

# Estimation of aboveground biomass and carbon stock in riparian woody species of the upstream Bengawan Solo River, Central Java, Indonesia

AZ ZAHRA MUTI'AH FADHILAH<sup>1</sup>, ARENDRA DWI PURWA SAPUTRA<sup>1</sup>,  
AWWALIN ROSITA AISYAHTUNNISA<sup>1</sup>, ASMA NADIAPUTRI ZAIN<sup>1</sup>, ARDITA RAHMANIA<sup>1</sup>,  
ABIZAN RAMADHAN TORIMBANU<sup>1</sup>, AMITA BELLA MUSTIKA<sup>1</sup>, ALYA ADYSTI REVALITHA<sup>1</sup>,  
ADHA NISFATULSANAH<sup>2</sup>, MUHAMMAD FIRDAUS WIRAATMAJA<sup>1</sup>, AHMAD DWI SETYAWAN<sup>1,\*</sup>

<sup>1</sup>Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57 126, Central Java, Indonesia. Tel./fax.:+62-271-663375, \*email: volatileoils@gmail.com

<sup>2</sup>Magister of Biology Education, Faculty of Teacher and Training Education, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57 126, Central Java, Indonesia

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**Abstract.** Fadhilah AM, Saputra ADP, Ahtunnisa AR, Zain AN, Rahmania A, Torimbanu AR, Mustika AB, Revalitha AA, Nisfatulsanah A, Wiraatmaja MF, Setyawan AD. 2025. Estimation of aboveground biomass and carbon stock in riparian woody species of the upstream Bengawan Solo River, Central Java, Indonesia. *Asian J Environ* 1: 1-16. This study aims to assess the diversity and carbon storage potential of riparian woody species in the upstream section of the Bengawan Solo River in Central Java, Indonesia. Riparian zones play a critical role in maintaining ecosystem balance and sequestering carbon, yet their carbon storage potential has been underexplored. Field surveys were conducted across three sites Gadingan, Sukoharjo District; Sidowarno, Klaten District and Giriwono, Wonogiri District, Central Java, Indonesia using a plot-based sampling method, with 57 plots of varying sizes (10 × 10 meters for pole-stage and 20×20 meters for tree-stage vegetation) distributed in two station for each district. A total of 19 species from 10 families were recorded, with *Tectona grandis* L.f (*jati/teak*) being the dominant species across all sites, despite its dominant presence, *Tectona grandis* is classified as Endangered by the IUCN. The highest recorded carbon stock was observed at Giriwono, Wonogiri District (1190.015 MgC/ha) with carbon stock estimated at approximately 50% of the AGB. These findings emphasize the substantial carbon storage potential of riparian vegetation, especially in mature forest stands dominated by teak. The results highlight the importance of riparian zones as effective carbon sinks and suggest that targeted conservation strategies are necessary to optimize their role in climate change mitigation and biodiversity preservation.

**Keywords:** Aboveground biomass, Bengawan Solo River, carbon stock, plot-based sampling, riparian zones

## INTRODUCTION

Riparian zones along river corridors are vital transition areas between terrestrial and aquatic ecosystems, providing multiple ecological and socio-economic functions, such as biodiversity support, regulation of hydrological processes, and contributions to carbon storage. Research in ecosystem ecology has highlighted the importance of Organic Carbon (OC) in riverine systems, where substantial amounts of land-derived carbon are stored and transformed within river networks (Sutfin et al. 2016). However, investment in riparian forest restoration has often been neglected compared to other forest types, partly due to the narrow and fragmented nature of riparian zones (Dybala et al. 2019). Restoring riparian forests is a highly efficient strategy for climate mitigation, as these ecosystems rapidly sequester carbon, act as biodiversity hotspots, and provide high-value ecosystem services (Lim et al. 2024). Agroforestry, especially tree planting in riparian buffers, has been recognized as an effective approach to enhance carbon storage while enriching local biodiversity (Buchanan et al. 2022).

Forests play a crucial role in regulating atmospheric Greenhouse Gas (GHG) concentrations by absorbing CO<sub>2</sub> through photosynthesis and storing carbon in living and

dead biomass (Adiaha et al. 2020). Ongoing deforestation continues to reduce terrestrial carbon stocks, particularly in riparian areas, where human activities such as land conversion and agriculture have significant impacts (Nzabarinda et al. 2025). Accurate estimates of carbon stocks across different forest types, including riparian forests, are essential for monitoring and reporting carbon uptake, as well as for developing effective mitigation strategies (Danarto and Yulistyarini 2019; Putri et al. 2022). In this context, estimating Aboveground Biomass (AGB) and associated carbon stocks in riparian vegetation is key to understanding their role as carbon sinks and supporting restoration efforts.

The Bengawan Solo River is the longest and largest river on Java Island, flowing through Central and East Java provinces. Its watershed covers approximately 12% of the island's total area and spans 20 districts and cities (Darmawan et al. 2018). The river's riparian ecosystems, characterized by a variety of plant communities along the riverbanks, are influenced by the dynamic interactions between water and land. These ecosystems are crucial for maintaining water quality, stabilizing banks, and providing habitats for a diverse range of species, including fish, crabs, insects, and moisture-dependent plants (Syukur 2020). Despite their ecological significance, riparian zones in the

upstream sections of the Bengawan Solo River are increasingly threatened by human activities such as agriculture, urbanization, and deforestation, which can alter species composition, reduce structural complexity, and diminish carbon storage capacity (Olokeogun and Kumar 2020).

Although studies have examined hydrological and environmental aspects of the Bengawan Solo watershed, there is a lack of quantitative data on woody species diversity, biomass, and carbon stocks in the upstream riparian zones. Specifically, there is limited site-specific data integrating floristic composition, diversity indices, and carbon estimates. This gap in knowledge is critical for understanding how riparian vegetation contributes to local carbon stocks and for providing the scientific basis for effective management and restoration in this tropical river system.

The diversity of woody plant species is a key attribute of riparian forests, as it reflects both species richness and the evenness of individuals across species. Diversity indices, such as the Shannon index, provide a quantitative measure of this complexity and can be used to assess the ecological resilience of riparian stands (Oktaviani and Yanuwadi 2016). At the same time, carbon stock refers to the total carbon stored in both aboveground and belowground biomass, and sometimes in soil pools (Setiawan et al. 2015). Estimating carbon stocks in riparian woody vegetation is crucial for assessing the potential impacts of land-use changes, such as tree removal or conversion to agricultural land, on local carbon reserves.

This study focuses on the upstream riparian zone of the Bengawan Solo River in Central Java, Indonesia, specifically in Gadingan, Sukoharjo; Sidowarno, Klaten and Giriwono, Wonogiri, Central Java, Indonesia. The

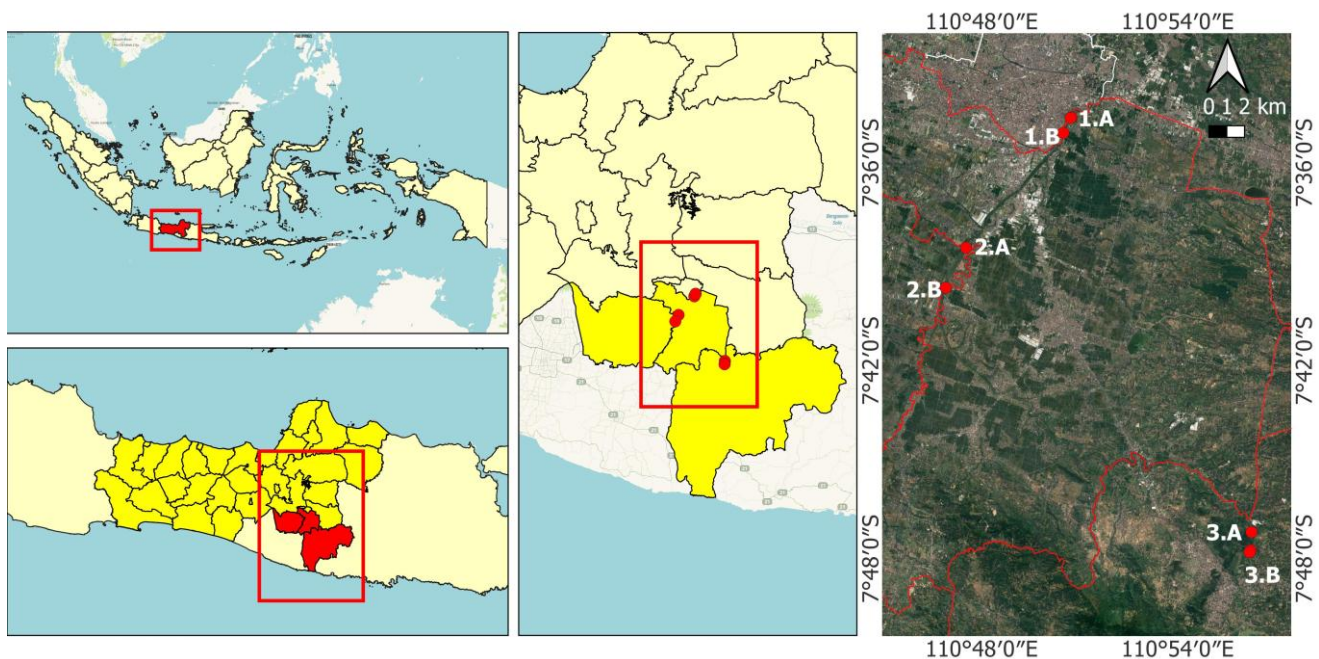
research aims to (i) identify the woody plant species present in these riparian segments, (ii) quantify their species diversity indices, and (iii) estimate the aboveground biomass and carbon stocks of woody vegetation. By providing integrated data on species composition, diversity, and carbon storage, this study contributes baseline information on the role of upstream riparian vegetation in supporting biodiversity and acting as a carbon sink, aiding future riparian restoration and management efforts.

## MATERIALS AND METHODS

### Study area

This study was conducted from March 2023 to 2025 along the upstream banks of the Bengawan Solo River, covering six observation stations located in three districts of Central Java, Indonesia (Figure 1). Data were collected across multiple seasons, from 2023 to 2025, to account for seasonal fluctuations in biomass growth and carbon uptake. These variations are important because riparian vegetation often shows distinct patterns of growth and carbon storage during the wet and dry seasons, influenced by seasonal changes in water availability, temperature, and soil moisture. By capturing these seasonal variations, the study aims to provide more accurate estimations of carbon stocks and biomass accumulation in these riparian ecosystems over time.

Each district was represented by two stations, strategically selected to capture varying vegetation types and environmental conditions relevant to the estimation of Aboveground Biomass (AGB) and carbon stocks of woody species in riparian zones (Table 1).



