Biosaintifika 17 (2) (2025): 358-369 p-ISSN 2085-191X | e-ISSN 2338-7610
Journal of Biology & Biology Education https://journal.unnes.ac.id/nju/index.php/biosaintifika

# Evaluating the Economic Value of Above-Ground Biomass Carbon Stocks in the Urban Forests of Banda Aceh City

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Submitted: 2025-03-23. Revised: 2025-05-27. Accepted: 2025-07-30.

**Abstract.** Urban forests play a pivotal role in climate change mitigation by storing carbon in biomass. However, the economic valuation of this ecosystem service in Banda Aceh City remains underexplored. This study aims to quantify aboveground biomass carbon stocks and assess their economic value in six selected urban forests across the city. Non-destructive sampling was conducted using 20 × 20 m plots to measure tree diameter, estimate biomass using species-specific allometric equations, and calculate carbon content (C = 0.5 × B). A carbon price of US$50/ton was applied for economic valuation. The total carbon stock was estimated at 11,579 tons, with Putroe Phang Forest contributing the highest proportion (45%). The corresponding economic value was approximately IDR 3.42 billion. A strong positive correlation ($R^2 = 0.9859$) was observed between tree diameter and biomass. This study presents a novel economic perspective on urban forest carbon in Banda Aceh by integrating ecological data with financial valuation. The findings underscore the importance of incorporating carbon trading mechanisms into urban planning to strengthen ecosystem service assessments and climate policy implementation.

**Keywords**: Urban forest; Carbon stock; Economic valuation; Aboveground biomass; Carbon trading,

**How to Cite:** Dharma, W., Yasmin, Y., Ariqah, N., Harnelly, E., Rizki, A., Fitri, L., Amirunnas, A., Rauzana, A., & Zakaria, R. (2025). Evaluating the Economic Value of Above-Ground Biomass Carbon Stocks in the Urban Forests of Banda Aceh City. *Biosaintifika: Journal of Biology & Biology Education, 17(2)*, 358-369.

**DOI:** http://dx.doi.org/10.15294/biosaintifika.v17i2.24368

## INTRODUCTION

Urban forests are planned efforts to bring green spaces into cities to improve people's well-being, ecological health, and local economies (Konijnendijk et al., 2006; Abetu, 2015; Nugroho, 2017). These urban green areas can function much like secondary forests that they are highly effective at capturing carbon because of their fast biomass growth, sometimes even more than mature primary forests (Paniagua-Ramirez et al., 2021). Urban forests deliver a wide array of ecosystem services, including air purification, moderation of urban heat island effects, biodiversity support, carbon storage, and economic contributions (Joe at al., 2020; Doua-Bi et al., 2021). Incorporating economic valuation of forest carbon sequestration helps policymakers compare environmental programs more effectively and boosts public support for forest conservation (Malik et al., 2015).

The System of Environmental Economic Accounting (SEEA) is working to standardize carbon valuation frameworks (Edens et al., 2019; Keith et al., 2021). Properly managed urban forests can provide data in carbon markets and support climate mitigation (Ordóñez & Duinker, 2010; Pascual et al., 2014). Urban forests also contribute to mental well-being, enhance the visual appeal of urban areas, increase property values, and help reduce pollution-related costs. They can deliver long-term, resilient benefits to cities and their residents (Bolund & Hunhammar, 1999; McPherson et al., 1997). Kotze and Boshoff (2016) estimated that urban forests can store approximately 131,767.4 tons of $CO_2$, with an economic value of US$1,226,875.60, based on the 2014 social cost of carbon. Their benefits depend on factors structure, species diversity, and overall condition (Livesley et al., 2016). However, the expansion of urban infrastructure has reduced these ecosystem services (Abass et al., 2018).

In Kumasi, Ghana, Quartey (2012) used a hedonic pricing approach to assess the economic value of urban trees by analyzing how the presence of trees influences property values and reflects broader economic benefits. Deforestation in the area leads to an estimated annual loss of about US$35 million in potential carbon credit value. Urban trees play a key role in mitigating climate change by absorbing $CO_2$ and reducing urban temperatures (Kartodihardjo et al., 2016). They also support climate adaptation by improving public health, increasing water availability, and lowering disaster risks (Sari et al., 2019).

