Original Research Article

Evaluating carbon stocks in *Rhizophora mucronata* planting of the PHE ONWJ REMAJA Program in Pantai Bahagia Villages, Bekasi Regency, Indonesia

Abstract. This study evaluates the carbon storage potential of *Rhizophora mucronata* plantations as part of the North Java Coast Mangrove Restoration Program (REMAJA) implemented by PT. Pertamina Hulu Energi Offshore North West Java (PHE ONWJ) in Pantai Bahagia Village, Bekasi Regency. A total of 8,000 mangrove seedlings were planted in 2020, and the diameter growth and carbon stock were monitored from 2020 to 2023. Biomass measurements were taken to estimate above-ground carbon (AGC) and below-ground carbon (BGC), as well as to calculate potential carbon dioxide sequestration (CO_2e). The results showed that the survival rate of *Rhizophora mucronata* seedlings was exceptionally high, averaging over 98%. The total carbon stock increased annually, reaching 15.59 tons of carbon (C) in 2023, 9.57 tons in AGC, and 6.02 tons in BGC. The result represents a significant increase compared to previous years, with an additional 5.14 tons of carbon compared to 2022, 13.75 tons more than in 2021, and 15.01 tons more than in 2020. Based on these results, the carbon dioxide sequestration contribution of *R. mucronata* during the periods of 2020-2021, 2021-2022, and 2022-2023 was 4.62 tons CO_2e, 31.58 tons CO_2e, and 18.83 tons CO2e, respectively. In conclusion, the *R. mucronata* plantation under this program significantly enhanced carbon stocks, supporting climate change mitigation through long-term carbon storage. This program demonstrates that mangrove rehabilitation can play a crucial role in protecting coastal ecosystems and reducing greenhouse gas emissions.

Keywords: Carbon stock, climate change mitigation, *R. mucronata*, mangrove rehabilitation.

1. Introduction

Mangrove ecosystems are the main blue carbon ecosystems found in coastal areas. These ecosystems have varying blue carbon potentials influenced by the density, canopy cover, and diameter of mangroves (Rahman et al., 2024a). The potential carbon stock of mangroves is 956 MgC ha^{-1} (Alongi, 2014) and even reaches 1082.55 MgC ha^{-1} (Murdiyarso et al., 2015). The potential of carbon stocks is much greater than those in other ecosystems, such as seagrasses, saline swamps, and tropical rainforests (Donato et al., 2011; Adame et al., 2015). Based on this potential, blue carbon has become a new paradigm for sustainable mangrove management (Sidik et al., 2023).

Indonesia's coastal area is one of the world's most significant mangrove ecosystem habitats. This area had a mangrove area of 3.12 million ha in 1996 and 2.95 million ha in 2020 (Rahman et al., 2024a). The decrease in area is caused by the conversion of land into ponds, settlements, and timbers (Ilman et al., 2016), which has an impact on the decrease in the density and carbon sequestration potential of several mangrove species, especially from the Rhizophora and Sonnerartia species (Rahman et al., 2020).

Deforestation of mangrove ecosystems in Indonesia occurs in almost all coastal areas of Indonesia, especially the island of Java, which is known as the Bekasi Regency. Amalo et al. (2023) reported that the mangrove ecosystem in Bekasi Regency has decreased by 85.58 ha triggered by the conversion of land into ponds, so conservation efforts are needed to maintain existing mangroves, for example as ecotourism and potential land rehabilitation for an increase in area and density.

The success of mangrove rehabilitation efforts can be achieved when considering ecological factors, primarily related to the adaptability of mangroves to environmental conditions such as temperature, salinity, and waves (Djamaluddin, 2018). One of the mangrove species that has high adaptability to the ecological environment is *Rhizophora mucronata* (Bengen et al., 2022; Samal et al., 2023). It is indicated by the existence of this species, commonly found in almost all coastal areas of Indonesia (Rahman et al., 2019; 2024b).