**Figure 1.** Map of study area in station 1.A-B. Gadingan, Sukoharjo District; 2.A-B. Sidowarno, Klaten District; 3.A-B. Giriwono, Wonogiri District, Central Java, Indonesia

**Table 1.** Coordinate point of research location

District	Station	Coordinate	
Gadingan, Sukoharjo	1	1.A	7°34'37.1"S 110°50'45.0"E
		2.B	7°34'38.2"S 110°50'43.3"E
Sidowarno, Klaten	2	3.A	7°38'34.2"S 110°47'31.3"E
		4.B	7°39'46.8"S 110°46'54.2"E
Giriwono, Wonogiri	3	5.A	7°47'44.3"S 110°56'14.0"E
		6.B	7°47'47.5"S 110°56'12.2"E

These six stations were selected to represent the diversity of riparian ecosystems along the upstream section of the Bengawan Solo River, where vegetation conditions and carbon storage potential may differ from downstream areas. The stations were chosen to capture a variety of environmental factors, such as soil moisture and water levels, that influence biomass accumulation and carbon sequestration in woody species.

The upstream section of the Bengawan Solo River was specifically targeted for this study due to its relatively natural state, with less human-induced disturbance compared to downstream sections, which have been heavily affected by urbanization and large-scale agricultural activities. The upstream riparian zones are expected to have a higher potential for carbon sequestration, offering insights into the natural carbon storage capacity of riparian ecosystems. In particular, these areas may harbor native vegetation that plays a significant role in carbon uptake, contrasting with the altered landscapes found downstream.

#### Data collection

Data for this study were collected from March 2023 to 2025 at three observation stations located in three districts of Central Java, Indonesia namely Sukoharjo, Klaten, and Wonogiri. Each district was represented by two observation stations, strategically selected to capture the variability in vegetation types and environmental conditions relevant to the estimation of Aboveground Biomass (AGB) and carbon stocks of woody species in riparian zones.

#### Sampling technique

The sampling technique employed in this study was a random systematic sampling method. This method ensured that the plots were randomly placed within each observation station but systematically distributed across different vegetation types and environmental conditions (Swacha et al. 2017). The random systematic sampling approach was used to capture a representative sample of the riparian vegetation along the upstream section of the Bengawan Solo River. The distribution of plots was designed to represent a variety of environmental conditions within each station, ensuring that the study area's heterogeneity in vegetation types, soil moisture, and water levels was adequately captured. The plots were systematically distributed across the study site to capture different environmental gradients within the riparian zones. The sampling design aimed to account for the variability of the ecosystem while minimizing bias in the selection of plots.

#### Procedure

##### Vegetation sampling

Vegetation sampling was conducted by placing two types of plots at each station where 10 × 10 meter plot for pole-stage vegetation (DBH 5-10 cm), and 20 × 20 meter plot for tree-stage vegetation (DBH >10 cm). Sapling-stage vegetation was defined as individuals with a diameter at breast height (DBH) between 5 and 10 cm, and tree-stage vegetation consisted of individuals with a DBH greater than 10 cm. Within each plot, all woody plant species were recorded, including species identification based on visual characteristics or field guides, height and number of individuals of each species also the stem circumference measured at 1.3 meters above the ground using a diameter tape (Setyasih et al. 2025).

The plots were placed according to the random systematic sampling method. This technique involved randomly selecting a starting point for each plot within the study area, followed by systematically placing additional plots at regular intervals to ensure that the plots were spread across different vegetation types and environmental conditions.

For each station, 19 plots were established, with 8 tree-stage plots and 11 pole-stage plots. In total, there were 57 plots across the three stations. These plots were used to gather data on species identification, stem circumference, tree height, and number of individuals within each stage of growth. This distribution was designed to provide a comprehensive representation of the vegetation structure, allowing for an accurate estimation of biomass and carbon stocks in both sapling and tree stages. The systematic arrangement of plots also ensured that the data captured a wide range of environmental gradients within each station, improving the reliability of the findings.

##### Environmental parameters

To understand the ecological conditions influencing vegetation composition and structure, environmental parameters were measured at each station. These parameters included air temperature and relative humidity, measured using a digital hygrometer for light intensity, measured with a lux meter, soil pH for determined using a pH meter at a depth of 10 cm and soil temperature, measured using a soil thermometer. These measurements were taken monthly during the sampling period to account for seasonal variations in environmental factors that may influence vegetation growth and carbon sequestration.

### Non-destructive data collection

To ensure minimal impact on the study sites and to preserve the ecological integrity of the riparian zones, the data collection was done non-destructively. In this study, no trees or plants were removed from the study sites. The measurement of biomass and carbon stocks was performed using allometric equations based on the DBH and tree height, which are standard methods for estimating aboveground biomass without cutting the trees. This non-destructive approach ensured that vegetation could continue to grow and contribute to carbon sequestration without affecting the long-term health of the riparian ecosystem (Dahy et al. 2019).

### Data analysis

There are various methods to estimate Above-Ground Biomass (AGB) and vegetation carbon stocks, one of which is through the use of allometric equations tailored to specific species (Streeter et al. 2023). The estimation of vegetation carbon content along the riparian area of the Bengawan Solo River was calculated based on AGB values obtained using species-specific allometric equations (Table 2). Then, carbon stocks are calculated based on 50% of the carbon content in tree biomass (Basyuni et al. 2023). The overall calculation results are converted into area per hectare with the following equation according to the or Standar Nasional Indonesia (2011).

$$Cn = \frac{Cx}{1.000} \times \frac{10.000}{L \text{ sub - plot}}$$

Where:

Cn = Carbon per hectare per sub-plot (MgC/ha);

Cx = Carbon per sub-plot in units of Kg; L sub-plot is the total area of the sub-plot (m<sup>2</sup>)

The biodiversity index will be determined using predetermined formulas. These indices include the Shannon-Wiener diversity index (H'), evenness index (E), Margalef species richness index (Dmg) (Haqqin et al. 2024).

Shannon-Wiener Index (H') to assess species diversity, which takes both the species richness and evenness of individuals into account (Odum 1996). The formula for the Shannon-Wiener index is:

$$H' = -\sum(p_i \cdot \ln(p_i))$$

Where  $p_i$  is the proportion of individuals belonging to species  $i$ .

Diversity index classification:

$H' < 1$ : low diversity

$1 < H' < 3$ : moderate diversity

$H' > 3$ : high diversity

Evenness Index (E) according to Krebs (1989) was to evaluate the evenness of species distribution across the plots, calculated as:

$$E = \frac{H'}{\ln(S)}$$

Evenness Index assessment criteria:

$E > 0.6$  : High species evenness

$0.4 < E < 0.6$  : Moderate species evenness

$E < 0.4$ : Low species evenness Where  $S$  is the total number of species.

Margalef's Index Margalef (1958) to estimate species richness, calculated as:

$$Dmg = \frac{S - 1}{\ln(N)}$$

Where  $S$  is the number of species and  $N$  is the total number of individuals in the sample.

Margalef species richness assessment criteria:

$Dmg < 2.5$  : Low level of species richness

$2.5 < Dmg < 4$  : Moderate level of species richness

$Dmg > 4$ : High level of species richness.

Those indices will be used to evaluate the ecological balance and diversity of the riparian vegetation along the Bengawan Solo River, providing insights into the structural complexity and ecological health of the area. The relationship between vegetation biodiversity and carbon sequestration will also be assessed to better understand the potential role of riparian forests in carbon storage.

**Table 2.** Species-specific allometric equations.

Species	Local name	Allometric equation	Source
<i>Acacia mangium</i> Willd.	<i>Akasia</i>	=0,0000478 × D <sup>2.76</sup>	(Fajar and Nur 2017)
<i>Averrhoa bilimbi</i> L.	<i>Belimbing wuluh</i>	=0,1043 × D <sup>2.6</sup>	(Samsu and Maros 2019)
<i>Calophyllum inophyllum</i> L.	<i>Nyamplung</i>	=-0,972 + 2,078 ln(DB)	(Basuki et al. 2022)
<i>Ceiba pentandra</i> (L.) Gaertn.	<i>Randu</i>	=(b × D) + (c × D <sup>2</sup> ) + e	(Gawali et al. 2014)
<i>Dalbergia latifolia</i> Roxb.	<i>Sonokeling</i>	=0,7458 (D <sup>2</sup> H) 0,63	(Antareja et al. 2024)
<i>Gmelina arborea</i> Roxb. ex Sm.	<i>Jati putih</i>	=exp(1,85029 × ln(DBH))	(Ruiz-Blandon et al. 2022)
<i>Hibiscus tiliaceus</i> L.	<i>Waru</i>	=116,6 [(DBH) × 2H] 0,8877	(Aulia et al. 2024)
<i>Leucaena leucocephala</i> Lam.	<i>Lamtoro</i>	=-5,187 + 6,187 × DBH	(Kanwar et al. 2021)
<i>Mangifera indica</i> L.	<i>Mangga</i>	=0,1043 (D <sup>2.6</sup> )	(Djafar and Nurnawati 2021)
<i>Paraserianthes falcataria</i> (L) Nielsen	<i>Sengon</i>	=0,08062 × D <sup>2.36816</sup>	(Hossain et al. 2023)
<i>Swietenia mahagoni</i> (L.) Jacq.	<i>Mahoni</i>	=0,048 (D <sup>2.3</sup> )	(Nur et al. 2022)
<i>Tamarindus indica</i> L.	<i>Asam</i>	=0,133 × DBH <sup>1.164</sup>	(Fajar and Nur 2017)
<i>Tectona grandis</i> L. f.	<i>Jati</i>	=0,290091 × D <sup>2.3</sup>	(Nur et al. 2022)
Other Species		=0.059.μ.(D <sup>2</sup> ).H	(Rahajoe et al. 2023)

Notes: b = coeff of D; c = coeff of D<sup>2</sup>; e = Residual component of the model (Gawali et al. 2014), D = DBH (Diameter at Breast Height) (cm), H = Height (m),  $\mu$  = wood density (Kg/cm<sup>3</sup>) obtained from <http://db.worldagroforestry.org/wd>

## RESULTS AND DISCUSSION

### Species and family distribution in the riparian zone of the Bengawan Solo River

The dataset from Table 3 provides a comprehensive list of 19 species from 10 families found in the riparian zone of the upstream Bengawan Solo River in Central Java, Indonesia. The species composition in this area reflects the dynamic nature of riparian ecosystems, which are essential for soil stabilization, water filtration, and providing habitats for both terrestrial and aquatic organisms.

