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Estimation of Biomass, Carbon Stocks, O_2 Production and Enviromental Services Value of CO_2 Sequestration of Mangrove Forests in Kurau Sub-District, Tanah Laut Regency

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ABSTRAK

Indonesia memiliki kawasan hutan mangrove terluas di dunia yang berperan penting dalam regulasi karbon global dan penyediaan jasa ekosistem pesisir. Namun, ekosistem ini menghadapi ancaman yang semakin meningkat akibat tekanan antropogenik, seperti perluasan budidaya perairan (khususnya tambak udang), alih fungsi lahan pertanian, serta pembangunan infrastruktur perkotaan. Aktivitas tersebut tidak hanya menyebabkan penurunan tutupan hutan, tetapi juga mengganggu fungsi ekologis mangrove, terutama sebagai penyerap karbon dan penghasil oksigen yang signifikan. Mengingat kapasitas penyimpanan karbon mangrove per hektare merupakan yang tertinggi di antara semua tipe hutan, konservasinya menjadi krusial dalam upaya mitigasi perubahan iklim. Penelitian ini bertujuan untuk mengevaluasi fungsi ekologis dan ekonomi hutan mangrove di Kecamatan Kurau, Kabupaten Tanah Laut, Kalimantan Selatan. Secara khusus, penelitian ini mengestimasi biomassa atas-permukaan, cadangan karbon, produksi oksigen, serta nilai ekonomi dari jasa lingkungan penyerapan CO_2. Pengambilan data dilakukan melalui metode stratified random sampling berdasarkan klasifikasi kerapatan vegetasi dari citra NDVI, yang dikategorikan ke dalam kelas jarang, sedang, dan lebat. Pengukuran lapangan difokuskan pada vegetasi dari tingkat semai hingga pohon dewasa. Biomassa dianalisis menggunakan persamaan alometrik spesifik jenis, cadangan karbon diturunkan dari biomassa menggunakan faktor konversi standar, dan produksi oksigen diestimasi melalui pendekatan stoikiometri. Valuasi ekonomi dilakukan dengan pendekatan berbasis harga pasar karbon internasional. Hasil penelitian menunjukkan bahwa kawasan dengan vegetasi dengan kerapatan tinggi memberikan manfaat ekologis tertinggi, dengan biomassa sebesar 54,72 ton/ha, cadangan karbon 25,72 ton/ha, dan produksi oksigen 68,66 ton/ha. Nilai ekonomi jasa lingkungan karbon tersebut diperkirakan mencapai Rp1,57 miliar per tahun, yang menunjukkan potensi integrasi konservasi mangrove dengan program pemberdayaan masyarakat berbasis pembangunan berkelanjutan.

Kata kunci: Biomassa, cadangan karbon, jasa lingkungan, produksi oksigen, mangrove, hutan

ABSTRACT

Indonesia possesses the world's largest mangrove forest area, which plays a vital role in global carbon regulation and coastal ecosystem services. However, these ecosystems are under increasing threat from anthropogenic pressures such as aquaculture expansion (especially shrimp farming), agricultural land conversion, and urban infrastructure development. These activities not only reduce forest cover but also compromise the ecological functions of mangroves, particularly their role as significant carbon sinks and oxygen producers. Given that mangroves have the highest carbon storage capacity per hectare compared to other forest types, their conservation is imperative in mitigating climate change. This study aims to assess the ecological and economic functions of mangrove forests in Kurau Sub-district, Tanah Laut Regency, South Kalimantan. Specifically, it quantifies aboveground biomass, carbon stocks, oxygen output, and the economic value of CO_2 sequestration. Data were collected through stratified random sampling based on vegetation density classes obtained from NDVI imagery, categorized into sparse, moderate, and dense classes. Field measurements focused on vegetation components from saplings to mature trees. Biomass was calculated using species-specific allometric equations, carbon stock was estimated by applying standard conversion factors, and oxygen production was derived using stoichiometric ratios. Economic valuation was conducted using a market-based approach, referencing global carbon pricing standards. The findings reveal that dense vegetation areas provide the greatest ecological benefit, with biomass of 54.72 tons/ha, carbon stock of 25.72 tons/ha, and oxygen production of 68.66 tons/ha. These ecological values translate into an estimated economic benefit of IDR 1.57 billion per year, indicating potential for integrating mangrove conservation with community-based development programs.