Forests play a crucial role in carbon sequestration and climate regulation (Baccini et al., 2019; IPCC, 2014). Afforestation and reforestation efforts contribute to emission offset targets (Lo & Cong, 2017), and forest carbon sinks are often more cost effective than mitigation strategies in other sectors (Griscom et al., 2017). However, the success of forest regeneration depends on the nature and extent of ecosystem disturbances (D'Oliveira, 2017). Within this framework, the forestry sector contributes primarily through certified emission reductions derived from afforestation initiatives (Lo & Cong, 2017). Griscom et al. (2017) highlight that forest based climate mitigation strategies are generally more cost effective than those in other sectors. While earlier research has focused on the ecological functions of forestry interventions (Liu & Li, 2012) and their socioeconomic impacts (Zhang, Z. et al., 2017), growing attention is now being given to the economic valuation of carbon sequestration from forest projects (Zhang et al., 2016). Woody vegetation such as trees and shrubs plays a vital role in carbon sequestration in urban environments by storing biomass both above and below ground (Ulianti et al., 2018).

As major carbon reservoirs, forests support biodiversity and contribute significantly to climate stability. However, deforestation can shift these ecosystems from carbon sinks to substantial sources of emissions, raising atmospheric carbon levels and intensifying climate change (Baccini et al., 2019). In urban areas, the extent of carbon emissions or retention resulting from forest loss due to expansion is closely linked to the amount of tree biomass present (Penboon et al., 2023). While urban forests are recognized for their important role in carbon sequestration, the economic evaluation of carbon stored in the Banda Aceh City Forest has been limited. This study aims to evaluate the economic value of above-ground biomass carbon stocks in the urban forests of Banda Aceh City, providing essential insights for urban planning, environmental policy, and sustainable development strategies based on scientific evidence.

## METHODS

This research was carried out at six urban forest sites in Banda Aceh City, Aceh Province, Indonesia. The sites are Masjid Raya (MR), Polisi Militer (PM), Putroe Phang (PP), Ratu Safiatuddin (RS), Tibang (TB), and Trembesi (TR). The size of each forest is detailed in Table 1.

Table 1. Study Sites in Six Urban Forests of Banda Aceh

| No. | Location | Area (ha) |
|---|---|---|
| 1 | Masjid Raya (MR) | 0.21 |
| 2 | POM (PM) | 0.34 |
| 3 | Putroe Phang (PP) | 2.42 |
| 4 | Ratu Safiatuddin (RS) | 0.24 |
| 5 | Tibang (TB) | 6.22 |
| 6 | Trembesi (TR) | 2.50 |

Banda Aceh City has a tropical climate characterized by average annual temperatures ranging from 24°C to 31°C. According to the Meteorology, Climatology, and Geophysics Agency (BMKG, 2023), the highest temperatures are typically recorded between May and September, whereas the lowest occur from December to February. The city experiences approximately 2,800 millimeters of annual rainfall, with the driest period typically from February to April and the heaviest rainfall occurring between October and January. Humidity consistently remains high, averaging around 80% year-round, primarily influenced by seasonal monsoon systems.

