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Analysis of the Eco-Physiological Characteristics of Street Trees in Urban Area for Sustainable Urban Greening

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ABSTRACT

The development of urban areas threatens the Earth's systems by damaging ecosystems and decreasing biodiversity, as well as contributing to climate change due to increased air pollution from transportation and industrial activities. Greening along streets can help mitigate climate change effects, making plant species selection crucial for greening programs. The suitability of a plant species can be understood by studying growth strategies through ecophysiological components analysis in leaves and stems. This study aimed to identify the ecophysiological characteristics of roadside trees in urban area for designing a sustainable urban greening strategy. Using this approach, we can understand the adaptation and performance of trees facing urban environmental pressures. Field observations or abiotic factor and laboratory analysis were employed to identify ecophysiological characteristics including specific leaf area (SLA), specific leaf weight (SLW), leaf dry matter content (LDMC), LA, leaf thickness, stomatal density, stomatal aperture, trichome density, chlorophyll content and wood density (WD). Analyses of important ecophysiological characteristics (LA, SLA, LDMC, and WD) showed that the trees could be grouped into non-native (*Swietenia mahagoni, Samanea saman, Muntingia calabura,* and *Monoon longifolium*) and native species (*Mimusops elengi, Pterocarpus indicus, Ficus benjamina*, and *Syzygium myrtifolium*). These results provide recommendations for tree species suitable for roadside planting based on ecophysiological performance data.

Keywords: Air pollution, Environmental factors, Physiological phenomena, Trees, Urban development

Introduction

Urban areas will continue to grow, with green open spaces being transformed into artificial infrastructure, such as buildings, roads, and industrial facilities, in an effort to improve economic sectors (Mursalin *et al.*, 2024). This encourages an increase in the rate of population growth, increases the rate of urbanization, and negatively impacts the systems of the Earth, especially by damaging ecosystems and reducing biodiversity, as well as accelerating climate change through increased emissions of air pollutants, which are largely generated by the increasing number of vehicles, industries, and urban development (Bratley & Ghoneim, 2018; Karmakar *et al.*, 2021; Sameh *et al.*, 2022).

The increase in air pollution is one of the negative impacts felt by city residents owing to the increasing rate

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of urbanization (Tripathi & Nema, 2023). Air pollution is a serious problem, especially in the urban areas inhabited by the majority of the world's population. Various pollutants with chemical compositions are released into the air and can cause serious problems to human health, such as lung diseases (WHO, 2016). In addition to contributing to the increase in air pollution, urbanization also has an impact on the increase in surface temperature (Pandey *et al*., 2015).

Urban greening can help absorb pollution, and reduce greenhouse gas emissions, and mitigat the impacts of climate change. Therefore, plant species selection plays an important role in greening programmes (Nurhayati, 2016). The suitability of a plant species for its environment and habitat can be understood by studying its growth strategies. This can be achieved by analyzing the characteristics of the relative growth rate and eco-physiological components in the leaves, roots, and stems (Rindyastuti *et al*., 2021). The use of multipurpose plants is a global trend to improve food security and aesthetic value while maintaining urban greening function (Junita *et al*., 2022).

Previous studies on roadside plant criteria have been conducted, including identifying the ability of plants to reduce pollution using morphological characteristics (such as leaf length and width), anatomical characteristics (such as stomatal density [SD] and distribution), and chlorophyll content (CC; Megia *et al*., 2015); absorbing heavy metals (Pb) by linking the eco-physiological performance traits of leaves and the level of particulate pollutant absorption (Krisnandika *et al*., 2019); and serving as noise reducers by referring to canopy density parameters, microclimate measurements (temperature and humidity), and noise levels (Pratama *et al*., 2021); trichome density (Cahyono *et al*., 2022); and aesthetic value (Murdaningsih *et al*., 2020). However, studies focusing on the identification of roadside plant species based on eco-physiological characteristics to measure their growth performance have not been fully reported.