Keywords: Biomass, carbon reserves, enviromental services, oxygen production, mangrove, forest

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1. INTRODUCTION

Mangrove forests significantly contribute to climate change mitigation efforts because they are important carbon sink and oxygen producers. These habitats are notoriously productive, sequestering 6-8 Mg CO_2 equivalent per hectare annually and contributing to the global carbon cycle (Harishma et al., 2020). Moreover, mangroves sequester carbon in their biomass at rates above those of other forest species, with carbon stocks varying from 990 to 1074 tons per hectare (Hamzah et al., 2020; Bai et al., 2021). This ability to store and retain carbon is crucial since mangrove forest loss contributes 0.08 to 0.48 Pg CO2 per year to global carbon emissions (Malik et al., 2022). Furthermore, mangroves increase oxygen generation, which benefits both terestrial and marine life (Carugati et al., 2018). Human-caused degradation of mangrove forests threatens their ability to offer these vital services, emphasizing the need for rapid conservation actions (Goldberg et al., 2020). Thus, extensive research into mangrove ecosystems is required to maintain ecological balance and maximize their worldwide advantages (Hakim et al., 2022).

Indonesia's mangrove forests, the most extensive globally, are confronting substantial threats from deforestation, land conversion, and enviromental degradation. The main factors contributing to this decline include the growth of aquaculture, especially shrimp farming, agricultural development, and urbanization, resulting in the loss of roughly 1,739.04 km2 of mangrove area from 1996 and 2020 (Panggabean, 2023). This conversion diminishes biodiversity and releases substantial quantities of stored carbon, increasing greenhouse gas emissions and compromising Indonesia's climate change mitigation efforts (Sidik et al., 2018; Kauffman et al., 2020). National strategies emphasize mangrove rehabilitation and greenhouse gas reduction to preserve these ecosystem for carbon sequestration capacities (Sumarga et al., 2022). Despite these efforts, mangrove loss continues, and halting deforestation could reduce national land-related emissions by 10% to 30% (Sasmito et al., 2019).

Mangrove forest are one of the most productive marine ecosystem (Hatta, et al., 2022) and have great potential, including mangrove forests in Kurau Sub-district. By producing oxygen and absorbing carbon dioxide, these ecosystems improve local communities (Indriyani et al., 2020). Mangroves are recognized as highly efficient carbon sinks, capable of sequestering up to four times more carbon per hectare than tropical forests, thereby contributing to climate change mitigation (Indriyani et al., 2020; Breithaupt et al., 2012). Furthermore, their unique ability to absorb CO_2 balances anthropogenic emissions and support enhanced air quality in the region (Kusuma et al., 2023). Mangroves' high primary productivity, driven by their sensitivity to environmental factors like precipitation and sea-level fluctuations, emphasizes their ecological important (Zhang, 2023; Jacotot et al., 2019). Overall, the mangrove ecosystems in Kurau Sub-district are vital for both ecological stability and the socio-economic well-being of local populations, highlighting the need for their conservation and sustainable management (Salam et al., 2017).

The current body of these research in the Kurau sub-district is notably limited. Although research has highlighted the crucial function of mangroves in carbon sequestration and ecosystem serviced worldwide, localized data specific to Kurau is sparse, hindering effective conservation policy formulation and sustainable management practices (Nguyen et al., 2021; Siddiq et al., 2020). The disparity in carbon stock estimations across locations like the Indo-Pacific underscores the need for specific evaluations to accurately gauge the potential of mangrove ecosystems in Kurau (Kauffman et al., 2020). Quantitative data is needed to inform management plans since mangrove ecosystem deterioration reduces carbon stocks (Sasmito et al., 2019; Maseta et al., 2022). Furthermore, mangrove provide ecosystem services such as habitat supply and storm protection, highlighting their ecological value; yet, these benefits remain under-quantified in Kurau (Fatonah et al., 2021; Handayani et al., 2023). Finally, quantitative data on Kurau mangrove ecosystems is needed to fully exploit its climate change mitigation and biodiversity conservation (Carugati et al., 2018).