Based on this, PT. Pertamina Hulu Energy Offshore North West Java (PT. PHE ONWJ) carries out mangrove rehabilitation on the coast of Bekasi Regency, especially Pantai Bahagia Village through the North Java Coast Mangrove Restoration (REMAJA) program. A total of 8000 *Rhizophora mucronata* seedlings were planted in 2020. The planting aims to improve the quality of the mangrove ecosystem, including biodiversity, area, density, and ecosystem services, as well as the potential for carbon sequestration in climate change mitigation efforts. Therefore, this study aims to evaluate the potential carbon storage from *planting Rhizophora mucronata* by monitoring diameter growth from 2020 to 2023.

2. Methods

2.1. Description of rehabilitation program

Mangrove rehabilitation was carried out in 2020 by PT. PHE ONWJ on the coast of Pantai Bahagia Village, Bekasi Regency (Figure 1). A total of 8000 *R. mucronata* seedlings were planted along the potential rehabilitation area with sandy mud substrate environmental conditions. *R. mucronata* is a species that is existentially found in the coastal area of Pantai Bahagia Village, so the selection of the seeds has been considered ecologically suitable in-depth and comprehensively.

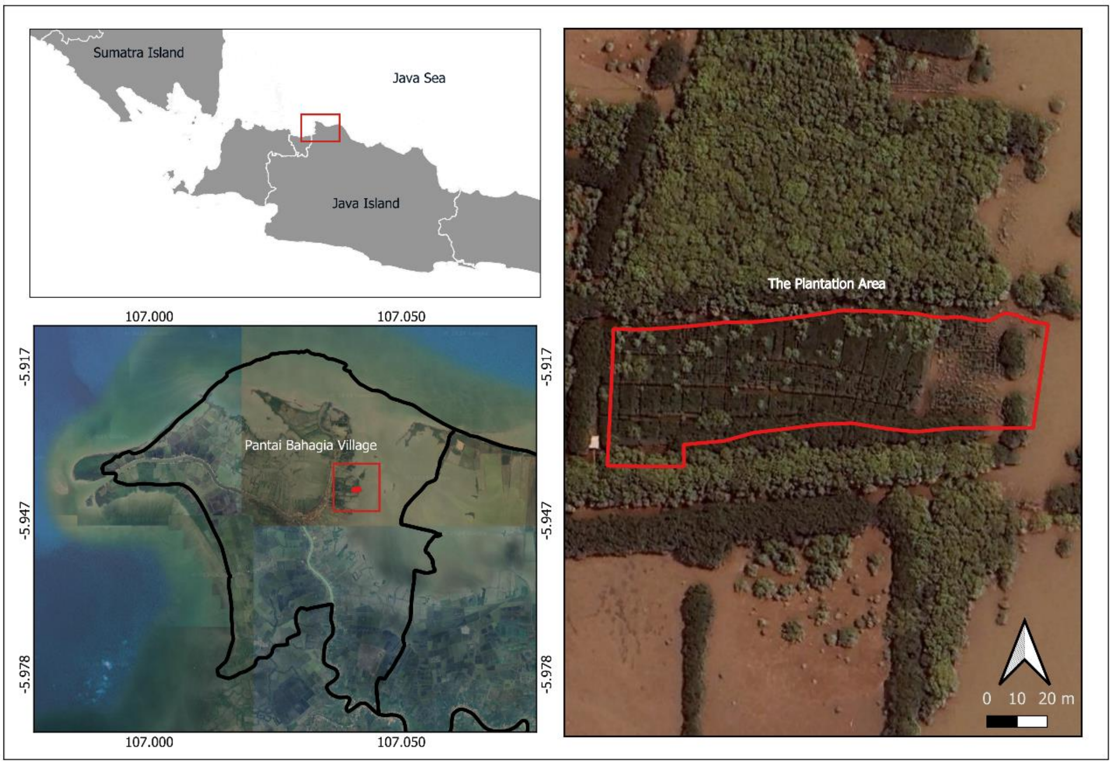

Figure 1. Map of the *R. mucronata planting* by PHE ONWJ

2.2. Measurement of mangrove diameter

Mangrove diameter measurements were conducted annually from 2020 to 2023. Three hundred (300) mangrove seedlings, selected from 8,000 planted seedlings, were measured using a stratified random sampling method. The selection of 300 seedlings ensured the representation of the ecological characteristics across the planting area. The data obtained from these measurements included each year's average diameter and growth rate.

