MgC/ha. In contrast, *Bruguiera gymnorrhiza* contributed only 1.61 MgC/ha, consistent with its low biomass and density at this site. The proportion of AGC to total carbon on Akat Island was approximately 73.9%, while

BGC accounted for 26.1%, which remains in line with general carbon allocation trends observed in mangrove forests.

On Parang Island, the total carbon stock was slightly lower at 219.85 MgC/ha. However, the diversity of species contributing to the carbon pool was higher compared to Akat Island. *S. alba* remained the dominant contributor, with a total of 119.74 MgC/ha (AGC 78.46 MgC/ha; BGC 41.28 MgC/ha), followed by *Xylocarpus granatum* with 30.59 MgC/ha and *R. stylosa* with 22.21 MgC/ha (Fig. 6). A key distinction from Akat Island was the presence of *X. granatum* and several other species such as *Ceriops decandra*, *Aegiceras corniculatum*, and *Aegialitis annulata*. Although their individual contributions were relatively small, they underscore the importance of species diversity in enhancing ecosystem-level carbon storage.

The proportion of belowground carbon (BGC) on Parang Island was slightly higher in certain species, such as *Sonneratia alba* and *Bruguiera gymnorrhiza*, reflecting physiological differences in root structures and adaptations to substrate conditions. This may indicate variation in soil physical properties and primary productivity levels between the two islands. Interestingly, although *Rhizophora apiculata* exhibited high dominance on Akat Island, its contribution on Parang Island was much lower, at only 4.40 MgC/ha, suggesting distinct spatial distribution patterns for this species.

Overall, the carbon stock structure on Akat Island is more concentrated in a few high-biomass species, whereas on Parang Island, carbon storage is distributed more evenly among a greater number of species with low to moderate biomass values. This contrast highlights differing ecosystem characteristics: Akat Island represents a system with high but species-specific carbon storage capacity, while Parang Island represents a more biodiversity-rich system with relatively dispersed carbon accumulation.

When compared to national averages, the mangrove carbon stocks at both sites are considered high. As a reference, the average carbon stock in Indonesian mangrove stands ranges between 100–150 MgC/ha **(Murdiyarso *et al*., 2015)**, indicating that both Akat and Parang exceed this threshold, particularly in dominant species. Similarly, compared to other regions in Maluku—such as Ambon Bay or Seram Island—these values demonstrate that East Seram Regency, holds significant blue carbon potential that could serve as the foundation for developing blue carbon schemes.

Given these findings, it is essential that site management efforts prioritize the protection of species with high carbon contributions while also maintaining species diversity to support long-term ecosystem stability **(Rahman *et al*., 2020c)**. Island-based or site-specific management approaches should be integrated into carbon-based conservation and restoration strategies along Maluku's coastal zones. For example, the REMAJA PHE ONWJ program in Pantai Bahagia Village successfully increased *Rhizophora mucronata* carbon stocks to 15.59 tonnes C within three years, demonstrating the long-term benefits of targeted mangrove rehabilitation for climate change mitigation **(Rahman *et al*., 2024f)**. If effectively utilized through carbon market mechanisms, these carbon reserves could contribute to local economic development while supporting global climate change mitigation goals **(Rahman *et al*., 2025)**.