The project aims to measure the biomass, carbon sequestration, oxygen production, and enviromental services value from CO_2 sequestration in Kurau Sub-distric's mangrove forest. Quantifying ecological parameters in Tanah Laut Regency will aid conservation planning and natural resource management (Borges et al., 2017). Furthermore, understanding the carbon dynamics and oxygen production in mangroves can enhance environmental policy formulation, ensuring that conservation efforts are grounded in scientific evidence (Ferreira & Lacerda, 2016). The findings from this research are expected to support the sustainable management of mangrove resources, thereby promoting biodiversity and ecosystem resilience (Feller et al., 2010). Ultimately, this research will contribute to broader goals of environmental sustainability and climate adaptation in coastal regions (Borges et al., 2017).

2. METHODS

2.1. Study Area

The research is conducted from Juli 2024 to September 2024 in Kurau Sub-District of Tanah Laut District, Indonesia. The coordinates for the Kurau sub-district are approximately 3.5° S latitude and 114.5° E longitude. The map of research location is provided in Figure 1. Kurau sub-district, which has an area of 127 km^2, is one of the sub-districts located at the edge of Tanah Laut regency where the western part directly borders the Java Sea. Based on this location, the mangrove forest area in Kurau Sub-district is mostly located in the western part of the region.

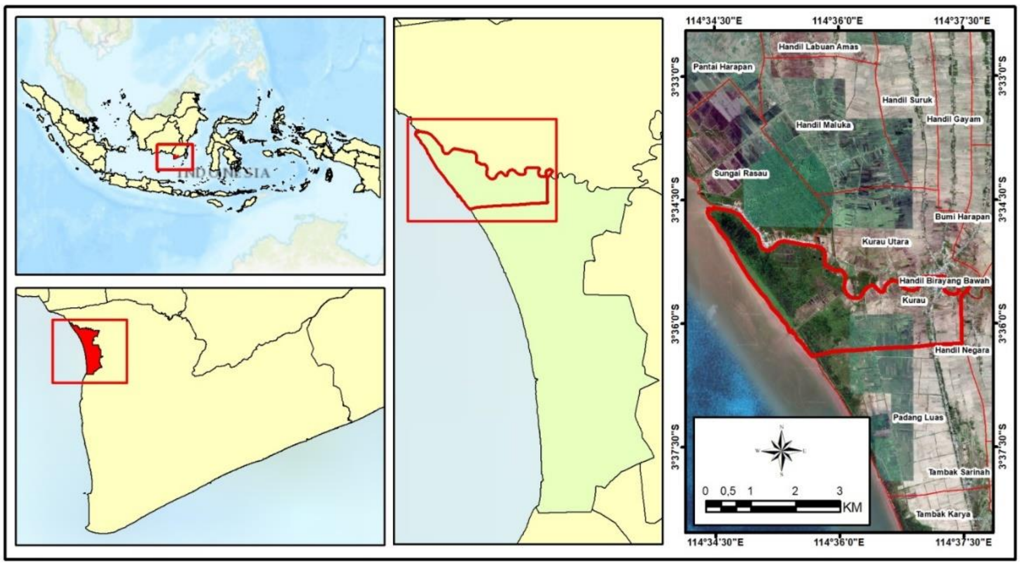

Figure 1. Map of the research location in Kurau Sub-District of Tanah Laut Regency, South Kalimantan Province, Indonesia

2.2. Materials and Methods

This study measured the aboveground carbon found in vegetation growing in the mangrove forest of Kurau Sub-district, Tanah Laut Regency. Mangrove vegetation from sapling to tree level was chosen because at that level the diameter of the plant might already be measured where the diameter of the tree is a parameter used in carbon calculations. Sampling was done by a purposive sampling method that adjusts the density level in Kurau Sub-district's mangrove forest area. Each density category was tahen 3 measuring plots each with each measuring plot taken 25 sub-plots with each plot measuring 5mx5m for the sapling level, 10mx10m for the pole level, and 25mx25m for the tree level.