Diameter measurements for seedlings were taken at the base of the propagule emergence (Rahman, 2020), while sapling diameters were measured 50 cm above the ground (trunk diameter), and tree diameters were measured 130 cm above the ground (Diameter at Breast Height – DBH) (Komiyama et al., 2005).

2.3. Data analysis

2.3.1. Survival rate

The survival rate of *R. mucronata* mangrove is the percentage of the ratio of live seedlings to the total planted seedlings. However, to represent 8000 seedlings, 300 were selected proportionally by paying attention to the representation of each ecological character of the mangrove planting area. Mathematically, the survival rate equation can be written as follows:

$$R\ (\%) = \frac{\sum SLt}{N} \times 100\ \%$$

R is the survival rate (%); $\sum SLt$ is the number of seedlings alive during observation; and N is the total number of seedlings planted.

2.3.2. Mangrove Biomass

Evaluation of R. *mucronata* biomass was carried out on diameter growth in the first year (2020-2021), second (2021-2022), and third (2022-2023). Biomass was estimated based on above-ground biomass (AGB) and below-ground biomass (BGB). The allometric equation used for biomass estimation refers to Komiyama et al. (2005) as follows:

$$\text{Above-ground biomass (kg)} = 0.251\rho D^{2.46}$$

$$\text{Below-ground biomass (kg)} = 0.199\rho^{0.899} D^{2.22}$$

Notes: ρ is mangrove wood density*, R. mucronata* is 0.8483 based on data from the World Agroforestry Center (2024).

2.3.3. Carbon stock and CO_2 absorption

Carbon stock estimation is carried out by multiplying the value of biomass by the carbon fraction. The magnitude of the carbon fraction value refers to Rahman et al. (2023), which is 0.4682. Meanwhile, the carbon absorption potential (CO_2e) is obtained by multiplying the potential carbon stock with the value of the comparison of the molecular mass of CO_2 (Mr. CO_2 = 44 grams/mol) to the atomic mass of C (Ar C = 12 grams/mol). Mathematically, the equation for stock estimation and carbon sequestration is as follows:

$$CS = B \times 0{,}4682$$

$$CO_2e = CS \times (44/12)$$

Information:

CS = Carbon Stock (kg/stand)

B = biomass (kg/stand) representing AGB and BGB

0.4682 = carbon fraction value referenced from Rahman et al. (2023)

CO2e = carbon sequestration (kg/stand)

3. Result and Discussion

3.1. Survival Rate

The planting of R. mucronata *mangroves* by PHE ONWJ on the coast of Pantai Bahagia Village shows excellent growth performance. It is indicated by the survival rate (R), which ranges from 98.67-100%. In the 2020-2021 range, 300 seedlings were observed to be alive (R = 100%); in the 2021-2022 range there were 296 out of 300 seedlings observed to live optimally (R = 98.67%), while in the 2022-2023 range, there were 295 out of 296 (R = 99.66%) seedlings alive and growing well (Figure 2).

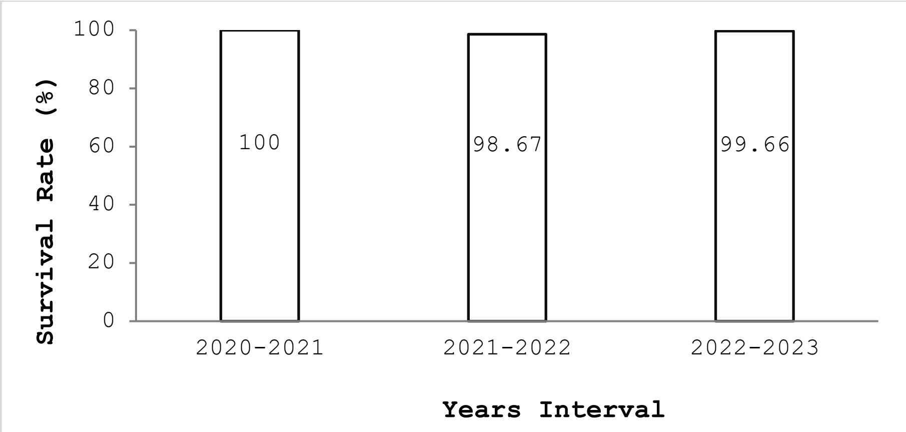

Figure 2. The survival rate of R . *mucronata* seedlings from the REMAJA PHE ONWJ program in Pantai Bahagia Village, Bekasi – Indonesia.