Several important aspects of eco-physiological characteristics have research limitations, particularly when measuring the growth performance of roadside plants in Malang. Several eco-physiological characteristics were used as parameters, including specific leaf area (SLA), which functions as an indicator of plant growth rate. In this context, the higher the SLA value, the faster the plants grow (Junaedi *et al*., 2021). Another characteristic is specific leaf weight (SLW); a higher SLW value results in slower growth rates but increases carbon storage capacity and resistance to herbivore attacks (Cornelissen *et al*., 2003). Leaf dry matter content (LDMC) plays a role in predicting net primary production, which is the ability of a plant to convert CO_2 and water into dry matter. High LDMC values reflected better plant resistance to dry conditions (Smart *et al*., 2017).

Two other crucial characteristics are LA and leaf thickness (LT) were also crucial characteristics. These characteristics influence the rate of transpiration in plants, which is a physiological activity that function as a mechanism for regulating and adjusting the plant's internal and external conditions, especially those related to controlling moisture balance in cells and tissues (turgidity), the ability to absorb and transport water, minerals, and regulating temperature in tissues (Lambers *et al*., 1998; Ridwan *et al*., 2018). A larger LA value indicates a better ability of the plant to absorb solar energy (Papuangan *et al*., 2014). However, the larger the LT value, the lower the plant's transpiration rate (Da Costa & Daningsih, 2022).

Other significant aspects include stomata and trichome densities, which play a role in plant adaptation to drought by reducing transpiration rates (Cahyono *et al*., 2022; Jaya *et al*., 2015). Therefore, eco-physiological characteristics such as SD, stomatal aperture (SA), and TD were also included in the assessment. CC measurements are used to predict the ability of plants to absorb solar energy and perform photosynthesis by converting CO_2 (Song & Banyo, 2011). Another eco-physiological characteristic is wood density (WD), which serves as an indicator of carbon content and wood quality. An increase in the WD values corresponds to an increase in the carbon content of the wood and better wood quality, making it stronger or more durable (Longuetaud & Caraglio, 2009). However, plants with high WD tend to grow more slowly (Hairiah *et al*., 2011).

Malang City is a level II city in East Java, after the city of Surabaya, and has experienced an increase in transportation mobility both within and outside Malang City (Grahadina, 2012). This is evident from the greenhouse gas emissions in Malang City, which reached 1,224,225 tons of CO_2 in 2010 and are expected to reach 1,880,447 tons CO_2 by 2020 (Axisa *et al*., 2012). Based on this estimate, it can be observed that over a 10-year period, these emissions have the potential to increase by around 86% of total emissions in 2010 (Prihastuty, 2016). Based on the results of a study on pollution concentrations in Malang City in 2016, it shows that the concentration of CO_2 ranges from 388.38 ppm to 413.56 ppm (Herlina *et al*., 2017). Therefore, this study aimed to analyze the eco-physiological characteristics of several roadside tree types in Malang City. Roadside plants with tree habits, both local and introduced, were chosen. Based on the results of this study, data on the ecophysiological characteristics of several types of roadside trees were obtained. These data are important because they can help increase the success of sustainable reforestation strategies.

Materials and Methods

Time and place of research

The study was conducted between August and December 2023. Research and measurements of abiotic factors were conducted on several arterial and collection roads in Malang City, East Java (Fig. 1). Observations and measurements of the eco-physiological characteristics of the plant samples were conducted at the Ecology Laboratory of the Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Negeri Malang, and the Laboratory of the National Research and Innovation Agency at the Purwodadi Botanical Garden.

Malang City is located at 7.06°-8.02° S and 112.06°-112.07° E. According to Regulation of the Minister of Home Affairs (Permendagri) No. 66 of 2011, Malang City has an area of 145.28 km². The topography of Malang City is similar to the highland geographical features of Malang Regency. The city is traversed by Brantas River, which is the second longest river on the island of Java, Indonesia. Malang City is situated at an elevation of 440-667 m above the sea level. The city is surrounded by Mount Arjuno to the north, Mount Semeru to the east, and Mount Panderman, Mount Kawi, and Mount Kelud to the west.