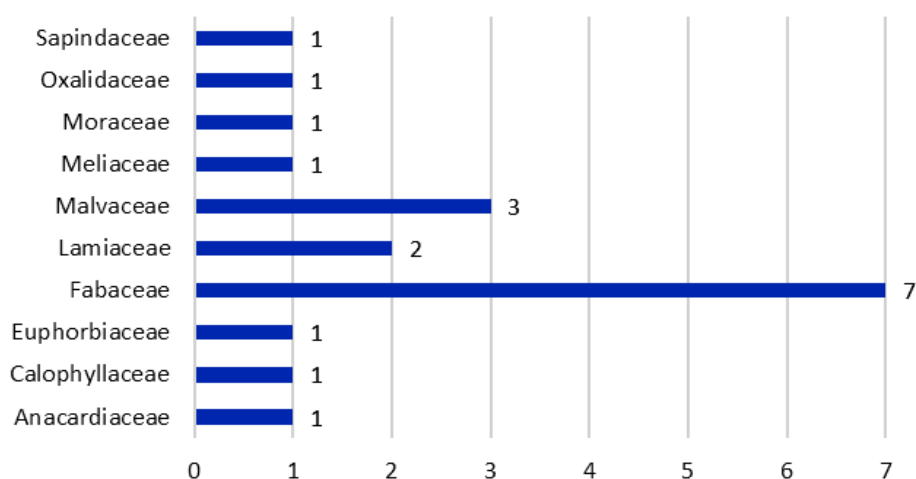
### Family and species distribution

The Fabaceae family is the most represented in the dataset, with 7 species namely *A. mangium*, *A. tomentosa*, *D. latifolia*, *L. leucocephala*, *P. falcataria*, *S. siamea*, and *T. indica* (Table 3 and Figure 2). The Fabaceae family plays a critical role in riparian ecosystems due to its nitrogen-fixing properties, which enhance soil fertility in areas prone to flooding and erosion (Saikia et al. 2020). Species such as *L. leucocephala* and *P. falcataria* are known for their fast growth and ability to thrive in disturbed environments, making them crucial for riparian forest regeneration (Krisnawati et al. 2011; Sharma et al. 2022).

**Table 3.** Amount individual of each species found in the station

Family	Nama Species	Station						Individual number of each species
		1.A	1.B	2.A	2.B	3.A	3.B	
Anacardiaceae	<i>Mangifera indica</i> L.	2	3		1			6
Calophyllaceae	<i>Calophyllum inophyllum</i> L.					15		15
Euphorbiaceae	<i>Ricinus communis</i> L.	1						1
Fabaceae	<i>Acacia mangium</i> Willd.	1				2		3
Fabaceae	<i>Acacia tomentosa</i> Willd.		1		6			7
Fabaceae	<i>Dalbergia latifolia</i> Roxb.					1		1
Fabaceae	<i>Leucaena leucocephala</i> (Lam.) de Wit	2		1	1			4
Fabaceae	<i>Paraserianthes falcataria</i> (L.) I.C.Nielsen				1			1
Fabaceae	<i>Senna siamea</i> (Lam.) H.S.Irwin & Barneby	12		5		4		21
Fabaceae	<i>Tamarindus indica</i> L.	1						1
Lamiaceae	<i>Gmelina arborea</i> Roxb. ex Sm.					1		1
Lamiaceae	<i>Tectona grandis</i> L.f.	2	7	13	9	26	73	130
Malvaceae	<i>Ceiba pentandra</i> (L.) Gaertn.		5			1		6
Malvaceae	<i>Guazuma ulmifolia</i> Lam.					1		1
Malvaceae	<i>Hibiscus tiliaceus</i> L.	1		2				3
Meliaceae	<i>Swietenia mahagoni</i> (L.) Jacq.			5	1	1		7
Moraceae	<i>Ficus racemosa</i> L.		5					5
Oxalidaceae	<i>Averrhoa bilimbi</i> L.	1						1
Sapindaceae	<i>Pometia pinnata</i> J.R.Forst. & G.Forst.	1						1
<b>Total individu from each station</b>		<b>24</b>	<b>21</b>	<b>26</b>	<b>19</b>	<b>52</b>	<b>73</b>	

Number of species from each family



**Figure 2.** Number of species from each family

In addition to Fabaceae, the Lamiaceae family also plays a significant role, with *T. grandis* (*jati/teak*) standing out as the most abundant species, with 130 individuals recorded across all stations. *T. grandis* is an economically valuable species, well-suited for riparian environments due to its adaptability to varying water levels and its deep root system, which helps stabilize riverbanks and reduce soil erosion.

Other families such as Malvaceae and Meliaceae are also present, with species like *C. pentandra*, *G. ulmifolia*, *H. tiliaceus*, and *S. mahagoni* contributing to the overall biodiversity of the riparian zone. Although these species are less abundant compared to *T. grandis*, they are still important components of the ecosystem, providing additional canopy cover and contributing to the structural complexity of the riparian forest.

The species *T. grandis* is the most frequently found in the dataset, with 130 individuals across all stations. This is not surprising, as *Tectona grandis* is widely cultivated for timber production and is well-adapted to riparian environments. Its deep root system helps stabilize riverbanks and mitigate soil erosion, especially during periods of high water flow or flooding. The species' economic value also explains its frequent presence in riparian areas, where it is often planted for both ecological and commercial purposes.

Other species like *S. siamea* (21 individuals) and *A. tomentosa* (7 individuals) are also common, with *S. siamea* contributing to soil enrichment through nitrogen fixation. The presence of *A. tomentosa* highlights the adaptability of certain species to varying soil conditions and water availability in riparian areas, where soil fertility can fluctuate.

In contrast to the more abundant species, some species are found in much smaller numbers in the riparian zone. For example, *R. communis* appears with only 3 individuals across the stations. Despite its fast-growing nature, *Ricinus communis* is more commonly found in disturbed or degraded areas, and its lower frequency in this dataset

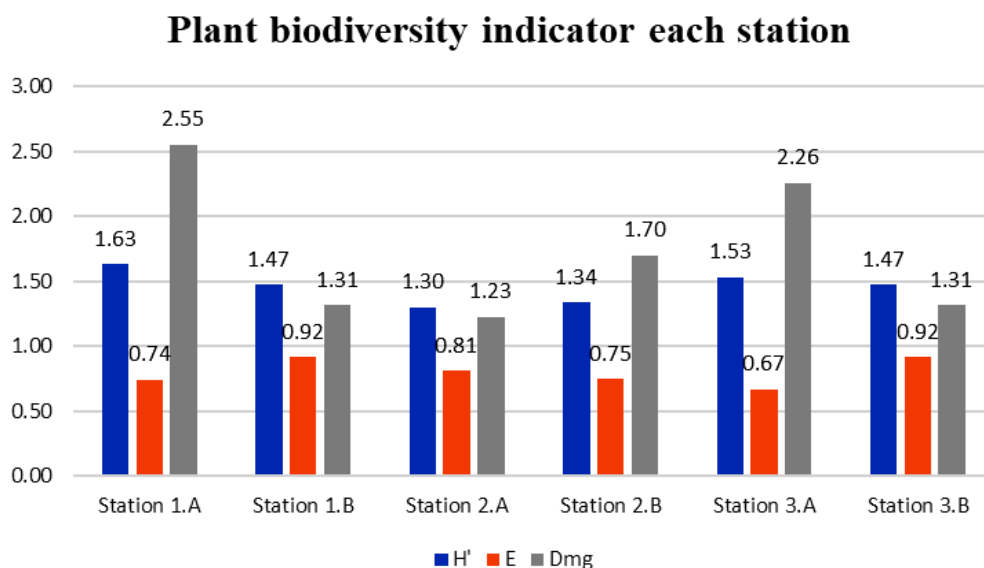
could be a result of competition from more established species or its sensitivity to environmental conditions typical of riparian zones. It is also possible that its presence is limited by its water requirements and susceptibility to flooding, making it less common in stable, mature riparian ecosystems.

Similarly, *M. indica*, which is often associated with tropical agroforestry systems, appears with just 6 individuals in the dataset. *M. indica* trees prefer well-drained, fertile soils and may not thrive in the waterlogged conditions that are typical of riparian zones. As a result, the low number of *M. indica* individuals may reflect its limited adaptation to the specific environmental conditions found in the riparian ecosystem of the Bengawan Solo River.

*Ficus racemosa* (5 individuals), a species typically found in tropical riparian areas, is also relatively infrequent in the dataset. Although this species can tolerate waterlogged conditions, its lower presence might indicate that it is outcompeted by other, more dominant species in the riparian zone, such as *T. grandis* or *A. mangium*, which may have a stronger competitive advantage in this environment.

Lastly, *S. mahagoni*, with only 1 individual recorded, is the least frequently encountered species. *S. mahagoni* is a high-value timber species that requires specific soil and water conditions to thrive. Its low frequency in the riparian zone could be attributed to the relatively limited distribution of *S. mahagoni* plantations in the area or its more specific habitat preferences compared to more adaptable species like *T. grandis*.

The data in Figure 3 provides key biodiversity indicators for each station in the riparian zone of the Bengawan Solo River, using three primary measures namely the Shannon-Wiener Index ( $H'$ ), Evenness ( $E$ ), and Margalef's Index ( $D_{mg}$ ). These indices help evaluate the species diversity, distribution, and richness within the riparian ecosystem, offering valuable insights into the overall ecological health of each station.



**Figure 3.** Biodiversity indicator of woody plant species found in each station

The Shannon-Wiener Index ( $H'$ ) measures the species diversity of an ecosystem by taking into account both the number of species and the evenness of their distribution. A higher  $H'$  value indicates greater biodiversity, while a lower  $H'$  value suggests lower diversity. Across the stations, the Shannon-Wiener Index values range from 1.30 to 1.63, with all stations falling into the moderate diversity category. For example, Station 1.A (Gadingan) has the highest Shannon-Wiener Index (1.63), suggesting that this station has a relatively higher species diversity compared to the others. This may reflect a more complex and stable ecosystem, with a broader mix of species distributed across different trophic levels. Conversely, Station 2.A (Sidowarno), with an index value of 1.30, shows relatively lower diversity, which could indicate that the station supports fewer species or that the species distribution is more uneven. The moderate diversity across stations reflects a balanced but not overly complex community structure, where the ecosystem is neither highly disturbed nor extremely diverse (Hanum et al. 2024).

The Evenness Index ( $E$ ) measures the relative abundance of species within an ecosystem. A value of 1 represents perfect evenness, where all species are equally abundant, and lower values indicate higher dominance by certain species. In this dataset, all stations have high evenness values, with scores ranging from 0.67 to 0.92, indicating a fairly even distribution of species across the riparian zones. For instance, Station 1.B (Gadingan) and Station 3.B (Giriwono) both have the highest evenness values (0.92), suggesting that species are relatively evenly distributed in these areas. High evenness is often indicative of a healthy ecosystem where no single species dominates, allowing for greater ecological stability and resilience. However, Station 3.A, with an evenness of 0.67, shows more dominance by specific species, which may suggest some level of imbalance or disturbance, as certain species are disproportionately abundant compared to others.

The Margalef's Index ( $D_{mg}$ ) is a measure of species richness, which reflects the number of different species present in a given area. A higher value indicates greater species richness. In the data, the Margalef's Index ranges from 1.31 to 2.55, with Station 1.A having the highest value (2.55) in the moderate category. This suggests that Station 1.A supports a relatively high number of species, which could contribute to a more resilient and functionally diverse ecosystem. On the other hand, stations like Station 3.B and Station 2.A, with lower Margalef's values of 1.31 and 1.23, respectively, indicate a lower species richness. These values might reflect less species diversity or more homogenous vegetation communities. Low species richness can be associated with disturbed ecosystems or those that are in the process of regeneration, which may not yet support a wide variety of species.