The indication of the success of planting *R. mucronata* mangroves was also seen in the significant diameter growth during the evaluation period (2020-2023). In the initial planting in 2020, the average seedling diameter *of R. mucronata* was 0.68 ± 0.0087 cm. The diameter increased by 0.43 cm in 2021 (D2021 = 1.11 cm), 1.2 cm in 2022 (D2022 = 2.31 cm), and 0.45 cm in 2023 (D2023 = 2.76 cm) (Figure 3).

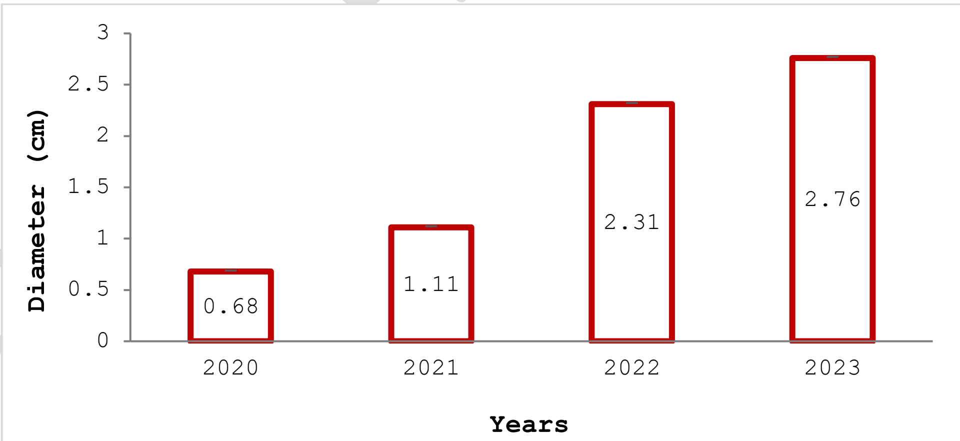

Figure 3. Growth of R. *mucronata seedling diameter* from the REMAJA PHE ONWJ program on the coast of Pantai Bahagia Village, Bekasi – Indonesia

The high survival rate and growth of *Rhizophora mucronata* mangroves on the coast of Pantai Bahagia Village is due to a combination of biological adaptation and supportive ecological conditions. *R. mucronata* can naturally adapt to extreme coastal environments, such as high salinity and anaerobic sediments, which allows them to grow optimally (Bengen et al., 2022). Good sediment quality and minimal biotic and abiotic disturbances also play an essential role in the success of the planting.

3.2. Mangrove Biomass

The average biomass value in 2020 (B2020) was 0.1554 kg/stand, consisting of 0.0825 kg AGB and 0.0729 kg BGB. This value continues to increase as the diameter grows every year. The biomass potential *of R. mucronata* based on its diameter growth is 0.4916 kg/stand (0.2752 kg AGB and 0.2164 kg BGB) in 2021, 2.8282 kg/stand (1.7058 kg AGB and 1.1224 kg BGB) in 2022, and 4.2321 kg/stand (2.5974 kg AGB and 1.6347 kg BGB) in 2023 (Figure 4).