The article titled "Estimation of Biomass, Carbon Reserves, O_2 Production and Environmental Services Value of CO_2 Sequestration of Mangrove Forests in Kurau Sub-district, Tanah Laut Regency" employs a combination of field measurements and analytical modeling to estimate the ecological contributions of mangrove forests. The methodology includes the collection of data on tree height, diameter at breast height (DBH), and species composition to calculate biomass using allometric equations tailored for mangrove species. This approach is supported by existing literature that emphasizes the importance of accurate biomass estimation in understanding carbon sequestration potential (Melo et al., 2020). Furthermore, the results of the allometric calculation were converted to the percentage approach of carbon stocks in mangrove forest so as to obtain carbon stocks at the research site. Carbon stock is one of the types of enviromental services that can be obtained from mangrove forests and can be measured in monetary value by multiplying the results of carbon uptake with the price of carbon. In addition, the results of carbon stocks can also be used to calculate oxygen production by converting carbon values through the atomic comparison approach and photosynthesis and respiration activities of plants (Salisbury & Ross, 1978).

In terms of analysis, the article likely employs statistical methods to interpret the collected data, including regression analysis to establish relationships between biomass, carbon reserves, and environmental services. The use of Monte Carlo simulations may also be applied to account for uncertainties in the data and model predictions (Melo et al., 2020). Furthermore, the economic valuation of the environmental services provided by mangrove forests, such as CO_2 sequestration, could be assessed using contingent valuation methods or benefit transfer approaches, which have been widely discussed in ecological economics literature (Prasetyo et al., 2017). This multifaceted analytical framework not only enhances the reliability of the findings but also underscores the significance of mangrove forests in contributing to both ecological stability and local economies (Kalsum et al., 2022).

2.3. Data Analysis

This study used a non-destructive method, which means that the carbon calculation research was carried out without damaging the plants. Data collected included tree diameter by recording the type of plants found in the research plot, measuring the circumference of the tree at 130 cm, and measuring the height of the plant.

2.3.1. Biomass Calculation

The carbon calculated in this study is measured based on the biomass contained in plants. Biomass in this study was obtained from the growth level of saplings to trees. The growth level was chosen because starting at the sapling level, the diameter of the plant can be measured where the diameter of the plant is one of the parameters used in the calculation of biomass. Based on the data obtained from the field, the calculation of biomass can be seen in Table 1.

Table 1. Biomass Calculation Formula in the Mangrove Forest of Kurau Sub-District

Species Name	Allometric Method	Source
Rhizophora macronata	B = 0.1466 x $D^{2.3126}$	Dharmawan (2010)
Avicennia marina	B = 0.1848 x $D^{2.3524}$	Dharmawan & Siregar (2008)
Sonneratia alba	B = ρ x 0.3841 x $D^{2.101}$	Kauffman & Donato (2012)
General equation	B = 0.251 x ρ x $D^{2.46}$	Komiyama et al (2008)

Where: B is Biomass (kg); ρ is Specific gravity (kg/m²); D ide diameter (m)

2.3.2. Carbon Calculation

After knowing the value of aboveground biomass, carbon is calculated using the following equation (Martin & Thomas, 2011l; Thomas & Martin, 2012; Carong et al., 2024).

$$C = B \times 47\%$$

Where: C is carbon reserves (ton)

2.3.3. Calculation of Oxygen Production

Oxygen production is obtained from the reduction of the photosynthesis process with respiration where in the photosynthesis process, plants produce oxygen (O_2) and in the respiration process, plants take oxygen (O_2) in the air (Salisbury & Ross, 1978). The approach by Nowak, et al. (2007) in calculating the oxygen produced can be done by multiplying the stored carbon reserves by the ratio of attom weight (Daud, et al., 2018). Calculation of estimated oxygen production as follows:

$$\text{Production of } O_2 = C \times \frac{32}{12} \text{ or } C \times 2{,}67$$

2.3.4. Economic Value of Carbon Sequestration

This study assessed the economic value of carbon sequestration by applying the World Bank's benchmark, which assigns a value of US$10 per ton of carbon per hectare (Kossoy & Guigon, 2012; Kasim et al., 2024). The valuation was calculated using the formula: Economic Value = C × total area (ha) × US$10. To convert the results into local currency, we used the average exchange rate at the time of data collection, where US$1 equaled IDR 15,850.65. This method offers a standardized approach to quantifying ecosystem services and supports evidence-based strategies for environmental conservation and climate policy formulation.

3. RESULTS

This study presents an integrated analysis of the ecological performance and environmental service values of mangrove forests in Kurau Sub-district, Tanah Laut Regency. The assessment focused on three key ecosystem indicators: aboveground biomass, carbon stock, and oxygen production, as well as the estimated economic value of carbon sequestration across three vegetation density classes—sparse, moderate, and dense.