Abiotic factor measurements

Environmental factor measurement data were sampled three times at each sampling location for ecophysiological analysis or beside the studied tree species. The observed environmental factors included CO_2 levels measured using a carbon dioxide meter, air temperature and relative humidity measured using a thermo-hygrometer, and light intensity measured using a lux meter. The abiotic factors were measured between 10:00 AM and 12:00 PM. In addition, the sampling locations were marked using GPS.

Measurement of ecophysiological traits

The eco-physiological characteristics of the roadside tree species were identified using a purposive sampling technique (Table 1). The ecophysiological characteristics were measured for each tree species, with three individuals used as replicates. The samples consisted of 20 mature leaves without petioles per replicate and three mature woody twigs per replicate.

The eco-physiological characteristics measured according to Cornelissen *et al*. (2003) were as follow:

Leaf area (cm^2)

LA measurements were performed using the ImageJ (National Institutes of Health, Bethesda, MD, USA) software. This method involved analyzing and measuring the leaf surface area in square centimeters (cm²).

Leaf thickness (μm)

LT measurements was conducted by preparing simple anatomical specimens, consisting of cross-sections of the leaf at the tip, middle, and base. This method was followed by measurements using a digital microscope (Dino-Lite AM3111/3113; AnMo Corp., New Taipei City, Taiwan). The results are expressed in micrometers (μm), providing an overview of the leaf tissue thickness from various sections.

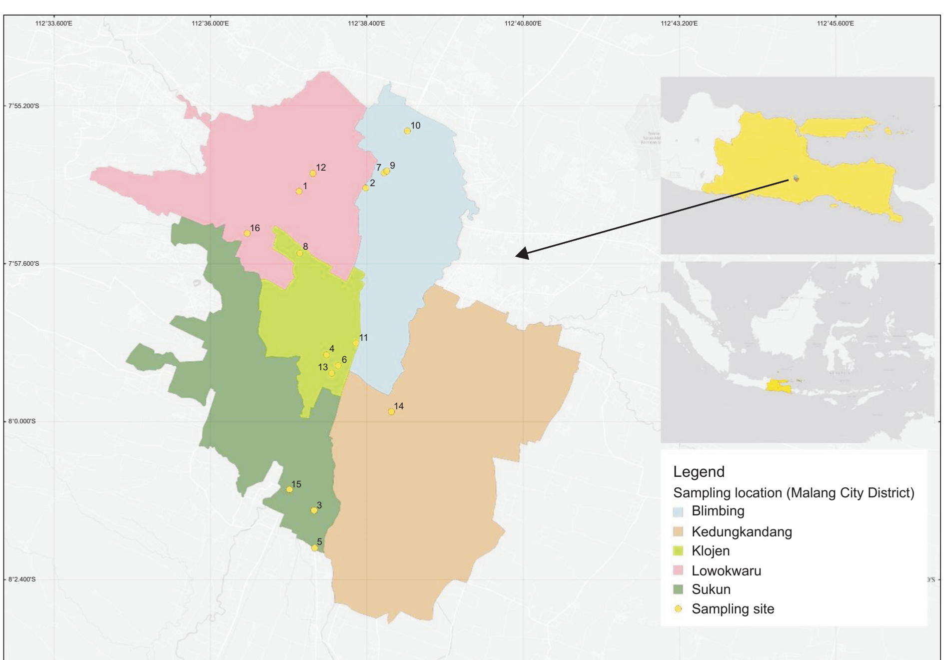


Fig. 1. Location of roadside tree data collection in Malang City, East Java, Indonesia.