The Shannon-Wiener Index, Evenness, and Margalef's Index together provide a comprehensive picture of the ecological health of the riparian zones (Xi et al. 2023). The moderate diversity seen across the stations, with high evenness, suggests that the ecosystems are relatively stable, but not overly diverse or complex. The high evenness values indicate that the ecosystems are not dominated by a

single species, promoting a more balanced ecological structure. This is important for maintaining the resilience of the riparian zone, as species that are evenly distributed are better able to withstand environmental changes or disturbances.

However, the relatively low species richness in some stations, such as Station 3.A and Station 2.A, could suggest that these areas are either still developing or experiencing some level of disturbance that limits species diversity. This is particularly important for riparian zone management, as areas with lower species richness may require restoration efforts to increase plant diversity and improve overall ecosystem functioning.

The findings from Figure 3 also suggest that Station 1.A, with its higher Shannon-Wiener Index and Margalef's Index, likely represents a more established and resilient part of the riparian zone, supporting a larger number of species and a more stable ecosystem structure. Station 1.B, while still exhibiting high evenness, shows lower species richness, which may indicate a less diverse or younger ecosystem. On the other hand, Station 2.A and Station 3.A, with lower species richness and diversity, may benefit from targeted restoration efforts aimed at enhancing biodiversity and increasing species diversity.

The biodiversity indicators Shannon-Wiener Index, Evenness, and Margalef's Index highlight the diversity and balance of the riparian ecosystems along the Bengawan Solo River. The findings suggest that while the riparian zone as a whole is moderately diverse, some stations, particularly Station 1.A, show higher levels of species richness and ecological stability. High evenness values across the stations indicate that species distributions are generally balanced, supporting ecosystem resilience. However, the relatively low species richness in certain areas suggests that some parts of the riparian zone may require restoration or more active management to enhance biodiversity.

For riparian ecosystem management, these biodiversity indices underscore the importance of maintaining species diversity and promoting ecological balance in order to strengthen ecosystem functions, improve carbon sequestration, and support biodiversity conservation in the long term.

#### *Ecological roles of species in the riparian zone*

The Fabaceae family, with its high species diversity, plays a vital role in the riparian ecosystem by enhancing soil fertility and stabilizing the riverbanks. Nitrogen-fixing species like *L. leucocephala* and *S. siamea* help restore soil quality in disturbed areas, which is crucial in riparian zones where soil erosion and nutrient loss are common due to flooding and water flow fluctuations. *T. grandis* not only contributes to the stabilization of the riparian zone but also provides significant ecological benefits by creating canopy cover that regulates the microclimate along the riverbank. Its large leaves and dense canopy help reduce evaporation, maintain moisture levels, and provide shade, which benefits other plant species and wildlife in the riparian area.

Species like *M. indica* and *R. communis* appear in smaller numbers, with *M. indica* (6 individuals) being more

common in well-drained, fertile soils rather than in waterlogged riparian areas. The presence of *Ricinus communis*, although in low numbers, suggests that it might be found in disturbed areas of the riparian zone, where rapid-growing species are more likely to establish themselves in the wake of soil disturbances or flooding events.

The data shows some variation in species distribution across the different stations, indicating that environmental conditions, such as proximity to the river, soil composition, and water levels, likely influence the presence and abundance of species. For example, *T. grandis* is widely distributed across the stations, but some species like *S. mahagoni* and *A. tomentosa* appear in specific stations, potentially due to their preference for particular soil or hydrological conditions. Further investigation into these environmental factors would be necessary to understand the reasons behind this variability.

The riparian zone of the Bengawan Solo River is home to a diverse array of species that contribute to the stability and functioning of this vital ecosystem. The dominance of the Fabaceae family, especially *S. siamea* and *L. leucocephala*, highlights the importance of nitrogen-fixing plants in enhancing soil fertility and supporting biodiversity in the riparian zone. Meanwhile, *T. grandis*, with its deep root system and large canopy, plays a key role in stabilizing riverbanks and providing important ecological services.

#### Abiotic factor

The dataset from Table 4 provides key abiotic factors across three research stations in the riparian zone of the upstream Bengawan Solo River, offering important insights into how these environmental parameters influence the species composition in the area. These factors include air temperature, humidity, light intensity, soil pH, and soil temperature, which vary across the stations and play crucial roles in shaping the riparian ecosystem.

At Station 1 (Gadingan), the air temperature is recorded at 31.1°C, while Station 2 (Sidowarno) has a slightly lower air temperature of 30.5°C, and Station 3 (Giriwono) experiences the highest air temperature at 32.5°C. These temperatures are consistent with typical tropical environments, but the slight variations between stations can influence plant species distributions (Bykova et al. 2012). For instance, species like *T. grandis*, which thrive in warmer climates, may be more abundant in Giriwono, where the temperature is highest. Warmer temperatures

also impact the evapotranspiration rate, which could affect water availability in the soil, influencing which species can establish and grow successfully.

Humidity levels show some differences across the stations, with Station 2 (Sidowarno) exhibiting the highest humidity at 81.1%, followed by Station 1 (Gadingan) at 76.5%, and Station 3 (Giriwono) with the lowest at 75.1%. Humidity is a critical factor for species that require high moisture levels in the air, such as many tropical tree species and understory plants (Perez and Freely 2018). The higher humidity in Sidowarno likely supports species that thrive in moist conditions, while Giriwono, with its lower humidity, may favor species that are more drought-tolerant or have adaptations to conserve water during drier periods.

Light intensity varies significantly between the stations, with Station 3 (Giriwono) receiving the highest light intensity at 13,920 lux, followed by Station 1 (Gadingan) at 5,120 lux, and Station 2 (Sidowarno) with the lowest light intensity at 2,290 lux. The higher light intensity in Giriwono likely favors sun-loving species such as *T. grandis*, which require full sunlight for optimal growth. In contrast, Sidowarno, with its lower light intensity, may support more shaded species or those adapted to low light, such as seedlings or certain understory plants that are better suited to more shaded, humid environments.

Soil pH is another important abiotic factor that influences species growth. Station 1 (Gadingan) has slightly acidic soil with a pH of 5.0, while Station 2 (Sidowarno) has more neutral soil at 6.4, and Station 3 (Giriwono) has a pH of 6.1. The lower pH in Gadingan may favor species that are adapted to slightly acidic soils, while the neutral pH at Sidowarno and Giriwono could support a wider range of species, as neutral soils are typically more conducive to nutrient availability. The differences in soil pH across stations may explain some of the variation in species composition, as different species have specific pH tolerances and preferences.

The soil temperature is relatively consistent across the three stations, ranging from 27°C at Station 1 (Gadingan) to 29°C at Station 2 (Sidowarno) and 28°C at Station 3 (Giriwono). Soil temperature directly impacts root growth and nutrient uptake, with warmer soils generally facilitating faster growth and microbial activity. The slight differences in soil temperature may influence the rate at which species grow and establish themselves in each location, with warmer soils in Sidowarno potentially promoting faster growth compared to Gadingan, where the soil is slightly cooler.

**Table. 4** Abiotic factor as environmental parameter in each research location

Station	Location	Air temperature (°C)	Humidity (%)	Light intensity (lux)	Soil acidity (pH)	Soil temperature (°C)
1.A, 1.B	Gadingan	31.1	76.5	5120	5	27
2.A, 2.B	Sidowarno	30.5	81.1	2290	6.4	29
3.A, 3.B	Giriwono	32.5	75.1	13920	6.1	28

These abiotic factors air temperature, humidity, light intensity, soil pH, and soil temperature create distinct environmental conditions at each station that influence the distribution and success of different plant species. The higher temperatures and light intensity at Giriwono likely favor sun-loving, drought-tolerant species, while the higher humidity in Sidowarno creates more favorable conditions for moisture-dependent species. The differences in soil pH across the stations further contribute to the variations in species composition, as each species has specific soil and pH preferences.

Understanding how these abiotic factors interact with each other and influence species distribution in the riparian zone is essential for managing and conserving these ecosystems. As riparian areas are particularly vulnerable to environmental changes such as flooding, drought, and land use alterations, recognizing the role of abiotic factors in shaping species composition can help inform strategies for maintaining ecosystem health and biodiversity in these critical areas (Singh et al. 2021).

### Conservation status

Observations from all types of plant species show that the 19 species identified fall into six categories namely Not Evaluated (NE), Data Deficient (DD), Least Concern (LC), Near Threatened (NT), Vulnerable (VU), and Endangered (EN). Specifically, two species are categorized as Not Evaluated (NE), one species as Data Deficient (DD), 13 species as Least Concern (LC), one species as Near Threatened (NT), one species as Vulnerable (VU), and one species as Endangered (EN) (Table 5). None of the species

fall under the extinct or critically endangered classifications. However, two species are included in the threatened classification, while the others are considered low risk or have not been evaluated.

There are two categories within the threatened classification: Vulnerable (VU) and Endangered (EN). *Dalbergia latifolia* Roxb. is classified as VU, indicating that it is vulnerable to extinction if extraction or usage in the past 100 years is not managed properly. *Tectona grandis* L. f. is classified as EN, with IUCN assessments indicating a declining population and increased risk of extinction. Within the low-risk classification, there are two subcategories: Least Concern (LC) and Near Threatened (NT). *A. mangium*, *A. bilimbi*, and the others are classified as LC, meaning they are not at risk of extinction and are relatively common in their natural habitats. *S. mahagoni* is classified as NT, meaning it is not currently threatened with extinction but is close to qualifying for a threatened category shortly. Finally, in the unevaluated classification, there are two categories i.e Not Evaluated (NE) and Data Deficient (DD). *A. tomentosa* and *L. leucocephala* Lam. are classified as NE, meaning they have not yet been assessed or measured under the IUCN classification. *M. indica* is classified as DD, meaning there is insufficient information available to make a clear conservation status assessment. Vulnerability classifications are essential for the management and further conservation of each species according to their respective needs. The IUCN Red List classification influences many aspects of conservation, such as policy development, raising awareness, setting priorities, and resource allocation (Betts et al. 2020).