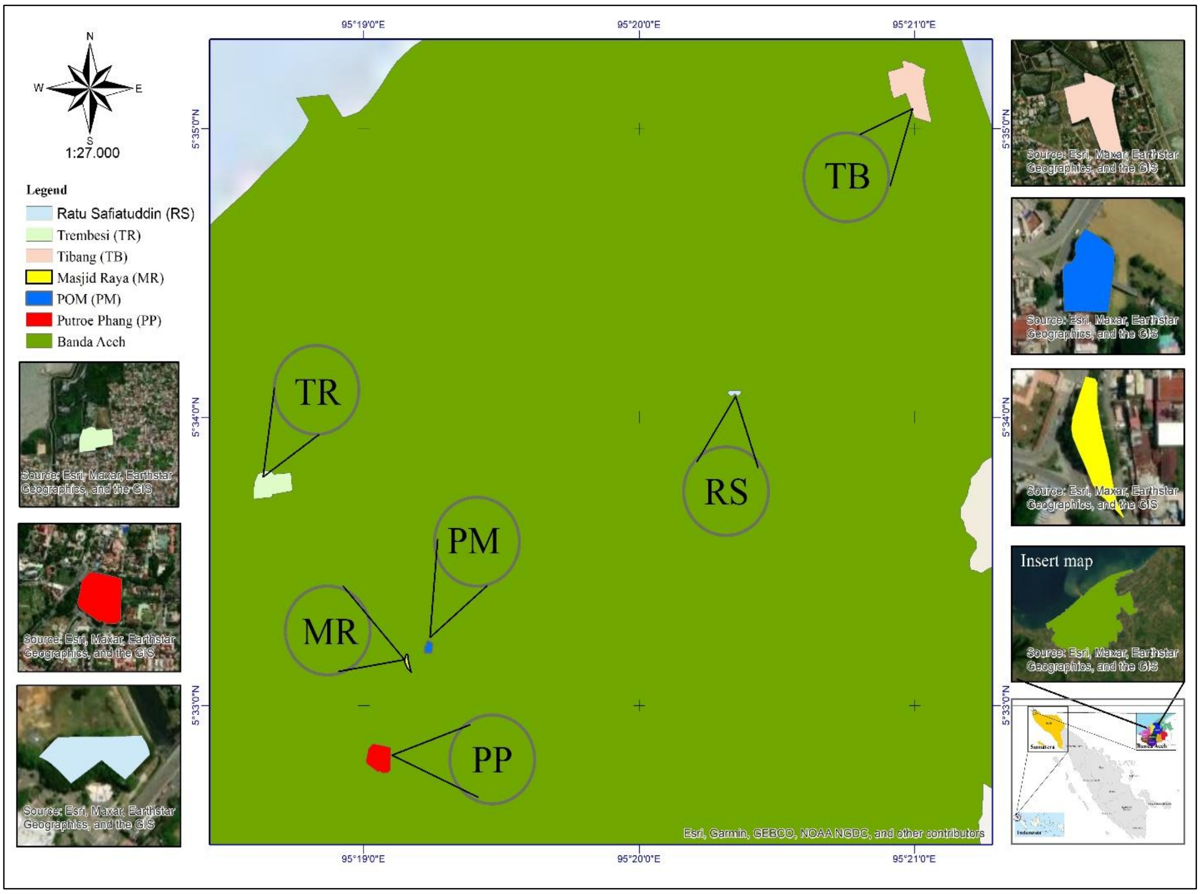


**Figure 1.** Location of the Study Areas

The study employed the following methodologies for data collection and analysis. Data were gathered through non-destructive carbon measurements at the tree level within 20 × 20 meter plots across six urban forests (Nasution et al., 2021). The number of plots was determined based on the size of each forest. Biomass was calculated using the allometric equation $B = 0.11 \times \rho \times D^{2.62}$ (Réjou-Méchain et al., 2025; McPherson et al., 2016). Carbon stocks were assessed with the equation $C = 0.5 \times B$ (Hairiah & Rahayu, 2007; Brown & Lugo, 1982). To estimate the economic value of the carbon stored, the maximum carbon price of US$50 per ton was applied (High-Level Commission on Carbon Prices, 2017). Statistical analyses were conducted to interpret the results, estimating the carbon reserves, biomass, and economic value for each urban forest location.

### Defining the Area and Number of Plots in Each Forest

Field applications were conducted prior to applying the purposive sampling method to determine the most suitable locations for sampling plots (Gillison & Brewer, 1985). In this study, the 20 × 20 m² plot was established in each forest. The 20 × 20 m² plot size is a standard used in forest vegetation analysis in Indonesia, particularly for tree-level assessments (Hairiah & Rahayu, 2007; FAO, 1998). The total number of sampling plots was determined based on the existing forest zones.

Table 2 below presents the number of sampling plots, adjusted according to the area of each forest.

**Table 2.** Distribution of Sampling Plots

| No | Forest | Number of Plots |
|---|---|---|
| 1 | Mesjid Raya (MR) | 2 |
| 2 | POM (PM) | 2 |
| 3 | Putroe Phang (PP) | 8 |
| 4 | Ratu Safiatuddin (RS) | 2 |
| 5 | Tibang (TB) | 20 |
| 6 | Trembesi (TR) | 8 |

### Measuring Tree Diameter and Biomass

Biomass and carbon stock of trees were estimated using non destructive sampling and species-specific allometric equations, considering species diversity and urban environmental dynamics for climate change mitigation (Hidayati et al., 2021). Assessed aboveground biomass and carbon storage in Singapore's urban trees using comparable methods, highlighting the significant role of urban forests in carbon sequestration (Wong et al., 2021). This aligns with Government Regulation No. 63 of 2003, Article 26(2), which prohibits damage to urban forest trees, emphasizing their environmental importance.

Ketterings et al. (2001) estimated tree carbon stocks using DBH measurements at 1.3 m above ground. For leaning trees, sloped terrain, or structural irregularities, DBH is measured at adjusted points to ensure accuracy. Trees with branches or buttresses at 1.3 m are measured at the nearest standard trunk section, with multiple stems treated individually.

**The economic value of stored carbon measurement**

To estimate the economic value of stored carbon, the total carbon stock is multiplied by the market price. According to Kepel et al. (2017), this value is calculated using a carbon price of US$50 per ton, providing a monetary approximation of forest carbon reserves based on the highest valuation.