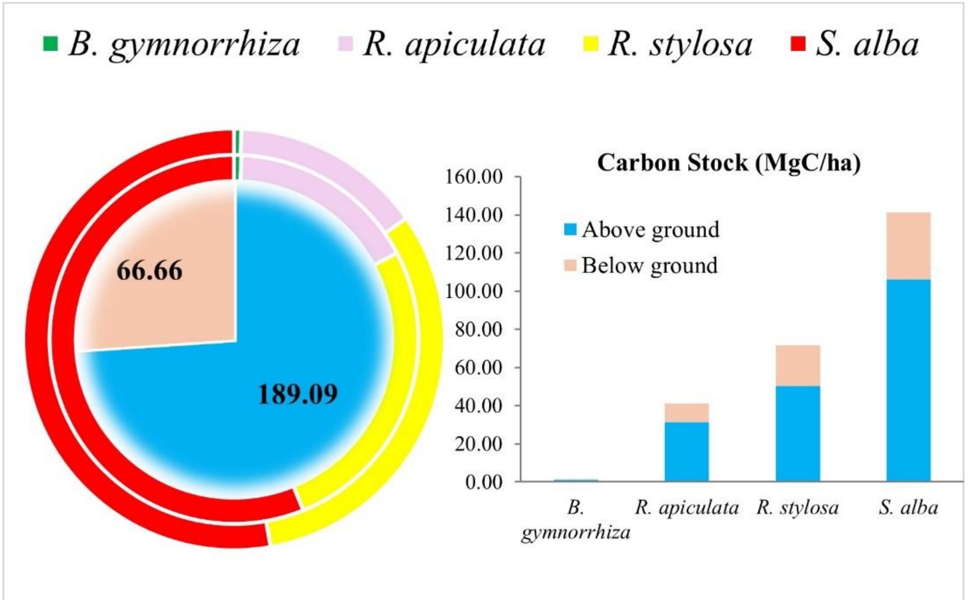

Fig. 5. Mangrove carbon stock (MgC/ha) in the Akat Island, East Seram Regency

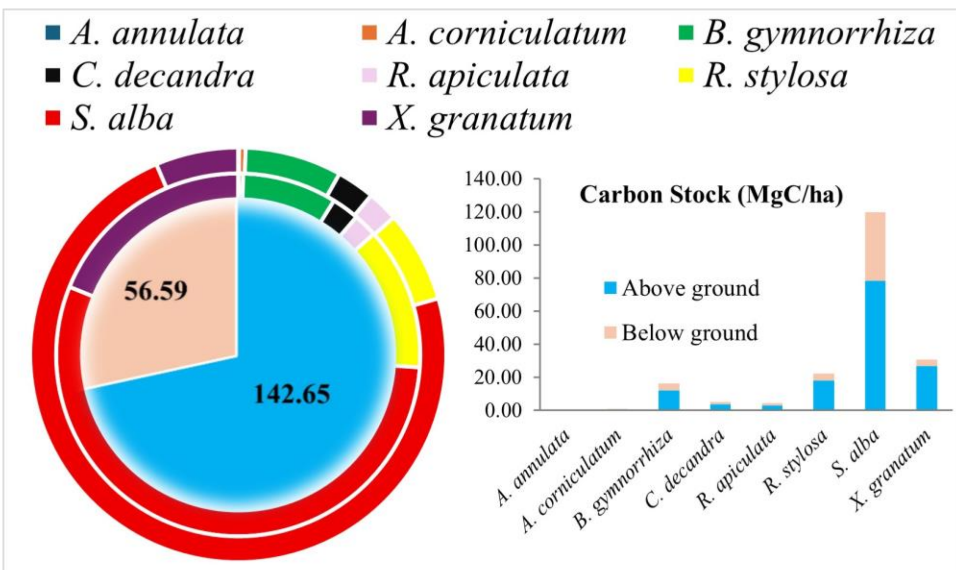

Fig. 6. Mangrove carbon stock (MgC/ha) in the Parang Island, East Seram Regency

4. Carbon sequestration and its implication to climate change mitigation

Mangroves are one of the most critical coastal ecosystems in terms of climate change mitigation due to their ability to sequester and store large amounts of carbon in both above-ground biomass (AGB) and below-ground biomass (BGB) **(Alongi, 2014; Adame *et al*., 2015)**. Carbon sequestration analysis conducted at two sites—Akat Island

and Parang Island—revealed that carbon uptake potential varies depending on species composition and site-specific environmental conditions.

On Akat Island, *Sonneratia alba* exhibited the highest carbon sequestration value, with a total of 518.14 MgCO_2e/ha. This value far exceeded that of other species at the same site, such as *Rhizophora stylosa* (262.73 MgCO_2e/ha) and *Rhizophora apiculata* (150.99 MgCO_2e/ha). In contrast, on Parang Island, although *S. alba* remained the dominant species in terms of carbon uptake (439.04 MgCO_2e/ha), its value was relatively lower than that observed on Akat Island (Fig. 7). Other species such as *Xylocarpus granatum* and *R. stylosa* also made notable contributions; however, overall carbon sequestration levels on Parang Island were generally lower compared to Akat.

These differences are likely associated with stand structure, tree age, as well as biophysical and anthropogenic conditions at each site. Akat Island, which is relatively more protected from human activity, appears to provide more favorable conditions for optimal mangrove growth, directly enhancing its carbon sequestration capacity. This finding aligns with the work of **Donato *et al*. (2011)**, which emphasized that environmental conditions and anthropogenic disturbances significantly influence carbon accumulation in mangrove ecosystems.

In terms of carbon uptake distribution, below-ground components contributed substantially to the total sequestration, ranging from 20% to 35%, depending on the species. For example, *Sonneratia alba* on Parang Island stored approximately 151 MgCO_2e/ha in below-ground compartments, highlighting the critical role of root systems and soil carbon accumulation in mangrove forests. This supports the findings of **Pendleton *et al*. (2012)**, who reported that the majority of carbon stocks in coastal ecosystems are stored in soils and robust root structures, making them vital for long-term climate mitigation strategies.