**Table 5.** Conservation status of species found in study area.

Species name	Local name	IUCN status	Information
<i>Acacia mangium</i> Willd.	Akasia	LC	Not endangered and quite common in its natural habitat
<i>Acacia tomentosa</i> Willd	Klampis	NE	Species is not assessed or measured
<i>Averrhoa bilimbi</i> L.	Belimbing wuluh	LC	Not endangered and quite common in its natural habitat
<i>Calophyllum inophyllum</i> L.	Nyamplung	LC	Not endangered and quite common in its natural habitat
<i>Ceiba pentandra</i> (L.) Gaertn	Randu	LC	Not endangered and quite common in its natural habitat
<i>Dalbergia latifolia</i> Roxb.	Sonokeling	VU	Over-extraction in the last 100 years has made this species vulnerable to extinction
<i>Ficus racemosa</i> L.	Loa	LC	Not endangered and quite common in its natural habitat
<i>Guazuma ulmifolia</i> Lam.	Jati Belanda	LC	Not endangered and quite common in its natural habitat
<i>Gmelina arborea</i> Roxb. ex Sm	Jati Putih	LC	Not endangered and quite common in its natural habitat
<i>Hibiscus tiliaceus</i> L.	Waru	LC	Not endangered and quite common in its natural habitat
<i>Leucaena leucocephala</i> Lam.	Lamtoro	NE	Species is not assessed or measured
<i>Mangifera indica</i> L.	Mangga	DD	Information on conservation status is unclear
<i>Paraserianthes falcataria</i> (L.) Nielsen	Sengon	LC	Not endangered and quite common in its natural habitat
<i>Pometia pinnata</i> J.R. Forst. & G. Forst.	Matoa	LC	Not endangered and quite common in its natural habitat
<i>Ricinus communis</i> L.	Jarak	LC	Not endangered and quite common in its natural habitat
<i>Senna siamea</i> Lam.	Johar	LC	Not endangered and quite common in its natural habitat
<i>Swietenia mahagoni</i> (L.) Jacq	Mahoni	NT	Species that are not currently endangered but are close to qualifying for a threatened category in the near future.
<i>Tamarindus indica</i> L.	Asam Jawa	LC	Not endangered and quite common in its natural habitat
<i>Tectona grandis</i> L. f.	Jati	EN	The population is declining and increasing the risk of its extinction

Notes: LC = Least Concern; VU = Vulnerable; NE = Not Evaluated; DD = Data Deficient; NT = Near Threatened; EN = Endangered

### Aboveground biomass and carbon stocks

#### Pole-stage vegetation

The data from Table 6 presents the aboveground biomass and carbon stocks of pole-stage vegetation across various stations in the riparian zone of the Bengawan Solo River. These values offer important insights into the role of different species in carbon sequestration within riparian ecosystems, which are crucial for mitigating climate change, stabilizing riverbanks, and maintaining biodiversity.

In terms of both AGB and carbon stocks, *T. grandis* emerges as the most significant contributor across all stations. At Station 1.A (Gadingan), teak holds 187.7 MgB/ha in AGB and 93.85 MgC/ha in carbon stock, with similar high values at Station 3.A (Giriwono), where it shows 207.37 MgB/ha and 103.68 MgC/ha. This high biomass and carbon storage capacity can be attributed to teak's large size, fast growth rate, and adaptability to a range of soil and water conditions typically found in riparian zones. Teak's role in carbon sequestration is significant due to its size and the long period over which it accumulates biomass, making it an essential species for carbon storage in these ecosystems.

The presence of *L. leucocephala* and *A. tomentosa* in several stations further contributes to the carbon storage capacity of the riparian zone, although to a lesser extent compared to teak. At Station 1.A, *L. leucocephala* shows 19.06 MgB/ha in AGB and 9.53 MgC/ha in carbon stock, while *A. tomentosa* at Station 2.B has 27.03 MgB/ha and 13.51 MgC/ha. These species, being nitrogen fixers, not only help in enhancing soil fertility but also support the

overall growth of vegetation in disturbed riparian environments. Their faster growth rates allow them to accumulate biomass more quickly than slower-growing species, although their carbon storage potential is still lower than that of teak.

Smaller species, such as *M. indica* and *S. mahagoni*, contribute to the biomass and carbon stock in the riparian zone, but their values are considerably lower. For instance, at Station 1.B (Gadingan), *M. indica* shows 5.5 MgB/ha and 2.75 MgC/ha in carbon storage, while *S. mahagoni* at Station 2.A (Sidowarno) shows 9.353 MgB/ha and 4.671 MgC/ha. While these species have slower growth rates and smaller sizes compared to teak, they still play important ecological roles in supporting biodiversity and maintaining the stability of the riparian ecosystem.

Despite their lower carbon storage capacity, *M. indica* and *S. mahagoni* contribute to the structural diversity of the riparian forest. Their presence in the ecosystem supports a variety of organisms, such as birds, insects, and understory plants, which benefit from the canopy and other ecological functions these species provide. Additionally, their ability to store carbon, albeit at a lower rate, still contributes to the overall carbon sequestration in the area.

The differences in biomass and carbon stock across species in the riparian zone reflect the importance of a diverse mix of species for long-term carbon storage. *T. grandis*, with its high AGB and carbon stock values, is a key species for carbon sequestration and riparian forest management. Its ability to store large amounts of carbon makes it an essential species for strategies aimed at enhancing carbon storage in riparian areas.

**Table 6.** Aboveground biomass and carbon stocks of pole stands

Station	Family	Local name	Scientific name	AGB (MgB/ha)	Carbon Stock (MgC/ha)
Station 1.A	Fabaceae	<i>Johar</i>	<i>Senna siamea</i> Lam.	8.671	4.335
	Fabaceae	<i>Lamtoro</i>	<i>Leucaena leucocephala</i> Lam.	19.06	9.53
	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L.f.	187.7	93.85
	Sapindaceae	<i>Belimbing wuluh</i>	<i>Averrhoa bilimbi</i> L.	17.832	8.916
Station 1.B	Anacardiaceae	<i>Mangga</i>	<i>Mangifera indica</i> L.	5.5	2.75
	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L.f.	57.91	28.95
Station 2.A	Anacardiaceae	<i>Mangga</i>	<i>Mangifera indica</i> L.	8.3	4.15
	Fabaceae	<i>Klampis</i>	<i>Acacia tomentosa</i> Willd	27.03	13.51
	Fabaceae	<i>Johar</i>	<i>Senna siamea</i> Lam.	6.722	3.361
	Fabaceae	<i>Lamtoro</i>	<i>Leucaena leucocephala</i> Lam.	9.333	4.667
	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L. f.	50.901	25.45
Station 2.B	Malvaceae	<i>Waru</i>	<i>Hibiscus tiliaceus</i> L.	1.55	0.77
	Meliaceae	<i>Mahoni</i>	<i>Swietenia mahagoni</i> (L.) Jacq.	9.353	4.671
	Meliaceae	<i>Mahoni</i>	<i>Swietenia mahagoni</i> (L.) Jacq.)	1.15	0.57
	Malvaceae	<i>Waru</i>	<i>Hibiscus tiliaceus</i>	1.55	0.77
	Anacardiaceae	<i>Mangga</i>	<i>Mangifera indica</i> L.	8.3	4.15
	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L.f	9.52	4.76
Station 3.A	Fabaceae	<i>Klampis</i>	<i>Acacia tomentosa</i> Willd	27.03	13.51
	Anacardiaceae	<i>Mangga</i>	<i>Mangifera indica</i> L.	5.5	2.75
	Anacardiaceae	<i>Akasia</i>	<i>Acacia mangium</i> Willd.	0.014	0.007
	Calophyllaceae	<i>Nyamplung</i>	<i>Calophyllum inophyllum</i> L.	2.419	1.209
	Euphorbiaceae	<i>Jarak</i>	<i>Ricinus communis</i> L.	1186.691	593.345
Station 3.B	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L. f.	207.372	103.681
	Meliaceae	<i>Mahoni</i>	<i>Swietenia mahagoni</i> (L.) Jacq.	1.229	0.615
	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L.f	187.7	93.85

However, relying solely on teak may not be the best approach for long-term ecological balance. Incorporating species like *L. leucocephala* and *A. tomentosa*, which can enhance soil fertility and promote the growth of other vegetation, is critical for maintaining biodiversity and supporting ecosystem functions in riparian zones. Smaller species like *M. indica* and *S. mahagoni* also have an important role, particularly in enhancing the diversity of the ecosystem. Although their contribution to carbon sequestration is lower, their presence supports a healthy, functioning ecosystem by providing habitat and food for wildlife, improving soil quality, and contributing to nutrient cycling.

The findings highlight the significant role of *Tectona grandis* in carbon sequestration within the riparian zone of the Bengawan Solo River, demonstrating its high potential for biomass accumulation and carbon storage. However, it is equally important to recognize the contributions of faster-growing, nitrogen-fixing species like *L. leucocephala* and *A. tomentosa*, which help maintain soil fertility and support ecosystem resilience. Smaller species,

although contributing less to carbon stocks, should not be overlooked, as they enhance biodiversity and ecosystem stability.

#### Tree-stage vegetation

The dataset provided in Table 7 presents the aboveground biomass and carbon stocks of tree stands across different stations in the riparian zone of the Bengawan Solo River. Tree stands, in contrast to pole-stage vegetation, are typically more mature, larger trees that have a more developed canopy and root system, resulting in greater biomass and carbon storage capacity. The data provides valuable information on how various species contribute to carbon sequestration and the overall functioning of the riparian ecosystem. Across the stations, *T. grandis* consistently emerges as the dominant species in terms of both AGB and carbon stocks. At Station 1.A (Gadingan), teak shows a significant AGB of 1,099.94 MgB/ha and carbon stock of 549.965 MgC/ha, indicating its large size and substantial role in carbon storage.