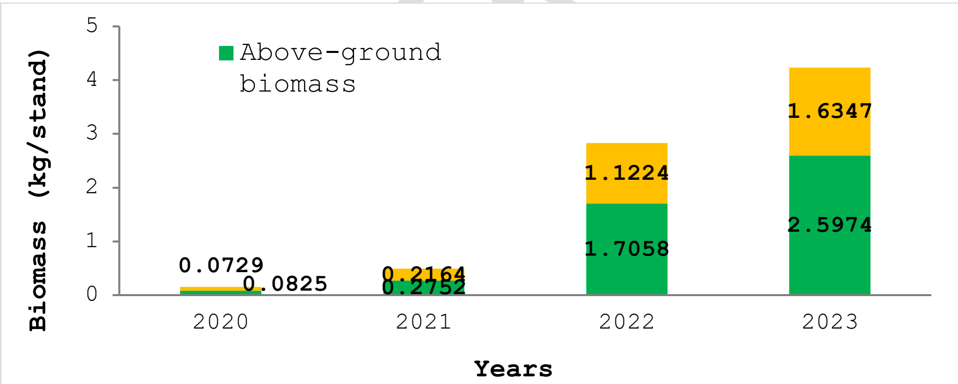

Figure 4. The potential of standing biomass of *R. mucronata* from the REMAJA PHE ONWJ program in the Pantai Bahagia Village, Bekasi – Indonesia coast.

Based on the standing biomass, the total biomass potential contributed from the planting of 8000 seedlings of the REMAJA PHE ONWJ program is 1.24 tons in 2020 (N = 8000), 3.93 tons in 2021 (N = 8000), 22.33 tons in 2022 (N = 7894), and 33.29 tons in 2023 (N = 7867) (Table 1).

Table 1. Total biomass potential *of R. mucronata* from the REMAJA PHE ONWJ program on the coast of Pantai Bahagia Village, Bekasi – Indonesia.

Years	N	AGB (ton)	BGB (ton)	Total (ton)
2020	8000	0.66	0.58	1.24
2021	8000	2.20	1.73	3.93
2022	7984	13.47	8.86	22.33
2023	7867	20.43	12.86	33.29

Notes: N is based on the survival rate, as shown in Figure 2; AGB is above-ground biomass, and BGB is below-ground biomass.

3.3. Carbon stock and CO_2 absorption

Based on the total biomass potential, planting *R. mucronata* mangroves from the REMAJA PHE ONWJ program significantly contributes to carbon storage. The results of the evaluation show that the total carbon stock stored in 2023 will reach 15.59 tons C, consisting of 9.57 tons of C on the above-ground (AGC) and 6.02 tons of C on the below-ground (BGC). The stock increased by 5.14 tons C compared to 2022, 13.75 tons C compared to 2021, and 15.01 tons C compared to 2020 (Figure 5).

This significant increase in carbon stock reflects the success of *the Rhizophora mucronata* mangrove planting program as part of a climate change mitigation strategy. Mangroves are known to have an extraordinary ability to absorb and store carbon, both at the top of the soil (AGC) through stems, leaves, and branches and below the ground level (BGC) through roots (Murdiyarso et al., 2015; Rahman et al. 2024c). The most significant contribution in 2023 came from AGC, which stores more carbon as more mature and more extensive mangrove vegetation grows.

The role of mangroves in sequestering carbon provides short-term benefits and contributes to the stability of coastal ecosystems in the long term. Carbon stocks stored underground, such as those recorded in the BGC, can remain trapped for centuries if mangrove ecosystems are protected from damage. With an annual upward trend in carbon storage, programs like REMAJA PHE ONWJ not only support environmental conservation but also help reduce greenhouse gas emissions, making mangrove planting areas an integral part of nature-based solutions to climate change (Huxham et al., 2023).

The contribution to reducing greenhouse gas emissions, especially CO2, can be equivalent based on the potential of carbon stocks (Rahman et al., 2024c). Based on this, the contribution of *R. mucronata* absorption in the 2020-2021, 2021-2022, and 2022-2023 ranges were 4.62 tons of CO2e, 31.58 tons of CO2e, and 18.83 tons of CO2e, respectively (Figure 6).