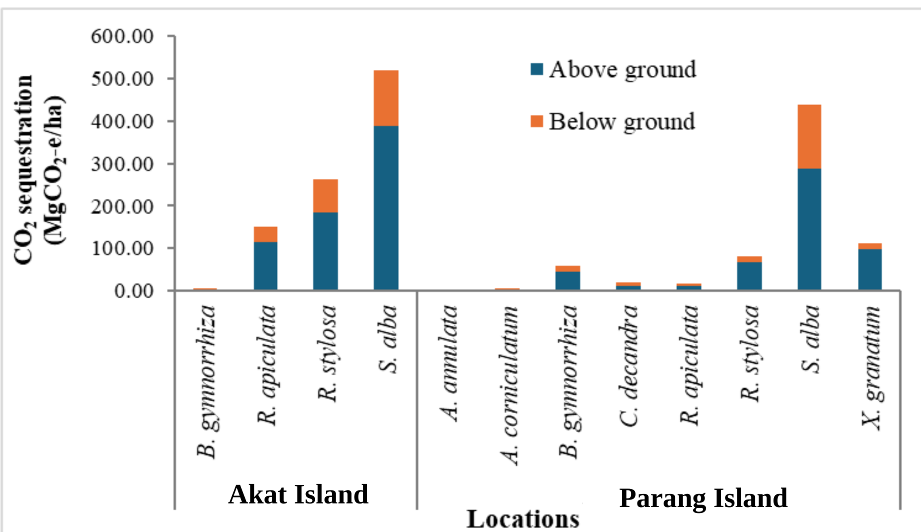

Fig. 7. Carbon sequestration potential (MgCO_2e/ha) of mangrove ecosystems on Akat and Parang islands, East Seram Regency

A comparative summary of key ecological indicators—including total biomass, carbon stock, and carbon sequestration potential—for Akat and Parang islands is presented in Table (4).

Table 4. Comparison of biomass, carbon stock, and $MgCO_2e$ sequestration in Akat and Parang islands

Island	Total Biomass (ton/ha)	Total Carbon Stock (MgC/ha)	Total CO_2e Sequestered ($MgCO_2e$/ha)
Akat	546.24	255.75	937.75
Parang	425.53	199.24	730.53

The implications for climate change mitigation are significant. With carbon sequestration values reaching several hundred $MgCO_2e$ per hectare, mangrove ecosystems represent a major asset for emission reduction efforts at both local and national levels. According to **Murdiyarso *et al*. (2015)**, the carbon storage potential of tropical mangroves may be three to five times higher than that of tropical terrestrial forests. Therefore, the conservation and rehabilitation of mangroves—particularly high-contributing species such as *S. alba* and *R. stylosa*—should be prioritized within national greenhouse gas (GHGs) mitigation strategies, including voluntary carbon markets and REDD+ mechanisms.

By integrating carbon stock and sequestration data, science-based mangrove management can be geared not only toward biodiversity conservation but also as an effective tool for achieving national climate targets (Nationally Determined Contributions, NDCs). As such, this study reinforces the urgency of protecting mangrove ecosystems as a nature-based climate solution (NbS) that delivers long-term ecological, social, and economic benefits.

CONCLUSION

This study underscores the critical role of mangrove ecosystems on small islands such as Akat and Parang in supporting climate change mitigation through substantial carbon storage and sequestration. The results indicate that Akat Island holds a higher total carbon stock (255.75 MgC/ha) than Parang Island (219.85 MgC/ha), with stocks primarily dominated by *Sonneratia alba* and *Rhizophora stylosa*. In contrast, Parang Island exhibits greater species diversity, reflecting higher ecological complexity and ecosystem resilience.

These contrasting ecosystem characteristics highlight the need for site-specific management approaches: carbon storage–oriented conservation for Akat, and biodiversity-focused protection for Parang. The findings provide scientific evidence that mangrove forests in remote eastern Indonesian islands have significant potential as nature-based climate solutions (NbS) and are highly suitable for integration into green economy mechanisms such as carbon trading and REDD+.

Integrating carbon stock and sequestration data from these small islands is therefore essential to strengthen evidence-based policymaking, contribute to national climate targets under the Nationally Determined Contributions (NDCs), and support sustainable development in coastal regions.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Ministry of Higher Education, Science, and Technology (Kemdiktisaintek) for funding this research.