**Table 7.** Aboveground biomass and carbon stocks of tree stands.

Station	Family	Local name	Scientific name	AGB (MgB/ha)	Carbon stock (MgC/ha)
Station 1.A	Anacardiaceae	<i>Akasia</i>	<i>Acacia mangium</i> Willd.	0.829	0.415
	Anacardiaceae	<i>Mangga</i>	<i>Mangifera indica</i> L.	91.152	45.576
	Fabaceae	<i>Asam</i>	<i>Tamarindus indica</i> L.	0.518	0.259
	Fabaceae	<i>Johar</i>	<i>Senna siamea</i> Lam.	357.894	178.947
	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L. f.	1099.94	549.965
	Malvaceae	<i>Waru</i>	<i>Hibiscus tiliaceus</i> L.	3.412	1.706
	Sapindaceae	<i>Matoa</i>	<i>Pometia pinnata</i> J.R. Forst. & G. Forst.	25.342	12.671
Station 1.B	Anacardiaceae	<i>Mangga</i>	<i>Mangifera indica</i> L.	90.94	45.47
	Malvaceae	<i>Randu</i>	<i>Ceiba pentandra</i> (L.) Gaertn.	5.42	2.71
	Fabaceae	<i>Klampis</i>	<i>Acacia tomentosa</i> Willd	58.06	29.03
	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L.f	59.53	29.78
	Moraceae	<i>Loa</i>	<i>Ficus racemosa</i>	86.01	43.005
Station 2.A	Fabaceae	<i>Klampis</i>	<i>Acacia tomentosa</i> Willd.	97.34	48.67
	Fabaceae	<i>Lamtoro</i>	<i>Leucaena leucocephala</i> (Lam.) de Wit	17.48	8.74
	Fabaceae	<i>Sengon</i>	<i>Paraserianthes falcataria</i> (L.) Nielsen	91.6	45.8
	Fabaceae	<i>Johar</i>	<i>Senna siamea</i> Lam.	76.578	38.289
	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L. f.	355.595	177.798
	Malvaceae	<i>Waru</i>	<i>Hibiscus tiliaceus</i> L.	17.04	8.52
	Meliaceae	<i>Mahoni</i>	<i>Swietenia mahagoni</i> (L.) Jacq.	8.686	4.343
Station 2.B	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L.f	149.2	74.6
	Fabaceae	<i>Klampis</i>	<i>Acacia tomentosa</i> Willd	97.34	48.67
	Fabaceae	<i>Lamtoro</i>	<i>Leucaena leucocephala</i> (Lam.) de Wit	17.48	8.74
	Fabaceae	<i>Sengon</i>	<i>Paraserianthes falcataria</i> (L.) Nielsen	91.6	45.8
Station 3.A	Anacardiaceae	<i>Mangga</i>	<i>Mangifera indica</i> L.	90.94	45.47
	Anacardiaceae	<i>Akasia</i>	<i>Acacia mangium</i> Willd.	0.013	0.006
	Calophyllaceae	<i>Nyamplung</i>	<i>Calophyllum inophyllum</i> L.	313.703	156.851
	Fabaceae	<i>Klampis</i>	<i>Acacia tomentosa</i> Willd.	58.06	29.03
	Fabaceae	<i>Johar</i>	<i>Senna siamea</i> Lam.	24.89	12.445
	Fabaceae	<i>Sonokeling</i>	<i>Dalbergia latifolia</i> Roxb.	11.684	5.842
	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L. f.	278.033	139.031
	Lamiaceae	<i>Jati putih</i>	<i>Gmelina arborea</i> Roxb. ex Sm.	28.147	14.074
	Malvaceae	<i>Randu</i>	<i>Ceiba pentandra</i> (L.) Gaertn.	5.42	2.71
	Malvaceae	<i>Jati Belanda</i>	<i>Guazuma ulmifolia</i> Lam.	19.968	9.984
	Moraceae	<i>Loa</i>	<i>Ficus racemosa</i> L.	86.01	43.005
Station 3.B	Lamiaceae	<i>Jati</i>	<i>Tectona grandis</i> L.f	1061.59	530.79

*Tectona grandis* continues to perform well across other stations, including Station 2.A (Sidowarno), where it has an AGB of 355.595 MgB/ha and carbon stock of 177.798 MgC/ha, and Station 3.A (Giriwono), where it shows an AGB of 278.033 MgB/ha and carbon stock of 139.031 MgC/ha. The high values for *T. grandis* across all stations reflect its fast growth rate, large canopy, and deep root system, which make it a key player in both biomass accumulation and carbon sequestration in riparian forests.

However, while *T. grandis* is dominant, other species also contribute to the overall biomass and carbon stocks in the riparian zone. *S. siamea*, a species commonly found in disturbed riparian areas, shows significant values for carbon storage. At Station 1.A, it has 357.894 MgB/ha in AGB and 178.947 MgC/ha in carbon stock, making it an important contributor to the ecosystem. *M. indica* also contributes, with AGB values of 91.152 MgB/ha and carbon stock of 45.576 MgC/ha at Station 1.A, and 90.94 MgB/ha and 45.47 MgC/ha at Station 1.B. While *M. indica* trees are not as large as teak, their presence in riparian zones provides important ecological functions, including supporting biodiversity and contributing to carbon sequestration, particularly in areas where other species may be slower to establish.

Several smaller, fast-growing species also contribute to biomass and carbon storage, although their values are generally lower than those of *T. grandis*. For example, *L. leucocephala*, known for its rapid growth and nitrogen-fixing capabilities, shows AGB values of 17.48 MgB/ha and carbon stocks of 8.74 MgC/ha at Station 2.A and Station 2.B. Similarly, *A. tomentosa*, another nitrogen-fixing species, shows AGB values of 97.34 MgB/ha and 48.67 MgC/ha at Station 2.A, and 58.06 MgB/ha and 29.03 MgC/ha at Station 3.A. These species, while not contributing as much as teak in terms of total biomass and carbon storage, play a crucial role in supporting the riparian ecosystem by enhancing soil fertility and accelerating the growth of other vegetation.

Additionally, species like *S. mahagoni*, *D. latifolia*, and *G. arborea* contribute modestly to carbon stocks, with values ranging from 4.67 MgC/ha to 14.07 MgC/ha. While these species have lower biomass and carbon storage compared to teak, their contribution to biodiversity and ecosystem structure is nonetheless significant. They provide canopy cover and habitat for wildlife, as well as contributing to the overall health of the riparian zone.

The key difference between tree stands and pole-stage vegetation lies in their age, size, and growth rate. Pole-stage vegetation, which consists of younger, smaller trees, generally has lower biomass and carbon storage potential compared to Tree stands. For example, in the data from Table 5 (pole-stage vegetation), species like *S. siamea* and *L. leucocephala* have AGB values ranging from 8,671 MgB/ha to 19,060 MgB/ha and carbon stocks between 4,335 MgC/ha and 9,530 MgC/ha. These values are significantly lower than those of mature trees such as *Tectona grandis*, which can store over 1,099 MgB/ha in biomass and 549 MgC/ha in carbon, reflecting the increased capacity for carbon sequestration in older, larger trees.

Tree stands like *T. grandis* not only accumulate more biomass but also contribute more to long-term carbon storage due to their larger root systems and longer lifespans. The higher AGB and carbon stock values in tree stands are also a result of the increased photosynthetic activity, larger canopy coverage, and more extensive root systems that allow these trees to store carbon over a prolonged period, in contrast to the faster-growing but shorter-lived pole-stage vegetation (Behera et al. 2017).

The data on tree stands highlights the critical role of large, mature trees in carbon sequestration and ecosystem stability. *T. grandis*, with its large size and ability to store significant amounts of carbon, plays a pivotal role in mitigating climate change and maintaining ecological balance in riparian zones. However, while these larger trees contribute most to carbon storage, the presence of smaller, fast-growing species such as *Leucaena leucocephala* and *A. tomentosa* is also essential. These species help to enrich soil fertility, stabilize riverbanks, and provide habitats for various species, making them vital for ecosystem functioning, particularly in disturbed or regenerating riparian zones.

Riparian zone management should prioritize the conservation of both large tree species like teak and smaller, nitrogen-fixing species. By promoting a mix of species with varying growth rates and carbon sequestration capacities, riparian ecosystems can maintain both biodiversity and long-term carbon storage potential. Moreover, the presence of diverse species can help buffer the ecosystem against climate variability, floods, and droughts, supporting a resilient and sustainable riparian environment.

The riparian zone of the Bengawan Solo River supports a diverse array of tree species, with *T. grandis* standing out as the dominant species for carbon sequestration. While smaller, fast-growing species contribute less to overall carbon storage, they still play vital ecological roles in maintaining soil fertility, stabilizing riverbanks, and supporting biodiversity (Marteau et al. 2018). Understanding the role of both tree stands and pole-stage vegetation in carbon storage is essential for the sustainable management of riparian ecosystems and for maximizing their potential in climate change mitigation.

#### Total AGB and carbon stocks

The data from Table 8 provides critical insights into the total aboveground biomass and carbon stocks of the riparian zone in the upstream Bengawan Solo River. This dataset, broken down into pole-stage vegetation and tree stands, reveals significant trends in carbon sequestration potential and highlights the essential roles that different stages of vegetation play in supporting the ecological and carbon storage functions of riparian ecosystems.

Across all stations, tree stands, especially *T. grandis*, dominate the contribution to both AGB and carbon stocks. At Station 1.A, the AGB of trees is 1,579.086 MgB/ha, contributing 789.538 MgC/ha to carbon storage. *T. grandis* accounts for the majority of this biomass and carbon storage, reflecting its large size, slow growth, and long lifespan. Teak trees are highly efficient in accumulating

biomass over time, making them key players in long-term carbon sequestration.

This dominance of teak is also evident at other stations, such as Station 2.A, where trees contribute 664.318 MgB/ha and 332.159 MgC/ha, primarily from *T. grandis*. These high values underscore the role of mature trees in storing carbon and enhancing the ecosystem's carbon sequestration capacity. The ability of *T. grandis* to store significant carbon, especially in its later growth stages, makes it an essential species for climate change mitigation and carbon sequestration in riparian zones.

While tree stands contribute the most to overall carbon storage, pole-stage vegetation also plays a vital role, particularly in the early stages of forest regeneration and carbon accumulation. Species like *L. leucocephala* and *A. tomentosa* contribute substantially to AGB and carbon stocks, especially in areas undergoing regeneration. At Station 1.A, pole-stage vegetation contributes 233.264 MgB/ha in AGB and 116.632 MgC/ha in carbon stock, while Station 2.A shows similar trends with 113.189 MgB/ha in AGB and 112.296 MgC/ha in carbon stock from pole-stage vegetation.

Despite their lower biomass and carbon storage compared to tree stands, pole-stage species play an important role in improving soil fertility and supporting ecosystem recovery in disturbed riparian zones. These species, being fast-growing and nitrogen-fixing, enhance soil health, prevent erosion, and create conditions that facilitate the establishment of more mature trees. This makes them critical in the early stages of riparian ecosystem recovery, where quick biomass accumulation is essential for stabilizing the environment (Chauhan et al. 2017).

The differences in AGB and carbon stock between stations reflect variations in vegetation structure, growth stages, and environmental conditions. For example, Station 3.A (Giriwono) shows the highest total AGB at 2,320.092 MgB/ha and carbon stock at 565.365 MgC/ha, largely due to the dominance of *T. grandis* and *C. inophyllum*, two species with significant biomass accumulation. In contrast, Station 1.B (Gadingan) has much lower total values, with 363.41 MgB/ha and 181.71 MgC/ha, primarily due to the higher contribution from pole-stage vegetation, which, while essential for ecosystem recovery, does not store as much carbon as mature trees.

This variation emphasizes the critical role of Tree stands in long-term carbon storage. However, the relatively high contribution of pole-stage vegetation in Station 1.B also points to the importance of promoting fast-growing species for short-term carbon accumulation and ecosystem restoration, especially in areas where forest cover is being restored after disturbance. The data highlights the complementary roles of pole-stage vegetation and tree stands in carbon sequestration. Pole-stage vegetation, although it stores less carbon due to its smaller size and faster growth rate, plays a significant role in soil enrichment and early-stage biomass accumulation. These species, such as *L. leucocephala*, *A. tomentosa*, and *S. siamea*, enhance soil fertility and stabilize riverbanks, which are critical for supporting the establishment of larger tree species in the long run.

In contrast, tree stands, particularly *T. grandis*, dominate the long-term carbon sequestration capacity of the riparian zone. Their ability to store large amounts of carbon over decades, coupled with their larger size and long lifespan, makes them essential for maintaining carbon stocks and ecological stability in the riparian ecosystem (Chayaporn et al. 2021). The combination of both vegetation types in riparian zones results in a more balanced and resilient ecosystem that can adapt to environmental changes while maximizing its capacity for carbon sequestration.