**Assessment of Carbon Reserves**

Ketterings et al. (2001) utilized an allometric model to estimate biomass, which was subsequently used to calculate the total carbon biomass. The general formula applied in their model is as follows:

$$B = 0.11 \times \rho \times D^{2.62}$$

B = biomass in (kg)
ρ = wood density (g/cm³)
D = diameter at breast height (cm).

The wood specific gravity used in this study was taken from the Global Wood Density Database (Zanne et al., 2009). The formula was adapted for carbon stock analysis and applied to estimate tree biomass. The total carbon content measured in this study comes from the samples collected from the six urban forests. To calculate biomass per hectare, the following formula is used.

Brown (1997) suggests that carbon reserves can be estimated based on 50% of the biomass content. The Indonesian National Standard (SNI, 2011) provides the methodology for calculating carbon inventories in this way:

$$C = 0.5 \times B$$

C = carbon stock (tons/ha)
B = biomass (tons/ha)

**Calculation of the Carbon Economic Value**

The indirect use values cluster includes the forest's value for carbon storage. According to Saloh & Clought (2002), the highest carbon price is used to determine the economic value of carbon. The carbon's economic value can be calculated using the following formula:

$$EVc = CS \times CP$$

EVc = economic value of carbon sequestration (IDR/year)
CS = carbon stock (tons/ha)
CP = carbon price per ton (IDR)
In this study, the carbon price is set at US$50 per ton. Using an exchange rate of IDR 15,000 per US dollar, the carbon price is equivalent to IDR 750,000 per ton.

## RESULTS AND DISCUSSION

Banda Aceh's urban forest is home to 24 plant species and 329 individual trees (Table 3). Among these, members of the Annonaceae and Lamiaceae families are the rarest, while Fabaceae is the most dominant. The most commonly found species is *Samanea saman*, with 153 individuals. *Samanea saman* is frequently planted in urban areas as a city forestry species to help mitigate air pollution and provide shade along roads, near office buildings, parks, and schoolyards (Kabir et al., 2012).

The large *Samanea saman* trees, with an average diameter of 0.38 meters, store up to 6,925.57 tons/ha of carbon. Their high carbon storage capacity is attributed to their large trunk diameter (Smith, 2020). Due to their rapid growth and abundant foliage, *Samanea saman* significantly contributes to the biomass of Banda Aceh's urban forests. The tree's deep root system enables it to absorb more water and nutrients, enhancing its biomass production in urban environments. Its broad canopy improves fodder production, and its pods serve as livestock feed during dry seasons. Selective harvesting in agroforestry systems can further increase carbon reserves and timber yields (Durr, 2001; Roshetko et al., 2007).

**Table 3.** Average diameter, number of individuals, and biomass of plant species

| Species | Number of Individuals | Diameter (m) | Average of Diameter (m) | Biomass (ton/ha) | Carbon Stock (Ton/ha) |
|---|---|---|---|---|---|
| *Adenanthera pavonina* | 1 | 0.94 | 0.94 | 600.29 | 240.12 |
| *Areca catechu* | 7 | 2.17 | 0.31 | 228.11 | 91.25 |
| *Azadirachta indica* | 2 | 0.55 | 0.27 | 77.81 | 31.13 |
| *Casuarina equisentifolia* | 5 | 1.65 | 0.33 | 266.25 | 106.50 |
| *Ceiba pentandra* | 7 | 3.05 | 0.44 | 272.21 | 108.89 |
| *Cocus nucifera* | 1 | 0.20 | 0.20 | 9.10 | 3.64 |
| *Crepe myrtle* | 4 | 1.04 | 0.26 | 127.46 | 50.99 |
| *Delonix regia* | 11 | 3.74 | 0.34 | 686.68 | 274.67 |
| *Elaeis guineensis* | 1 | 0.53 | 0.53 | 182.01 | 72.80 |
| *Ficus benjamina* | 3 | 1.00 | 0.33 | 90.96 | 36.38 |
| *Hura crepitans* | 2 | 0.67 | 0.34 | 54.84 | 21.94 |
| *Mangifera indica* | 2 | 0.87 | 0.43 | 121.53 | 48.61 |
| *Mimusops elengi* | 6 | 2.06 | 0.34 | 526.05 | 210.42 |
| *Monoon longifolium* | 2 | 0.59 | 0.29 | 86.39 | 34.55 |
| *Pterocarpus indicus* | 57 | 22.54 | 0.40 | 4,943.63 | 1,977.45 |
| *Pterospermum javanicum* | 1 | 0.26 | 0.26 | 16.75 | 6.70 |
| *Roystonea regia* | 7 | 3.01 | 0.43 | 469.79 | 187.92 |
| *Samanea saman* | 153 | 57.62 | 0.38 | 17,313.94 | 6,925.57 |
| *Spondias dulcis* | 3 | 1.13 | 0.38 | 94.95 | 37.98 |
| *Sterculia foetida* | 3 | 0.95 | 0.32 | 112.60 | 45.04 |
| *Swietenia mahagoni* | 20 | 6.12 | 0.31 | 754.21 | 301.68 |
| *Tamarindus indica* | 22 | 8.54 | 0.39 | 1,768.71 | 707.49 |
| *Terminalia catappa* | 7 | 1.86 | 0.27 | 114.28 | 45.71 |
| *Vitex pinnata* | 2 | 0.47 | 0.23 | 28.15 | 11.26 |
| Grand Total | 329 | 121.54 | 8.70 | 28,946.70 | 11,578.68 |