3.1. Estimation of Biomass and Carbon Reserves in Mangrove Forest in Kurau Sub-District

Biomass calculations in this study were categorised into three NDVI density classes: sparse, medium and dense. In each class, at least one vegetation was found at the sapling, pole, and tree growth levels because tree diameter is needed in calculating biomass estimates. Mangrove ecosystems can absorb carbon dioxide through diffusion through stomata. The results of this diffusion are then stored in the form of biomass (Windardi, 2014; Rezekiah, et al., 2024) which we use in conducting carbon analysis. This carbon value can be analysed by estimating and one of the carbon values that can be analysed is mangrove vegetation. The potential biomass of good mangrove ecosystems in Southeast Asia ranges from 250-275 tons/ha and the lowest biomass is less than 7.9 tons/ha (Donato, et al., 2011; Rezekiah, et al., 2024).

The calculation results show that overall, the highest biomass value is at the high forest density level with a value of 30.87 tons/ha. Followed by the medium class at 22.75 tons/ha and the sparse class obtained a biomass value of 1.10 tons/ha. The average biomass calculation data in this study was 18.24 tons/ha. Based on previous data, it is known that the highest carbon value is in the dense class with a value of 14.51 tons/ha, followed by the medium class of 10.69 tons/ha, and the sparse class of 0.52 tons/ha. The average carbon value in this study was 8.57 tons/ha. Calculation of mangrove forest biomass and carbon in this study can be seen in Figure 2.

Vegetation types that can be found at the research site include *Avicennia officinalis, Avicennia lanata, Avicennia marina, Excoecaria agallocha, Sonneratia caseolaris, Rhizophora mangle*, and *Rhizophora mucronata*. The results of observations on each density at each level of vegetation have different types of dominance. At the sapling level dominated by the type of Excoecaria agallocha, at the pole level dominated by the type of Rhizophora mangle, and at the tree level dominated by the type of Sonneratia caseolaris. Verma et al. (2024) states that biomass is affected by 'size of the bar' where if the bar size decreases, the biomass at that location disappears. In this study, the factors that influenced the carbon content values were tree diameter, height and forest density. The higher the level of vegetation does not guarantee that the value of biomass absorbed is also higher. This is because usually the larger the diameter size, the smaller the number in the field. Especially in forests that have been touched by human activities.

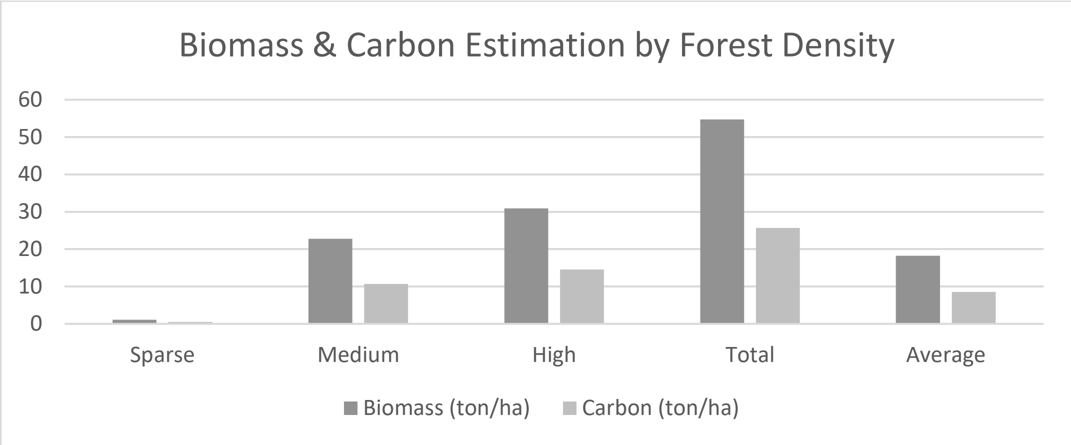

Figure 2. Biomass and Carbon Estimation by Forest Density in Mangrove Forest of Kurau Sub-District, Tanah Laut Regency, South Kalimantan Province, Indonesia