The findings from the total AGB and carbon stock data underscore the significant contribution of Tree stands, particularly *T. grandis*, to carbon sequestration in riparian ecosystems. However, the role of pole-stage vegetation in early biomass accumulation and ecosystem restoration cannot be overlooked. Both types of vegetation are essential for the health and resilience of riparian zones. For riparian zone management, it is crucial to protect and promote both trees and fast-growing species. Tree stands should be prioritized for their long-term carbon storage potential, while pole-stage vegetation should be supported in areas where forest regeneration is needed. Encouraging the growth of both vegetation types will optimize carbon sequestration and enhance the ecological functions of riparian ecosystems, contributing to broader climate change mitigation goals.

**Table 8.** Total aboveground biomass and carbon stocks at each station

Station	Pole		Tree		Total	
	AGB (MgB/ha)	Carbon stock (MgC/ha)	AGB (MgB/ha)	Carbon stock (MgC/ha)	AGB (MgB/ha)	Carbon stock (MgC/ha)
Station 1.A	233.264	116.632	1579.086	789.538	1812.350	906.170
Station 1.B	63.42	31.71	299.99	150.00	363.41	181.71
Station 2.A	113.189	112.296	664.318	332.159	777.507	444.456
Station 2.B	47.58	23.79	355.64	177.82	403.22	201.61
Station 3.A	1403.225	106.916	916.867	458.449	2320.092	565.365
Station 3.B	187.70	93.85	1061.59	530.80	1249.30	624.65
				<b>Total</b>	6925.879	1915.991
				<b>Average</b>	1154.313	638.6637

The stations with higher carbon stocks, particularly Station 1 (Gadingan, Sukoharjo) and Station 3 (Giriwono, Wonogiri), with total carbon stocks of 1,087.88 MgC/ha and 1,190.015 MgC/ha respectively, indicate ecosystems that are more mature and have had the time to accumulate significant biomass over time (Figure 4). High carbon stocks generally reflect mature ecosystems where large, established vegetation has developed extensive root systems and large canopies capable of sequestering substantial amounts of carbon. These areas have likely reached a state of ecosystem stability, where carbon storage can continue to increase over time, particularly through the growth of larger trees and their continued carbon sequestration capabilities (Stephenson et al. 2014).

The high carbon stock values at these stations suggest that the riparian zones are functioning well in terms of their carbon storage potential, making them important components of the landscape for climate change mitigation. Such ecosystems, with their high carbon sequestration capacity, are likely playing a key role in carbon sink functions in the region. Protecting and maintaining these areas is crucial, as they offer significant opportunities for long-term carbon sequestration and help in buffering the effects of climate change by storing carbon over extended periods.

Additionally, these high-carbon-stock areas are likely to have better ecological health, contributing to greater biodiversity, soil stability, and water quality. The high biomass accumulation suggests that these ecosystems are well-established and able to provide vital ecosystem services, including supporting a wide range of species, preventing erosion, and maintaining hydrological cycles in the riparian zone.

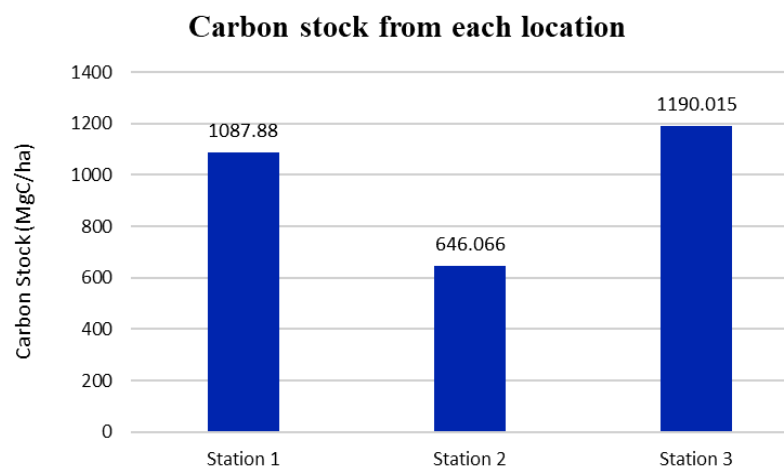
In contrast, Station 2 (Sidowarno, Klaten), with a total carbon stock of 646.066 MgC/ha, shows lower carbon storage capacity compared to Station 1 and Station 3. This lower carbon stock indicates that the riparian zone may be in an earlier or more disturbed stage of vegetation development. Areas with lower carbon stocks often reflect younger ecosystems that have not yet accumulated the same level of biomass as more mature ecosystems. These areas might still be in the process of vegetation

regeneration or recovering from environmental disturbances such as flooding, land use changes, or deforestation.

While the carbon storage is lower in such ecosystems, the importance of these areas cannot be understated. Lower carbon stocks may indicate that the ecosystem is in a recovery phase, where species are still establishing themselves and building biomass. Despite the lower total carbon storage, these ecosystems still play an important role in early-stage carbon sequestration and are critical for restoring soil fertility and providing habitats for biodiversity. Over time, as the vegetation matures, carbon storage will likely increase, and these areas could contribute significantly to overall ecosystem resilience and carbon storage in the long run.

The differences in carbon stock values between stations suggest that ecosystem maturity plays a central role in determining the riparian zone's ability to store carbon. Ecosystems with higher carbon stocks, typically more mature and stable, have a greater capacity for long-term carbon sequestration. These areas should be prioritized for conservation and protection as they contribute significantly to the region's carbon sink capacity.

On the other hand, areas with lower carbon stocks, though still important for carbon sequestration, require targeted efforts to support their regeneration and vegetation recovery. Restoring disturbed riparian zones and enhancing the growth of vegetation, particularly through planting or protecting fast-growing species that can quickly accumulate biomass, will help boost carbon storage capacity in these areas over time. Restoration and sustainable management of riparian ecosystems are key to increasing their carbon sequestration potential and ensuring they can reach maturity, at which point their carbon storage capacity will significantly improve. To maximize the carbon sequestration potential of riparian ecosystems, conservation efforts should focus on both protecting mature forests with high carbon storage potential and restoring disturbed ecosystems to accelerate the accumulation of biomass. This dual approach will help enhance the overall carbon sink capacity of the region, supporting climate change mitigation efforts.



**Figure 4.** The total of carbon stock from each location Station 1 (Gadingan), Station 2 (Sidowarno), and Station 3 (Giriwono)

Additionally, monitoring and management strategies should account for the varying carbon stock levels across different stations, guiding targeted actions based on the current state of each riparian zone. For example, areas with low carbon stocks might benefit from specific restoration practices, such as reforestation, soil enrichment, and the introduction of fast-growing, nitrogen-fixing species. In contrast, high-carbon-stock areas should be preserved and protected, ensuring that they continue to function as carbon sinks over the long term.

In conclusion the aboveground biomass (AGB) and carbon stock of woody species in the riparian zone of the upstream Bengawan Solo River. The results show that 19 species from 10 families were found across the research stations. The data revealed that *Tectona grandis* (teak), a mature tree species, is the dominant contributor to carbon sequestration in the riparian zone, with the highest total AGB and carbon stock recorded at Station 3 (Giriwono), which holds 2,320.092 MgB/ha and 565.365 MgC/ha. *T. grandis* large size, slow growth rate, and long lifespan make it a key species for long-term carbon storage. In addition to *T. grandis*, other species such as *S. siamea* and *L. leucocephala* also contribute to the carbon stocks, although at a smaller scale due to their faster growth and smaller size. The findings underscore the importance of both tree stands and fast-growing species in enhancing the overall carbon sequestration capacity of riparian ecosystems. While mature trees like *T. grandis* dominate carbon storage, species like *L. leucocephala* and *A. tomentosa* support soil fertility and contribute to carbon sequestration in early stages of forest regeneration. Effective riparian zone management should prioritize the conservation of mature forests for their long-term carbon storage potential while also promoting the growth of fast-growing species in disturbed areas for ecosystem recovery. These riparian zones play a crucial role in climate change mitigation, emphasizing the need for targeted conservation strategies to protect and optimize these vital ecosystems.

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#### REFERENCES

- Adiaha MS, Buba AH, Okpoho AN, Tangban EE. 2020. Mitigating global greenhouse gas emission: The role of trees as a clean mechanism for CO<sub>2</sub> sequestration. *J Agric Sci Sri Lanka* 15(1): 101-115. DOI: 10.4038/jas.v15i1.8675.
- Antareja GM, Wahyuningsih E, Valentino N. 2024. Estimation of carbon reserves above soil surface in agroforestry patterns in Mount Sasak, West Lombok District. *J Biol Trop* 24 (4): 252-259. DOI: 10.29303/jbt.v24i4.7583.
- Aulia AA, Revalitha AA, Rahmania A. 2024. Estimation of aboveground biomass and carbon storage in pole and tree stands along the main road of Sumber Village, Surakarta. *Innovative J Soc Sci Res* 4 (6): 7849-7864.
- Basuki TM, Leksono B, Baral H, Andini S, Wahyuni NS, Artati Y, Windyarini E. 2022. Allometric equations for the biomass estimation of *Calophyllum inophyllum* L. in Java, Indonesia. *Forests* 13 (7): 1057. DOI: 10.3390/f13071057.
- Basyuni M, Wirasatriya A, Iryanthony SB, Amelia R, Slamet B, Sulistiyono N, Pribadi R, Sumarga E, Eddy S, Al-Mustaniroh SS, Sasmito SD, Sidik F, Kajita T, Ali HM, Macklin PA, Arifanti VB. 2023. Aboveground biomass and carbon stock estimation using UAV photogrammetry in Indonesian mangroves and other competing land uses. *Ecol Inform* 77: 102227. DOI: 10.1016/j.ecoinf.2023.102227.
- Behera SK, Sahu N, Mishra AK, Bargali SS, Behera MD, Tuli R. 2017. Aboveground biomass and carbon stock assessment in Indian tropical deciduous forest and relationship with stand structural attributes. *Ecol Eng* 99: 513-524. DOI: 10.1016/j.ecoleng.2016.11.046.
- Betts J, Young RP, Hilton-Taylor C, Hoffmann M, Rodríguez JP, Stuart SN, Milner-Gulland EJ. 2020. A framework for evaluating the impact of the IUCN Red List of threatened species. *Conserv Biol* 34 (3): 632-643. DOI: 10.1111/cobi.13454.
- Buchanan SW, Mafa-Attoye T, Dunfield K, Thevathasan NV, Isaac ME. 2022. The role of plant functional traits and diversity in soil carbon dynamics within riparian agroforests. *J Environ Qual* 51 (1): 33-43. DOI: 10.1002/jeq2.20303.
- Bykova O, Chuine I, Morin X, Higgins SI. 2012. Temperature dependence of the reproduction niche and its relevance for plant species distributions. *J Biogeogr* 39 (12): 2191-2200. DOI: 10.1111/j.1365-2699.2012.02764.x.
- Chauhan SK, Sharma R, Chander J. 2017. Short rotation forestry: its application for biomass, energy, soil health and carbon sequestration. In: Parthiban KT, Sudhagar RJ, Cinthia Fernandez CC, Suresh KK (eds). *Agroforestry strategies for climate change: mitigation and adaptation*. Jaya Publishing House, Delhi.
- Chayaporn P, Sasaki N, Venkatappa M, Abe I. 2021. Assessment of the overall carbon storage in a teak plantation in Kanchanaburi Province, Thailand: implications for carbon-based incentives. *Cleaner Environ Syst* 2: 100023. DOI: 10.1016/j.cesys.2021.100023.
- Dahy B, Issa S, Ksiksi T, Saleous N. 2019. Non-conventional methods as a new alternative for the estimation of terrestrial biomass and carbon sequestered. *World J Agric Soil Sci* 4: 1-8. DOI: 10.33552/WJASS.2019.04.000579.
- Danarto SA, Yulistyarini T. 2019. Seleksi tumbuhan dataran rendah kering yang berpotensi tinggi dalam sekuestrasi karbon untuk rehabilitasi kawasan terdegradasi. *Masyarakat Biodiversitas Indonesia* 5(1): 33-37. [Indonesian]
- Darmawan A, Sulardiono B, Haeruddin. 2018. Analisis kesuburan perairan berdasarkan kelimpahan fitoplankton, nitrat dan fosfat di perairan Sungai Bengawan Solo Kota Surakarta. *Manag Aquat Resour J (MAQUARES)* 7(1): 1-8. DOI: 10.14710/marj.v7i1.22519. [Indonesian]
- Djafar M, Nurnawati AA. 2021. Pemanfaatan citra ALOS PALSAR untuk estimasi kandungan serapan karbon di wilayah pesisir Kabupaten Maros. *J Eboni* 3 (1): 49-56. [Indonesian]
- Dybala KE, Matzek V, Gardali T, Seavy NE. 2019. Carbon sequestration in riparian forests: a global synthesis and meta-analysis. *Glob Change Biol* 25 (1): 57-67. DOI: 10.1111/gcb.14475.
- Fajar AR, Nur BA. 2017. Pendugaan Cadangan Karbon Permodelan Penerapan Penanaman Asam Jawa pada Jalur Hijau Jalan di Kabupaten Rembang. *Proceed Biol Edu Conf* 14 (1): 229-232. [Indonesian]
- Gawali A, Puri S, Swamy SL. 2014. Growth, biomass, carbon sequestration and nutrient storage in *Ceiba pentandra* (L.) Gaertn.