*Samanea saman* trees in the urban forest of Banda Aceh have the highest Important Value Index (IVI) among all recorded species, as reported by Dharma and Zakaria (2022). This species provides several environmental benefits, particularly in addressing urban ecological challenges. According to Ma et al. (2019), members of the Fabaceae family are commonly found in urban forests due to their exceptional tolerance to diverse environmental conditions, which enables them to thrive in such settings.

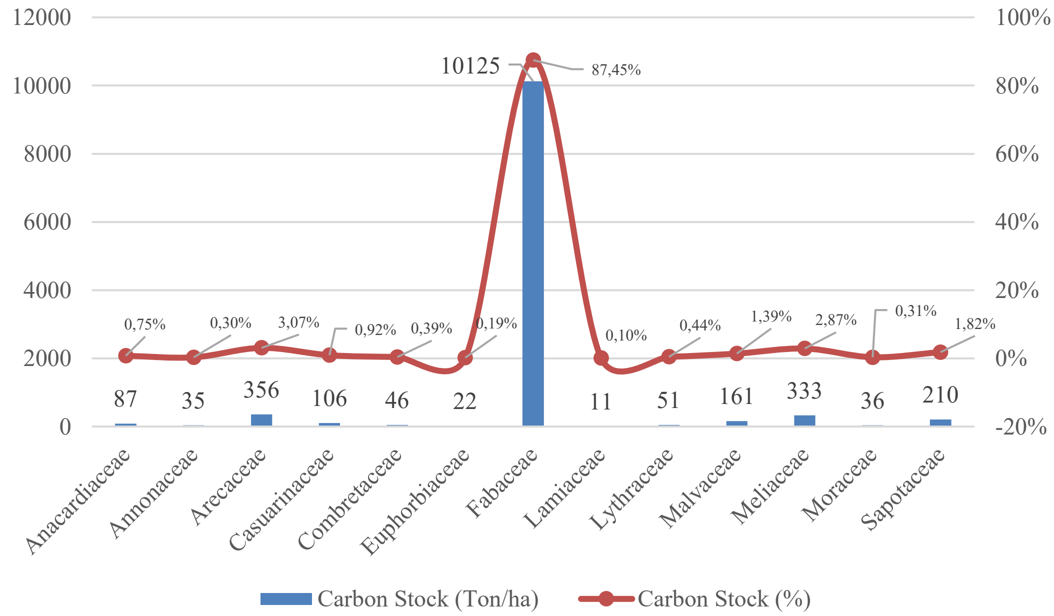


**Figure 2.** Distribution of biomass carbon stock by plant family in the urban forests of Banda Aceh.

Figure 2 illustrates the dominance of the Fabaceae family in Banda Aceh's urban forests, accounting for 87.45% (10.125 tons/ha) of the total carbon stock in the area. This family thrives under a wide range of environmental conditions, supporting robust plant growth. Agbelade et al. (2016) reported that the Fabaceae family is prevalent in the urban areas of Abuja, a savanna region, and similar patterns have been observed in Brazilian urban forests (Toledo et al., 2021).

The large circumference of *Samanea saman* significantly contributes to its high biomass levels. Variations in tree diameter measurements, particularly their influence on biomass estimates, have been separately analyzed in terms of tree height and diameter, as discussed by Brokaw and Thompson (2000) and Melson et al. (2011). The amount of carbon absorbed by plants as biomass is a reliable indicator of the carbon stored in urban forests. These remaining urban forest areas play a crucial role in biomass accumulation and carbon sequestration (Liu & Li, 2012). The amount of carbon stored in a tree is closely linked to its biomass. Species with greater biomass typically store more carbon. According to Purnomo et al. (2015), each species contributes uniquely to a site's total carbon reserves and biomass, with older forests often exhibiting higher biomass and carbon values. In general, trees with larger stems tend to have higher biomass.