FUNDING

This research was funded by the Kemdiktisaintek, Indonesia, under the 2025 Fiscal Year Regular Fundamental Research scheme, contract number 096/C3/DT.05.00/PL/2025 and 247/UN13.3/PT/2025.

REFERENCES

Adame, M. F.; Santini, N. S.; Tovilla, C.; Lule, A. V.; Castro. L. and Guevara, M. (2015). Carbon stock and soil sequestration rates of tropical riverine wetlands. *Biogeosci,* (12), 3805-3818. https://doi.org/10.5194/bg-12-3805-2015

Alongi, D. M. (2014). Carbon cycling and storage in mangrove forests. Ann. Rev. of Mar. Sci. 195 – 219. DOI: 10.1146/annurev-marine-010213-135020

Bengen, D. G.; Yonvitner. and Rahman. (2022). *Pedoman Teknis Pengenalan dan Pengelolaan Ekosistem Mangrove*. IPB Press. 88p.

Berhitu, P. Th.; Boreel, A. and Pattiasina, A.G. (2025). Adaptation strategies to climate change in coastal communities of Ambon City, Indonesia. *Egyptian Journal of Aquatic Biology and Fisheries*, *29*(2): 1939 – 1955.

Clough, B. F. and Scott, K. (1989). Allometric relationships for estimating above-ground biomass in six mangrove species. *Forest Ecology and Management*, *27*,117−127.

Comley, B. W. T. and McGuinness, K.A. (2005). Above and below-ground biomass and allometry of four common northern Australian mangroves. *Australian Journal of. Botany*, *53*, 431–436.

Donato, D. C.; Kauffman, J. B.; Murdiyarso, D.; Kurnianto, S.; Stidham, M. and Kannien, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geosci.*, 4, 293–297. https://doi.org/10.1038/ngeo1123

Formuli, F.; Mazza, F.; Medeleanu, M.; Sant'Ana, T. T. and Wong, J. (2023). *A Virtuous Cycle: Mangrove Conservation and Blue Carbon Initiatives in Coastal Kenya.* Reach Alliance, 25p.

Friess, D. A. (2023). The potential for mangrove and seagrass blue carbon in Small Island States. *Environmental Sustainability*, 64, 101324.

Gevana, D. T. and IM, S. (2016). Allometric models for *Rhizophora stylosa* Grief. in dense monoculture plantation in the Philippines. *Malay Forest*, *79*(1 & 2): 39-53.

Karpowicz, D. A.; Mohan, M.; Watt, M. S.; Montenegro, J. E. and *et al.* (2024). Mangrove-Based Carbon Market Projects: 15 Considerations for Engaging and Supporting Local Communities. *Diversity*, 16,574.

Komiyama, A.; Poungparn, S. and Kato, S. (2005). Common allometric equation for estimating the tree weight of mangroves. *Journal of Tropical Ecology*. 21:471-477. https://doi.org/10.1017/S0266467405002476

Kusmana, C.; Hidayat, T.; Tiryana, T.; Rusdiana, O. and Istomo. (2018). Allometric models for above – and bellow – ground biomass of *Sonneratia* spp. Global Ecololy and Conservation. 15:e00417. https://doi.org/10.1016/j.gecco.2018.e00417

Murdiyarso, D.; Purbopuspito, J.; Kauffman, J. and *et al.* (2015). The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, 5, 1089–1092. https://doi.org/10.1038/nclimate2734

Noor, Y. R.; Khazali, M. and Suryadiputra, I.N.N. (2006). *Panduan Pengenalan Mangrove di Indonesia.* Wetlands International. Bogor.

Nurhati, I. S. and Murdiyarso, D. (2022). *Strategi Nasional Pengelolaan Ekosistem Mangrove: Sebagai Rujukan Konservasi dan Rehabilitasi Kawasan Pesisir untuk Tujuan Pembangunan Berkelanjutan dan Pembangunan Rendah Karbon*. Working Paper 10. Bogor, Indonesia: CIFOR.

Ong, J. E.; Gong, W. K. and Wong, C. H. (2004). Allometry and partitioning of the mangrove *Rhizophora apiculata*. *Forest Ecology and Management*, *188*, 395–408

Pendleton, L.; Donato, D. C.; Murray, B. C.; Crooks, S.; Jenkins, A. W.; Sifleet, S. and *et al*. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLOS ONE*, 7(9): e43542.

Poungparn, S.; Komiyama, A.; Jintana, V.; Piriyayaota, S.; Sangtiean, T.; Tanapermpool, P.; Patanaponpaiboon, P., and Kato, S. (2002). A quantitative analysis on the root system of a mangrove, *Xylocarpus granatum* Koenig.*Tropics*, *12*, 35–42.