- stands in sub humid tropics of Eastern India. *Ecol Environ Conserv* 20: 71-81.
- Hanum Z, Armadhan WS, Kusuma D, Perwitasari IG, Almadani AR, Safira RN, Setyawan AD. 2024. Vegetation composition and structure in the green open space (GOS) area of Surakarta City, Central Java, Indonesia. *Pros Sem Nas Masy Biodiv Indon* 10: 72-88.
- Haqqin F, Arkan F, Ibriza NM, Fadhilah RN, Safira RN, Dewangga A, Kusumaningrum L, Thenya T, Setyawan AD. 2024. Diversity, composition, and role of woody non-timber forest products in Tawangmangu, Central Java, Indonesia. *Asian J Ethnobiol* 7 (1): 68-78. DOI: 10.13057/asianjethnobiol/y070108.
- Hossain MS, Oluwajuwon TV, Ludgen AN, Hasert DP, Sitanggang M, Offiah C. 2023. Formulating biomass allometric model for *Paraserianthes falcataria* (L.) Nielsen (*sengon*) in smallholder plantations, Central Kalimantan, Indonesia. *For Sci Technol* 19 (4): 268-284. DOI: 10.1080/21580103.2023.2256355.
- Kanwar A, Bhardwaj DR, Panwar P, Pal S. 2021. Allometric models for predicting above-ground biomass and carbon stock of fodder tree species in northwestern Himalayas. *Indian J Ecol* 48 (2): 387-392.
- Krebs CJ. 1989. *Ecology: The experimental analysis of distribution and abundance*. Harper and Row, New York.
- Krisnawati H, Varis E, Kallio M, Kanninen M. 2011. *Paraserianthes falcataria* (L.) Nielsen: Ekologi, silvikultur, dan produktivitas. CIFOR, Bogor.
- Lim BS, Joo SJ, Seok JE, Lee CS. 2024. An assessment of the carbon budget of the passively restored willow forests along the Miho River, Central South Korea. *Climate* 12 (11): 182. DOI: 10.3390/cli12110182.
- Margalef R. 1958. Information theory in ecology. *Gen Syst* 3: 36-71.
- Marteau B, Gibbins C, Batalla RJ, Vericat D. 2018. Review of good practice in managing riverbank instability and erosion. WWF Malaysia, Kuala Lumpur.
- Nur AAI, Arifiani KN, Ramadhani AR, Sabrina AD, Nugroho GD, Kusumaningrum L, Ramdhun D, Bao TQ, Yap CK, Budiharta S, Setyawan AD. 2022. Estimation of aboveground biomass and carbon stock in Damas Beach, Trenggalek District, East Java, Indonesia. *Indo Pac J Ocean Life* 6 (2): 80-86. DOI: 10.13057/oceanlife/o060203.
- Nzabarinda V, Bao A, Tie L, Uwamahoro S, Kayiranga A, Ochege FU, Muhirwa F, Bao J. 2025. Expanding forest carbon sinks to mitigate climate change in Africa. *Renew Sustain Energy Rev* 207: 114849. DOI: 10.1016/j.rser.2024.114849.
- Odum EP. 1996. *Dasar-dasar ekologi*. Edisi ketiga. Gadjah Mada University Press, Yogyakarta. [Indonesian]
- Oktaviani R, Yanuwadi B. 2016. Analisis vegetasi riparian di tepi Sungai Porong, Kabupaten Sidoarjo. *Biotropika J Trop Biol* 4 (1): 25-31. [Indonesian]
- Olokeogun OS, Kumar M. 2020. An indicator-based approach for assessing the vulnerability of riparian ecosystem under the influence of urbanization in the Indian Himalayan city, Dehradun. *Ecol Indic* 119: 106796.
- Perez TM, Feeley KJ. 2018. Increasing humidity threatens tropical rainforests. *Front Ecol Evol* 6: 68. DOI: 10.3389/fevo.2018.00068.
- Putri AR, Gunarto T, Emalia Z, Murwiati A. 2022. Pengaruh pertumbuhan ekonomi, pertumbuhan penduduk, dan konsumsi energi terhadap emisi CO<sub>2</sub> di Indonesia. *BULLET J Multidisiplin Ilmu* 1(6): 1070-1080. [Indonesian]
- Rahajoe JS, Jakalalana S, Oksari AA, Yuliani N. 2023. The estimated carbon stored in underutilized fruit trees (UFTs) collection of Cibodas and Cibinong Botanic Gardens. *IOP Conf Ser Earth Environ Sci* 1271(1): 012034. DOI: 10.1088/1755-1315/1271/1/012034.
- Ruiz-Blandon BA, Salcedo-Pérez E, Rodríguez-Macías R, Hernández-Alvarez E, Campo J, Merino A. 2022. Growth, biomass, carbon and nutrient pools in *Gmelina arborea* established in pure and mixed forest stand production systems in Mexico. *New For* 53 (4): 735-757. DOI: 10.1007/s11056-021-09878-7.
- Saikia P, Nag A, Anurag S, Chatterjee S, Khan ML. 2020. Tropical legumes: status, distribution, biology and importance. In: Khan ML, Mistri J (eds). *The Plant Family Fabaceae: Biology And Physiological Responses To Environmental Stresses*. Springer, Singapore. DOI: 10.1007/978-981-15-4752-2\_2.
- Samsu AKA, Maros UM. 2019. Pendugaan potensi simpanan karbon permukaan pada ruang terbuka hijau di Hutan Kota Jompie Kecamatan Soreang Kota Parepare. *J Environ* 1(10): 34-43. DOI: 10.26618/j-linears.v1i1.1321. DOI: 10.26618/j-linears.v1i1.1321. [Indonesian]
- Setiawan G, Syaufina L, Puspaningsih N. 2015. Estimasi hilangnya cadangan karbon dari perubahan penggunaan lahan di Kabupaten Bogor. *J Pengelolaan Sumberdaya Alam Lingkung* 5 (2): 141-150. DOI: 10.19081/jpsl.5.2.141. [Indonesian]
- Setyasih DMD, Putri RAS, Raharjo YAA, Izdihar RS, Kusumaningrum L, Setyawan AD. 2025. Potential aboveground carbon storage in the community forest area of Tawangmangu, Karanganyar District, Indonesia. *Asian J For* 9 (1): 108-114. DOI: 10.13057/asianjfor/r090111.
- Sharma P, Kaur A, Batish DR, Kaur S, Chauhan BS. 2022. Critical insights into the ecological and invasive attributes of *Leucaena leucocephala*, a tropical agroforestry species. *Front Agron* 4: 890992. DOI: 10.3389/fagro.2022.890992.
- Singh R, Tiwari AK, Singh GS. 2021. Managing riparian zones for river health improvement: an integrated approach. *Landsc Ecol Eng* 17 (2): 195-223. DOI: 10.1007/s11355-020-00436-5.
- Standar Nasional Indonesia. 2011. Pengukuran dan penghitungan cadangan karbon: pengukuran lapangan untuk penaksiran cadangan karbon hutan (ground-based forest carbon accounting). Badan Standardisasi Nasional (BSN), Jakarta. [Indonesian]
- Stephenson NL, Das AJ, Condit R et al. 2014. Rate of tree carbon accumulation increases continuously with tree size. *Nature* 507 (7490): 90-93. DOI: 10.1038/nature12914.
- Streeter JR, Bhattacharjee J, Kandel B. 2023. Aboveground carbon stock in a bottomland hardwood forest in the southeastern United States. *Forests* 14 (5): 974. DOI: 10.3390/f14050974.
- Sutfin NA, Wohl EE, Dwire KA. 2016. Banking carbon: a review of organic carbon storage and physical factors influencing retention in floodplains and riparian ecosystems. *Earth Surf Process Landf* 41 (1): 38-60. DOI: 10.1002/esp.3857.
- Swacha G, Botta-Dukát Z, Kački Z, Pruchniewicz D, Żołnierz L. 2017. A performance comparison of sampling methods in the assessment of species composition patterns and environment-vegetation relationships in species-rich grasslands. *Acta Soc Bot Pol* 86 (4): 3561. DOI: 10.5586/asbp.3561.
- Syukur M. 2020. Jenis-jenis pohon penyangga Sungai Bonti Kecamatan Bonti Kabupaten Sanggau. *Piper* 16 (30): 9-15. DOI: 10.51826/piper.v16i30.386. [Indonesian]
- Xi H, Li T, Yuan Y, Chen Q, Wen Z. 2023. River ecosystem health assessment based on fuzzy logic and harmony degree evaluation in a human-dominated river basin. *Ecosyst Health Sustain* 9: 0041. DOI: 10.34133/ehs.0041.