Encouraging plant biomass growth and carbon storage is a key strategy in addressing global warming. *Samanea saman* is particularly effective in this regard due to its substantial carbon biomass, which enables it to absorb carbon dioxide efficiently. Ma'arif et al. (2019) found that this species possesses significant carbon storage capacity, supporting its role in carbon sequestration. Tree size and biomass are critical factors in carbon storage (Analuddin et al., 2020), and studies in Hainan, China, further confirm *Samanea saman*'s potential for climate change mitigation through carbon capture. There is a strong positive correlation between a tree's diameter and its circumference, as both are measured at breast height (DBH). As the diameter increases, so does the circumference. This relationship is essential for estimating tree volume, biomass, and carbon content. Figure 3 illustrates the correlation between biomass and stem girth (circumference), highlighting the significance of tree size in carbon storage estimations.

Based on Figure 3, which illustrates the relationship between tree diameter and biomass, there is a strong positive linear correlation between the two variables. As tree diameter increases, biomass also increases. This relationship is described by the linear equation $y = 293.24x - 278.89$**,** where $y$ represents biomass (in thousands of tons per hectare) and $x$ represents tree diameter (in meters). The coefficient of determination **(**$R^2 = 0.9859$) indicates that 98.59% of the variation in biomass can be explained by changes in tree diameter. This high $R^2$ value highlights the strong predictive power of the model and confirms the strong linear relationship between tree diameter and biomass. The remaining 1.41% of variation may be due to other environmental or biological factors or measurement error.

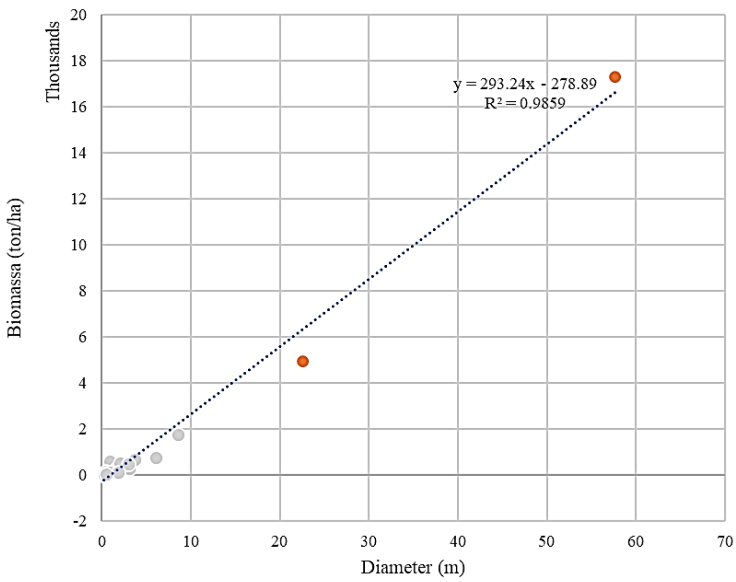


**Figure 3.** Relationship between tree diameter and biomass in urban forest trees.

Figure 3 clearly demonstrates that tree diameter is a major determinant of biomass. This finding aligns with Brown et al. (1989), who emphasized that tree biomass is a reliable indicator of carbon stock in tropical forests and that diameter is directly linked to total biomass in an ecosystem. According to the regression equation, each increase in diameter corresponds to a proportional increase in biomass, reinforcing its value as an indicator of carbon storage. Similarly, Pandey et al. (2017) found a significant positive correlation between biomass and tree diameter in tropical forests of India, with $R^2$ values ranging from 0.64 to 0.87 depending on forest type. Their results support the general conclusion that larger trees tend to contain more biomass.

The research by Chave et al. (2005) further supports these findings, noting that tropical forests store substantial carbon stocks, although uncertainties remain regarding their exact contribution to the global carbon cycle. The study emphasizes the use of regression models to convert forest inventory data into estimates of above-ground biomass. This underscores the importance of using allometric models to estimate carbon stocks based on tree diameter, an approach directly relevant to the findings presented in Figure 3. In summary, a deeper understanding of the relationship between tree diameter and biomass is crucial for climate change mitigation, as it enhances the accuracy of carbon stock estimates and informs more effective natural resource management strategies. It is important to note that the correlation between tree diameter and biomass represents an association, not causation. As biomass increases, so does carbon storage, thereby strengthening an area's capacity as a carbon sink. Accurate measurements of tree diameter and biomass are essential to assess carbon sequestration potential. Allometric equations, such as those developed by Ketterings et al. (2001), facilitate biomass estimation based on tree diameter, providing valuable data for forest management and climate action.

Figure 4 displays total carbon storage across six urban forest sites: Tibang (TB), Putroe Phang (PP), Trembesi (TR), POM (PM), Mesjid Raya (MR), and Ratu Safiatuddin (RS), based on an analysis of tree-derived carbon reserves at each location.