Rahman.; Yulianda, F.; Rusmana, I. and Wardiatno, Y. (2019). Production ratio of seedlings and density status of mangrove forests in coastal areas of Indonesia. *Advances in Environmental Biology*, *13*(6), 13-20.

Rahman, Effendi, H.; Rusmana, I.; Yulianda, F.; Wardiatno, Y. and Bengen, D. G. (2020a). *Metode dan Analisis Studi Ekosistem Mangrove.* IPB Press. 124p.

Rahman, Effendi, H.; Rusmana, I.; Yulianda, F. and Wardiatno, Y. (2020b). Sebaran spesies dan status kerapatan ekosistem mangrove di pesisir Kabupaten Muna Barat, Sulawesi Tenggara. *Jurnal Pengelolaan Sumberdaya Alam dan Lingkungan*, 10(3), 461-478.

Rahman, Effendi, H.; Rusmana, I.; Yulianda, F. and Wardiatno, Y. (2020c). Pengelolaan ekosistem mangrove untuk ruang terbuka hijau sebagai mitigasi gas rumah kaca di kawasan Sungai Tallo Kota Makassar. *Jurnal Pengelolaan Sumberdaya Alam dan Lingkungan*, 10(2), 320-328.

Rahman.; Maryono. and Sigiro, O. N. (2023). What is the true carbon fraction of mangrove biomass? *Malaysian Journal of Science, 42*(2): 1 – 6.

Rahman.; Ceantury, A.; Tuahatu, J. W.; Lokollo, F. F.; Supusepa, J.; Hulopi, M.; Permatahati, Y. I.; Lewerissa, Y. A. and Wardiatno, Y. (2024a). Mangrove ecosystems in Southeast Asia region: Mangrove extent, blue carbon potential and CO_2 emissions in 1996–2020. *Science of the Total Environment,* 915, 170052.

Rahman.; Tuahatu, J. W. and Tuhehay, C. (2024b). Blue carbon potential of mangrove ecosystem on the coast of Negeri Waai, Central Maluku Regency. *Jurnal Ilmu Kehutanan*, *18*(1): 7-15.

Rahman.; Lokollo, F.F.; Manuputty, G.D.; Hukubun, R.D.; Krisye.; Maryono,; Wawo, M.; and Wardiatno Y. (2024c). A review on the biodiversity and conservation of mangrove ecosystems in Indonesia. *Biodiversity and Conservation*, 3(33): 875-903.

Rahman.; Lokollo, F. F.; Wawo, M.; Ceantury, A.; Lewerissa, Y. A.; Hulopi, M.; Handayani, L. D.; Zuhri, M. I.; Effendi, H. and Wardiatno. Y (2024d). Blue Carbon Potential of Mangrove Ecosystems and Its Management to Promote Climate Change Mitigation in Indonesia. *Jurnal Ilmu Kehutanan,* 18(2): 208 – 218.

Rahman.; Lokollo, F. F.; Supusepa, J.; Natan, J.; Mamesah, J. A. B.; Wawo, M. and Latumahina, F. (2024e). Recruitment Index as a Novel Approach to Assessing the Resilience of Natural Mangrove Ecosystems: A Case Study on the Coast of West Muna Regency. *Asian Journal of Aquatic Research, 26*(10), 12 – 23.

Rahman.; Amalo, L. F.; Putra, M. D.; Handayani, L. D. W.; Zuhri, M. I.; Supardi, H.; Bena, L. M. A. A. and Rahman, A. (2024f). Existing and future carbon stock of mangrove restoration of the REMAJA PHE ONWJ Program in Mekarpohaci Village, Karawang Regency, Indonesia. *Egyptian Journal of Aquatic Biology and Fisheries*, *28*(6), 29 – 42.

Rahman.; Lokollo, F. F.; Wardiatno, Y.; Yulianda, F.; Rusmana, I.; Bengen, D. G. and Berhitu, P. Th. (2025). *Pengelolaan Ekosistem Mangrove dan Mitigasi Perubahan Iklim.* PT. Mafy Media Literasi Indonesia. Solok. 96p.

Suyadi, S. (2009). Kondisi hutan mangrove di Teluk Ambon: Prospek dan tantangan**.** *Berita Biologi*, *9*(5), 481-481.

Tubalawony, S.; Mailoa, M. N.; Rahman, and Pasanea, K. (2024). Fluxes of Methane gases (CH_4) in sediments of mangrove and seagrass ecosystems in Tanjung Tiram, Ambon Bay, Indonesia. *Egyptian Journal of Aquatic Biology and Fisheries, 28*(4), 951 – 963.