Table 1. List of roadside tree species and their sampling locations

No.	Species	Family	Locality	Primary habitat	Photosynthesis type	Location
1	*Barringtonia asiatica* (L.) Kurz.	Lecythidaceae	Native	Wet tropics	CAM	Jl. Soekarno Hatta, Lowokwaru
2	*Bauhinia purpurea* L.	Caesalpiniaceae	Non-native	Wet tropics	C3	Jl. A. Yani, Blimbing
3	*Cerbera manghas* L.	Apocynaceae	Native	Wet tropics	C3	Jl. Ps Gadang, Sukun
4	*Ficus benjamina* L.	Moraceae	Native	Wet tropics	C3	Jl. Kolonel Sugiono, Kedungkandang
5	*Filicium decipiens* L.	Sapindaceae	Non-native	Dry tropics	C3	Jl. Lowokdoro, Sukun
6	*Handroanthus chysotrichus* (Jacq.)	Bignoniaceae	Non-native	Dry tropics	C3	Jl. Ps Besar, Klojen
7	*Lagerstromia indica* L.	Bignoniaceae	Non-native	Subtropical	C3	Jl. A. Yani, Blimbing
8	*Mimusops elengi* L.	Sapotaceae	Native	Tropics, subtropical	C3	Jl. M. Panjaitan. Klojen
9	*Monoon longifolium.*	Annonaceae	Non-native	Wet tropics	C3	Jl. A. Yani Utara, Blimbing
10	*Muntingia calabura* L.	Mutingiaceae	Non-native	Dry tropics	C3	Jl. M. Sungkono, Kedungkandang
11	*Pterocarpus indicus* Willd.	Papilionaceae	Native	Dry tropics	C3	Jl. Trunojoyo, Klojen
12	*Samanea saman* (Jacq.) Merr.	Fabaceae	Non-native	Dry tropics	C3	Jl. Soekarno Hatta, Lowokwaru
13	*Spathodea campanulata* Beauv.	Bignoniaceae	Non-native	Wet tropics	C3	Jl. Kyai Tamin, Klojen
14	*Swietenia mahagoni* (L.) Jacq.	Meliaceae	Non-native	Wet tropics	C3	Jl. Muharto, Kedungkandang
15	*Syzygium myrtifolium* Walp.	Myrtaceae	Native	Wet tropics	C3	Jl.S. Supriadi, Sukun
16	*Tabebuia rosea* (Bertol.)	Bignoniaceae	Non-native	Wet tropics	C3	Jl. Sumbersari, Lowokwaru

Specific leaf area (cm^2/g)

SLA measurements involved calculating the ratio between the leaf surface area and dry weight of the leaf. This method provides insight into the extent of structural changes and leaf growth. Calculations were can be performed using the following formula:

$$\mathrm{SLA} = \frac{\mathrm{LA}\ (\mathrm{cm}^2)}{\text{Leaf dry weight (g)}}$$

Specific leaf weight (g/cm^2)

SLW measurements involved calculating the ratio between the dry weight of the leaf and its corresponding surface area. This measurement provides an understanding of the leaf's structural density and material composition using the following formula:

$$\mathrm{SLW} = \frac{\text{Leaf dry weight (g)}}{\mathrm{LA}\ (\mathrm{cm}^2)}$$

Leaf dry matter content (mg/g)

LDMC measurement involved drying leaf samples in an oven at 80°C for 48 hours. This method allows the calculation of the proportion of dry matter in the leaf after the evaporation of water from the plant tissue. This measurement provides insight into the amount of solid components remaining in the leaves after the removal of water. Calculations were performed using the following formula:

$$\mathrm{LDMC} = \frac{\text{Leaf dry weight (mg)}}{\text{Leaf fresh weight (g)}}$$

Chlorophyll content (ccm)

Leaf CC was measured using a chlorophyll content meter, specifically a CCM-200 plus chlorophyll content meter (Opti-Sciences, Inc., Hudson, NH, USA). This method was used to measure the level of chlorophyll in leaves, with the results expressed in units of a chlorophyll content meter (ccm).

Stomata density and stomata aperture (μm)

SD and TD measurements were conducted using the replica method, with a thin layer of clear nail polish applied to the underside of the leaf. Leaves were then observed using an Olympus CX31 light microscope (Olympus Corporation, Tokyo, Japan) at 40× magnification for SD and 10× or 40× magnification for SA. The observations are expressed in units of number of stomata per square millimeter (/mm²), while the length of SA is expressed in micrometers (μm).