The Putroe Phang (PP) urban forest in Banda Aceh holds the largest carbon stock, totaling 5,189 tons/ha, which represents 45% of the city's total urban forest carbon storage. Trembesi (TR) ranks second with 2,620 tons/ha (20%), followed by Tibang (TB) with 1,820 tons/ha (16%). Mesjid Raya (MR) stores 1,254 tons/ha (11%), POM (PM) holds 584 tons/ha (5%), and Ratu Safiatuddin (RS) stores 468 tons/ha (4%).

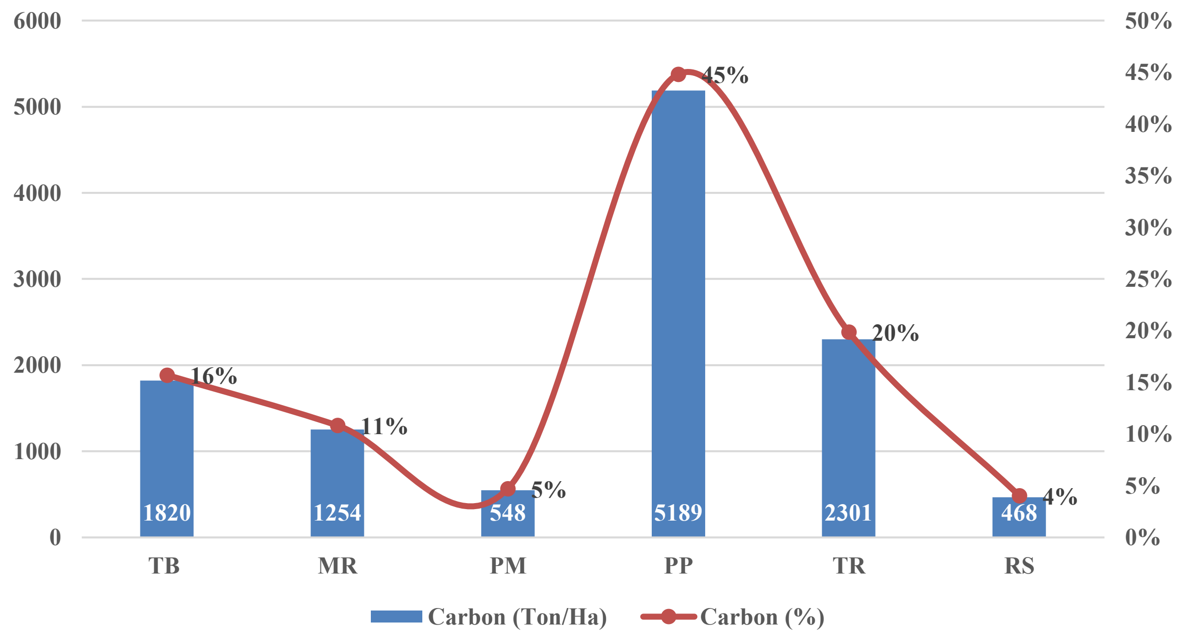


**Figure 4.** Comparison of Total Carbon in each Forest

In total, the carbon stock across Banda Aceh's urban forests reaches 11,579 tons/ha, significantly surpassing the 73.51 tons/ha recorded in DKI Jakarta's urban forests. This finding aligns with research from the Pesanggrahan Protected Forest, which reported a carbon stock of 112.39 tons C/ha from 39 tree species, reinforcing the important role of urban and protected forests in natural carbon sequestration (Kundariatin et al., 2024). Forest attributes such as species composition, topography, and air temperature influence soil moisture and nutrient availability, which subsequently affect tree growth and carbon storage (He et al., 2019). In addition, factors like terrain, climate, species diversity, and forest management practices play a significant role in determining carbon retention (Sari et al., 2020). Despite these contributing factors, the total carbon stocks observed remain below the typical range of 161–300 tons/ha found in tropical natural forests (Murdiyarso et al., 1994). According to Hendrayana et al. (2018), fast-growing tree species tend to store more carbon, making them more effective in supporting greenhouse gas reduction efforts.

**The Economic Appraisal of Forest-Based Carbon Reserves**

The economic value of carbon reserves reflects the monetary worth of services like aesthetics, recreation, and carbon sequestration. Methods to assess this value include considering factors such as stormwater management and avoided costs (Nowak et al., 2018). The total economic value of carbon in Banda Aceh's urban forests is estimated at IDR 3,427,289,798 based on a carbon stock of 11,579 tons per hectare.