Table 2. Biomass and Carbon Stocks of Mangrove Forests in Various Location

Location	Biomass (ton/ha)	Carbon (ton/ha)	Source
Benoa Bay, Bali, Indonesia	364.241	171.193	Mahasani et al. (2021)
Sirik Azini Creek, Ormozgan, Iran		96	Askari et al. (2022)
Pagatan Besar, Kabupaten Tanah Laut, Indonesia		40.10	Rezekiah et al. (2021)
Sulaman Lake Forest Reserve, Sabah, Malaysia		67.30	Suhaili et al. (2020)
Kerala, Southwest Coast, India		58.56	Harishma et al. (2020)
Guangdong Province, China		84.61	Liu et al. (2014)
The rehabilitated area of Sinjai, South Sulawesi, Indonesia	125.48	60.23	Malik et al. (2020)

The total value of carbon stocks in this study is smaller (25.72 tons/ha) than the studies shown in Table 2. This is because this study only calculated vegetation carbon and did not calculate the value of other carbon parameters such as litter necromass, understorey biomass, and soil carbon stocks. If only the value of vegetation carbon is considered, then the results of carbon stocks in this study are higher than the three studies. The biomass value of 54.72 tons/ha and carbon value of 25.72 tons/ha is the total value of biomass and carbon stored in the aboveground vegetation only. This value does not include all carbon accounting parameters that can be analysed. Much of the biomass in the mangrove forest is stored in soil, debris and other substrates that were not analysed in this study. The low average carbon stock in this study needs to be addressed as soon as possible so that the value does not continue to decrease. This decline in value is due to human activities such as overexploitation of forests and the impacts of climate change.

Biomass estimates are vital to understanding forests' role in climate change (Haile, et al., 2024). In accordance with the results of the study, vegetation biomass is positively correlated with vegetation density. The denser the vegetation, the higher the biomass value. Similarly, carbon value is related to biomass value. Figure 2 shows that the higher the vegetation density, the higher the biomass and carbon values. Rezekiah et al. (2024) stated that the number of stands and high stand density caused the biomass and carbon values at that location to also have high values.

3.2. Estimation of Oxygen Production in Mangrove Forest in Kurau Sub-District

Photosynthesis activities can only be carried out by living things that have chlorophyll, one of which is vegetation. This activity is not only useful in absorbing carbon dioxide in the atmosphere but also plays a role in releasing its production in the form of oxygen into the air. Humans as living creatures depend on the environment, oxygen and food needs provided by forests (Sejati, et al., 2023; Sugiarto, et al., 2024). Oxygen produced in the photosynthesis process depends on the amount of carbon dioxide absorbed by vegetation as raw material.

Calculation of oxygen production is based on net carbon reserves stored (Nowak et al., 2007), which is an estimate that the amount of net oxygen production by plants is the result of the reduction of the results of carbon absorbed for photosynthesis and carbon released by plants to respire (Sribianti et al., 2022). Oxygen production was divided into three categories based on NDVI class: dense class, medium class, and sparse class. The results showed that the highest oxygen production was in the dense class with a value of 38.74 ton/ha. Then, the medium class was in second position with a value of 28.55 ton/ha and the sparse class had the smallest oxygen production in this study at 1.38 ton/ha. The accumulated and average oxygen production in this study was 68.66 ton/ha and 22.89 ton/ha which can be seen in Table 3.

Oxygen production per year can be calculated by multiplying the production results with the area of each forest density class. In high forest density, oxygen production was 25,262.78 tons, medium forest density was 1,092.31 tons, and sparse forest density was 42.24 tons. Total oxygen production in one year in the mangrove forest Kecaamatan Kurau amounted to 26,262.78 tons. The value of oxygen production in this study is greater than the research by Sribianti et al. (2022) conducted in the Abdul Latief Sinjai East Forest Park which was 8,078.40 tons. This is because the types of forests studied are different and the potential carbon stocks in mangrove forests are greater.