Wood density (g/cm³)

WD measurement involves drying wood twig samples in an oven at 80°C for 48 hours. This method allows for the calculation of the density of the wood tissue. WD measurement is performed to understand the extent to which the wood contains solid material and moisture. The calculation can be performed using the following formula:

$$\mathrm{WD} = \frac{\text{Dry weight of twig (g)}}{\text{Volume of twig (cm}^3\text{)}}$$

Data analysis

Mean values of eco-physiological characteristics among tree species were compared using analysis of variance (ANOVA), followed by Duncan's test at a 95% confidence level (P<0.05), using SPSS 16.0 (SPSS Inc., Chicago, IL, USA). The relationships between eco-physiological characteristics and the most important characteristics were analyzed using Pearson correlation tests at a 95% confidence level (P<0.05), using Paleontological Statistics (PAST 4.03; Natural History Museum, Oslo, Norway) software. Eco-physiological characteristics were analyzed with a correlation matrix (univariate covariance Pearson) and scatter biplots using the PAST 4.03 software. The association patterns of tree species with eco-physiological characteristics were analyzed using multivariate ordination via principal component analysis (PCA).

The comparison of the mean environmental factor values at 16 locations in Malang City was analyzed using ANOVA, followed by Duncan's test at a 95% confidence level (P<0.05) using SPSS software (version 16.0). The relationship between the ecophysiological characteristics of roadside tree species and environmental factors was also analyzed using PCA. The determination of tree species with the best ecophysiological performance for roadside greening programs was based on the association patterns of species positively correlated with the most important ecophysiological characteristics on the PCA diagram (Rindyastuti *et al*., 2021).

Results

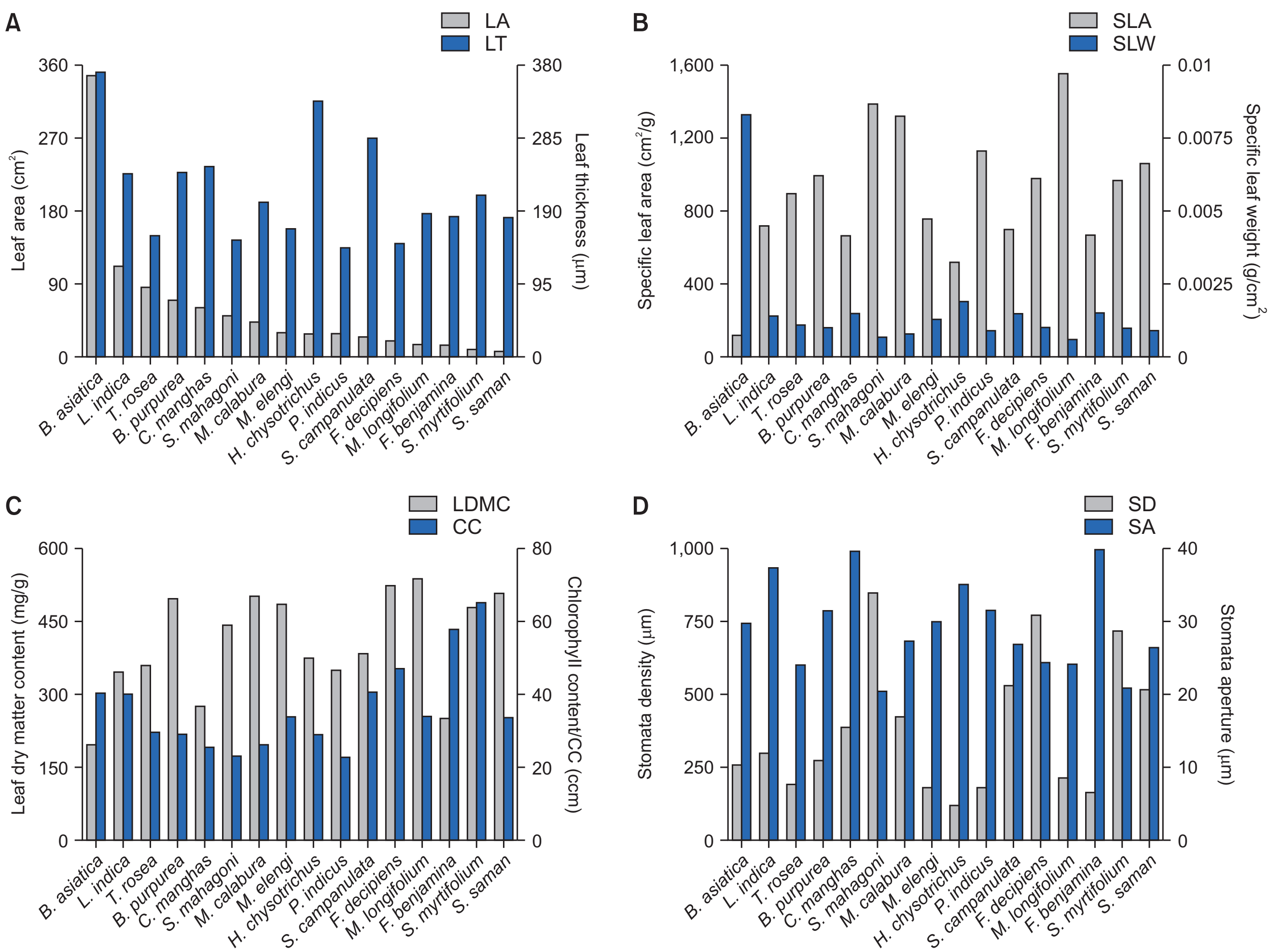
Eco-physiological characteristics of roadside trees in Malang City