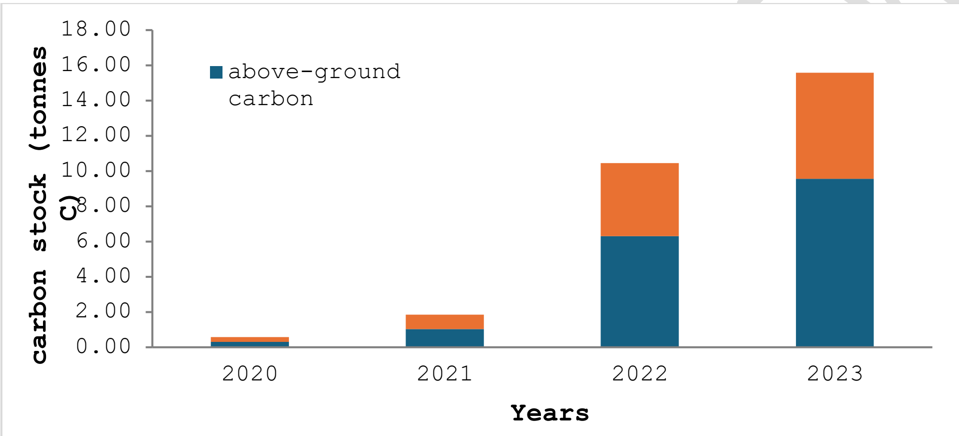

Figure 5. Potential carbon stock *of R. mucronata* from the REMAJA PHE ONWJ program on the coast of Pantai Bahagia Village, Bekasi – Indonesia.

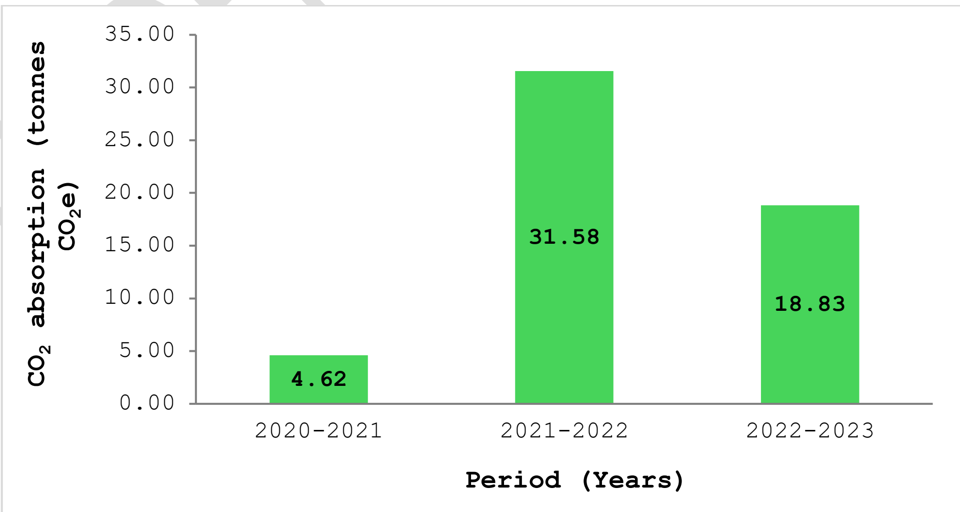

Figure 6. Carbon sequestration rate (CO_2e) *of R. mucronata* from the REMAJA PROGRAM PHE ONWJ program on the coast of Pantai Bahagia Village, Bekasi – Indonesia.

4. Conclusion

The planting *of R. mucronata* through the REMAJA PHE ONWJ program in the Karawang Regency's coastal area significantly contributes to increasing carbon stocks. From 2020 to 2023, the total carbon stock stored increased consistently, reaching 15.59 tonnes C in 2023, 9.57 tonnes C at above-ground carbon (AGC), and 6.02 tonnes C at below-ground carbon (BGC). This increase reflects the program's success in supporting climate change mitigation through long-term carbon storage, with carbon stocks continuing to grow as more mature mangrove vegetation grows.

The program also demonstrated its effectiveness in maintaining a high survival rate of mangrove seedlings, with a survival rate of more than 98% throughout the evaluation period. In addition, the increase in mangrove biomass, both above and below ground, contributes to a more significant total carbon stock year over year. Overall, the planting of *R. mucronata* under this program provides ecological benefits in the form of carbon storage and supports the long-term stability of coastal ecosystems while serving as a natural solution to reduce greenhouse gas emissions.

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