Table 3. Estimation of Oxygen Production in Mangrove Forest in Kurau Sub-District

No.	Forest Density Class	O_2 Production (ton/ha)	O_2 Production (ton)
1	Sparse	1.38	42.24
2	Medium	28.55	1,092.31
3	High	38.74	25,262.78
	Total	**68.66**	**26,397.34**
	Average	**22.89**	**8,799.11**

The net value of oxygen production in this study is based on the research of Sribianti et al. (2022), which is in addition to calculating the oxygen released by plants, it is also reduced by the oxygen absorbed by plants for the respiration process. The results of the reduction are used in analysing oxygen production by plants used by humans. According to the data in Table 3, it is known that the oxygen production in a year at this research location is 26,397.34 tons. Oxygen production is strongly influenced by the value of carbon stocks with the largest oxygen production at the pole level in high forest density. This is because the pole growth level is the dominating vegetation in the Kurau sub-district mangrove forest. Sonneratia caseolaris plants are the plants that produce the most oxygen at the pole level with an estimated production of 8.06 tons/ha. Knowing the amount of oxygen production from plants can help make people aware of the importance of forests in everyday life.

3.3. Carbon Sequestration Value of Mangrove Forest in Kurau Sub-District

The economic value of carbon stocks in this study was obtained from multiplying the results of carbon stocks of each density class by the area and carbon price. The carbon price used in the study was US$10 from the World Bank standard assumption with the determination of US$1 is the average selling rate in the study period. The average economic value of carbon stocks obtained in the study was IDR 522,365,692.14 per year with the highest value in the dense class of IDR 1,499,743,496.32 per year. Followed by the medium class of IDR 64,845,943.16 per year and the sparse class of IDR 2,507,636.94 per year. The percentage of carbon economic value in this study can be seen in Table 4.

The economic value of mangrove forests as carbon storage is one of the benefits that can be felt by humans indirectly. This value is obtained from the estimation of the economic value contained in mangrove forests. The calculation of the economic value of mangrove forest carbon in this study was obtained at IDR 1,567,097,076.42 with an average of IDR 522,365,692.14 per year. This figure is the number that will be lost if the mangrove forest is not preserved and managed properly and it is a considerable benefit to be considered for its existence and sustainability.

The results of this study (IDR 1,567,097,076.42 per year) are greater than the research of Rezekiah et al. (2024) in the Indonesian Tropical Rainforest Park of IDR 26,536,273.31 per year, Farista & Virgota (2021) in the Bagek Kembar Mangrove Ecotourism Area of IDR 482,384,700 per year. However, the results of this study are smaller than the research of Kasim et al. (2024) in Nipa-Nipa Grand Forest Park with value of carbon is IDR 148,223,019,859.84 per year. The different research areas and types of forests studied with the types of vegetation that grow in them greatly affect the results of carbon economy calculations.

The value does not directly accrue to society in material terms. However, the figure can be a reference to countries that compensate for their industrial activities that produce carbon emissions. So, Indonesia or the state and communities around the forest will get benefits or compensation for these activities as well as compensation to communities that have preserved the forest. This condition has also been regulated in the Minister of Environment and Forestry Regulation Number 21 of 2022 concerning the Implementation Procedure of Carbon Economic Value. The community will receive these benefits in the form of programmes or activities that can help improve the community's economy.

4. DISCUSSION

The mangrove ecosystems in Kurau Sub-district, Tanah Laut Regency, demonstrate a dual importance—ecological and economic—that is evident through their capacity to store carbon, generate oxygen, and offer environmental service values. This study confirms that mangrove stands with denser canopy cover exhibit higher levels of aboveground biomass, resulting in greater carbon sequestration and oxygen output compared to stands of moderate or sparse density. Such outcomes are consistent with findings at the global scale, where mangroves are recognized as exceptional carbon sinks, often outperforming terrestrial forests in their blue carbon storage capability (Breithaupt et al., 2012; Kauffman et al., 2020). The carbon stock measured in Kurau, which reached 25.72 tons per hectare, exclusively represents aboveground biomass. It does not include belowground biomass or soil organic carbon, which are known to constitute up to 80% of total ecosystem carbon in mangrove forests (Donato et al., 2011).

Table 4. Calculation of the Economic Value of Mangrove Forest Carbon in Kurau Sub-District

No.	Forest Density Class	Area (ha)	Carbon (ton/ha)	Economic Value of Carbon (IDR)	Percentage (%)
1	Sparse	30.66	0.52	2,507,637.94	0%
2	Medium	38.26	10.69	64,845,943.16	4%
3	High	652.15	14.51	1,499,743,496.32	96%
	Total	**721.07**	**25.72**	**1,567,097,076.42**	**100%**
	Average	**240.36**	**8.57**	**522,365,692.14**	

In terms of oxygen production, the observed rate of 68.66 tons per hectare per year illustrates the mangrove forest's vital role in maintaining atmospheric balance. Nowak et al. (2007) highlighted that forests with dense biomass and high rates of photosynthesis significantly influence global oxygen regeneration. This function becomes increasingly crucial as deforestation accelerates, and anthropogenic greenhouse gas emissions continue to rise.