Barringtonia asiatica had the highest in LA and LT, resulting in the lowest LDMC (Fig. 2A). Its larger leaf size and thickness compared to those of other tree species make *B. asiatica* more prone to water loss during transpiration, leading to lower dry weight after oven drying. Bareja *et al*. (2013) also noted that plants with larger leaves absorbed more water because their larger leaf surface area. However, plants with high LA tend to lose more water through transpiration than plants with smaller leaves. Increased LT (succulence) is associated with greater heat retention in leaves, causing leaf temperatures to be higher than those of the surrounding environment, which can accelerate transpiration (Dacosta & Daningsih, 2022).

The eco-physiological characteristics of *Swietenia mahagoni* include high SLA and high WD, indicating relatively fast growth and good carbon storage capacity. Along with *S. mahagoni* and *Pterocarpus indicus*, *Muntingia calabura* also exhibited a high SLA (Fig. 2B). However, this species has low SLW and WD, leading to suboptimal wood quality. A high SLA often prioritizes growth over carbon storage, which can affect wood quality (Cornelissen *et al*., 2003). Conversely, high SLW is associated with slower growth and denser, more durable wood. High SLW correlates with higher leaf carbon content, which can reduce photosynthesis rates and growth speed, whereas low SLW relates to smaller leaf areas that capture less light and slow growth (Donovan *et al*., 2014). The trees with the highest SLW include *Handroanthus chysotrichus* and *Mimusops elengi*, which align with the finding that these species had good WD (Fig. 2B).

LDMC is crucial for assessing plant drought resistance. Trees such as *M. calabura*, *Filicium decipiens*, *Samanea saman*, *Monoon longifolium*, *Bauhinia purpurea*, and *M. elengi* had high LDMC values, whereas *B. asiatica*, *Ficus benjamina*, and *Cerbera manghas* had the lowest LDMC values (Fig. 2C). A high LDMC reflects better resistance to water scarcity (Smart *et al*., 2017). Conversely, a low LDMC indicates higher water content in the leaves and suggests higher fire resistance (Cornelissen *et al*., 2003; Garnier *et al*., 2001). Therefore, plants with a low LDMC are recommended for restoration in fire-prone areas.