**Table 4.** The economic valuation of carbon reserves in Banda Aceh's forests

| Study Area | Carbon (Ton/Ha) | Carbon (%) | Valuation (IDR) |
|---|---|---|---|
| TB | 1820 | 16 | 538,579,256 |
| MR | 1254 | 11 | 371,181,288 |
| PM | 548 | 5 | 162,149,878 |
| PP | 5189 | 45 | 1,535,947,242 |
| TR | 2301 | 20 | 680,999,772 |
| RS | 468 | 4 | 138,432,362 |
| Total | 11579 | 100 | 3,427,289,798 |

Effectively addressing climate change requires a clear understanding of carbon valuation in urban forests. One widely used method for estimating carbon storage involves calculating biomass and carbon content (Zeng et al., 2017). Accurate assessments of urban carbon stocks provide essential data for policymakers to develop strategies that reduce carbon footprints and promote sustainable development.

Assigning economic value to carbon emissions encourages the adoption of low-carbon practices and attracts investment in green technologies. Carbon valuation also informs key policy decisions and supports urban forest management. Li et al. (2022) emphasize the importance of monitoring spatial and temporal phenological changes to optimize carbon sequestration potential. By understanding the economic value of carbon, urban policymakers can prioritize strategies that most effectively reduce greenhouse gas emissions. Measuring carbon stocks contributes to data-driven planning and supports the development of carbon markets, which enable emissions trading and offsetting. Mechanisms such as emissions trading schemes, carbon taxes, and voluntary carbon markets allow both emitted and avoided carbon dioxide to be monetized (Hungate et al., 2017). Furthermore, assessing the economic value of carbon in urban forests highlights their contribution to public goods and climate mitigation. This involves estimating carbon stocks and converting them into monetary terms. According to the IPCC (2014), such valuation supports informed policy-making and effective climate action. Higher carbon stocks reflect a greater capacity for $CO_2$ absorption (Dharma et al., 2025), positioning urban forests as key climate solutions. Urban forests play a vital role in reducing emissions, mitigating climate impacts, and enhancing resilience. Proper management of these green spaces not only strengthens ecological health but also helps lower urban temperatures, reduces energy consumption, and improves public well-being (Aulia et al., 2023). Additionally, their benefits extend to reducing healthcare costs and supporting overall environmental quality (Nowak et al., 2014).

This research integrates carbon stock estimation with economic valuation in the urban forests of Banda Aceh City, addressing the scarcity of prior data on urban carbon accounting. This research combines ecological and economic analysis to reveal the monetary value of carbon sequestration in urban forests. This dual approach is relevant for developing countries, where economic arguments often drive investment in green infrastructure. The study informs policy making, urban planning, and carbon offset strategies. It highlights the role of urban forests in reducing emissions, boosting climate resilience, and supporting sustainable development.

## CONCLUSION

This study revealed that among the six urban forests assessed in Banda Aceh, Putroe Phang (PP) had the highest carbon stock at 5,189 tons/ha, followed by Trembesi (TR) with 2,301 tons/ha and Ratu Safiatuddin (RS) with 468 tons/ha. The corresponding economic values were IDR 1.53 billion, IDR 680 million, and IDR 138 million, respectively, contributing to a total carbon value of IDR 3.42 billion. These findings underscore the substantial environmental and economic value of urban forests, emphasizing the importance of their protection and sustainable management as part of climate mitigation strategies.

The future studies should include research on belowground biomass and soil carbon for a complete carbon assessment. Investigating social factors and community roles in forest management could improve conservation efforts. Lastly, modeling future carbon changes under urban growth and climate change would help guide planning and mitigation.

## ACKNOWLEDGMENTS

We extend our sincere gratitude to the Ministry of Education, Culture, Research, and Technology, and Universitas Syiah Kuala for their financial support under Grant Number: 239/UN11.2.1/PT.01.03/PNBP/2022, dated February 14, 2022. We also thank all individuals and institutions who contributed to the successful completion of this research.

## AUTHOR CONTRIBUTION STATEMENT

All authors made substantial contributions to the work reported in this manuscript. WD, analyzed the data and led the manuscript writing. YY was responsible for data collection and manuscript review. NA assisted with the literature review and data visualization. EH contributed to the analysis of results and the discussion. AR supported fieldwork coordination. RZ and AS provided feedback and assisted with manuscript revisions. AR and LF also contributed to the overall work. All authors reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

## CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest regarding the publication of this manuscript.

## USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors confirm that no artificial intelligence (AI)-assisted technologies were used in the generation, analysis, or writing of this manuscript. All components of the research, including data collection, interpretation, and manuscript preparation, were conducted solely by the authors without the support of AI-based tools.

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