A comparative review with other regional studies positions the Kurau mangrove forest above Pagatan Besar in Tanah Laut—where carbon storage was only 18.85 tons per hectare (Rezekiah et al., 2021)—yet below the notably higher carbon values found in more mature mangrove systems such as those in Benoa Bay, Bali. In the latter, Mahasani et al. (2021) recorded 171.19 tons of carbon per hectare, reflecting the forest's undisturbed status and the dominance of high-biomass species like *Rhizophora* and *Sonneratia* (Komiyama et al., 2008).

Globally, carbon stock values vary significantly. Liu et al. (2014) reported biomass of 84.61 tons/ha in Chinese mangroves, while Askari et al. (2022) found about 96 tons/ha in Iran's Sirik Azini Creek. The lower biomass recorded in Kurau could be a result of younger or recovering vegetation, as evidenced by the dominance of pole-stage mangrove growth. These characteristics suggest that the area is undergoing ecological succession and thus has potential for further carbon accumulation if protected and restored appropriately.

Economically, the annual value of carbon sequestration in Kurau mangroves—approximately IDR 1.56 billion or USD 98,878—is noteworthy. This amount surpasses that of the Bagek Kembar Ecotourism site in West Nusa Tenggara, valued at IDR 482 million (Farista & Virgota, 2021), but is still substantially lower than the IDR 148 billion recorded in Nipa-Nipa Grand Forest Park, Southeast Sulawesi (Kasim et al., 2024). These disparities underscore the importance of scale, species composition, forest condition, and valuation methodology. By expressing the valuation in international currency, this study facilitates its relevance to global climate financing mechanisms such as REDD+ and voluntary carbon markets (Kossoy & Guigon, 2012).

The results suggest an urgent need to prioritize the conservation of high-density mangrove zones, as they contribute disproportionately to carbon storage and oxygen generation. Furthermore, from a socio-economic perspective, the integration of mangrove ecosystems into sustainable community-based programs—such as carbon offsetting and nature-based tourism—could provide long-term incentives for local stewardship. The dominance of species like *Sonneratia caseolaris* and *Rhizophora mangle* provides an opportunity to focus restoration efforts on high-performing species known for their carbon fixation potential (Indriyani et al., 2020). Meanwhile, areas with low canopy density represent opportunities for targeted rehabilitation to restore ecological functionality and enhance service delivery (Sasmito et al., 2019).

This study reaffirms the positioning of mangroves as nature-based solutions to climate change, particularly in tropical coastal regions. However, to fully capture the carbon sequestration capacity of these forests, future research must incorporate a more comprehensive carbon accounting framework—one that includes soil carbon, deadwood, and belowground biomass. Continuous monitoring is also essential, particularly in systems affected by tidal dynamics and seasonal climatic variability (Zhang et al., 2023).

In conclusion, the Kurau mangrove forest offers a valuable suite of ecological services and economic opportunities. While the current carbon stock reflects moderate storage capacity, it serves as both a functional baseline and a potential benchmark for future improvement through sustainable management and active restoration.

5. CONCLUSION

Estimates of biomass, carbon stocks and oxygen production were categorised by density class in NDVI. This study resulted in biomass, carbon stock, and oxygen production values of 54.72 tons/ha, 25.72 tons/ha, and 68.66 tons/ha, respectively. The economic value of carbon stocks generated in the Kurau sub-district mangrove forest is IDR 1,567,097,076.42 per year. This value will be obtained by the community in the form of empowerment programmes or activities that can improve their economy. The biomass analysed in this study is only biomass in the standing category, so it still does not cover the entire biomass value in the Kurau sub-district mangrove forest. Further research can be carried out at the research location to determine the value of biomass and carbon reserves stored in mangrove forests because in addition to stands, carbon in mangrove forests can be stored in the soil, litter and understory. There are still many parameters that can be analysed in this study so that the information collected will be more complete by conducting further research.

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