Leaf CC is a critical indicator of the metabolic balance between photosynthesis and production during water scarcity. The highest CC values were observed in *Syzygium myrtifolium*, whereas *P. indicus* and *S. mahagoni* showed the lowest (Fig. 2C). Persistent green foliage is associated with increased photosynthetic and transpiration efficiencies under drought conditions. Plants with a high CC have a high capacity and rate of photosynthesis (Li *et al*., 2018), indicating that the plant is resistant to the adverse



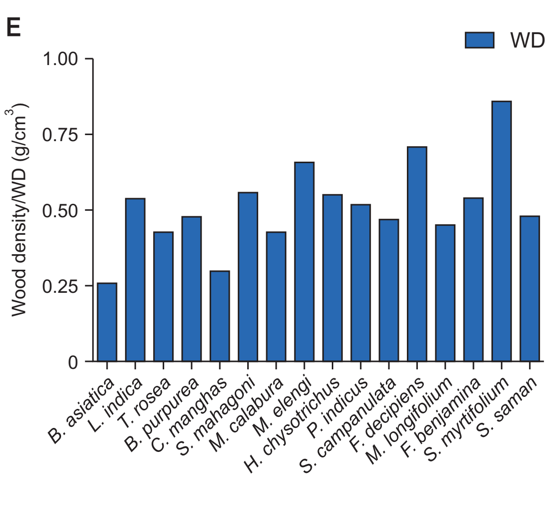


Fig. 2. Result of eco-physiological characterization of 16 roadside tree species in Malang City. (A) LA and LT. (B) SLA and SLW. (C) LDMC and CC. (D) SD and SA. (E) WD. LA, leaf area; LT, leaf thickness; SLA, specific leaf area; SLW, specific leaf weight; LDMC, leaf dry matter content; CC, chlorophyll content; SD, stomata density; SA, stomatal aperture; WD, wood density.

effects of pollution and other environmental stresses, allowing it to grow well (Karmakar *et al*., 2021; Molnár *et al*., 2020). Therefore, a decrease in CC negatively affects photosynthetic efficiency (Song & Banyo, 2011). The presence of air pollutants, such as sulfur dioxide (SO_2) and nitrogen oxide (NOx), that enter plants through stomata will affect physiological processes in plants, for example, by lowering the pH of leaves, which causes the photosynthesis process to not be optimal (Karmakar *et al*., 2021).

Stomatal characteristics, such as SD and SA play a role in the efficiency of leaf water use. Trees, such as *S. mahagoni*, *F. decipiens*, and *S. myrtifolium* exhibited the highest SD (Fig. 2D). SD variations indicate plant responses to extreme environmental conditions (e.g., water stress and nutrient levels) to maintain physiological functions such as photosynthesis, respiration, and transpiration. SD is a genetic factor in each plant species (Juairiah, 2014). Higher SD enhances CO_2 assimilation during stomatal opening periods both in the morning and evening (Lynch *et al*., 1992).

Species with the highest SA values include *F. benjamina* and *C. manghas* (Fig. 2D). Prior research indicates that *F. benjamina* has a water content of approximately 75-90%, reflecting significant water content. SA size in *Ficus* species is influenced by adaptive mechanisms (Pierantoni *et al*., 2020). Plants with low water content generally have smaller SAs to reduce evaporation, whereas those with high water content have larger apertures to balance internal and and external conditions. Larger SA optimize CO_2 absorption (Shen *et al*., 2017).

WD is a key determinant of wood quality and is correlated with mechanical and physical properties. *S. myrtifolium*, *F. decipiens*, *M. elengi*, and S. *mahagoni* exhibited the highest WD values, whereas *B. asiatica* and *C. manghas* had the lowest WD values. A high WD indicates better wood quality, greater carbon storage potential, and potentially slower growth rates, owing to resource allocation towards denser wood formation (Sudrajat *et al*., 2021).

In the present study, *S. mahagoni* exhibited high SLA values (Fig. 2B). SLA serves as a bioindicator of growth rate, and in this study, it was positively correlated with high WD values (Fig. 2E). This suggests that *S. mahagoni* has a relatively fast growth rate, good wood quality, and carbon storage capabilities. Sudrajat *et al*. (2021) confirmed that mahogany exhibited a relatively rapid growth rate.

A study on mahogany progeny found that the tree height at 10 years ranges from 2.00 to 19.00 meters, and at 20 years, from 8.50 to 27.00 meters. Additionally, the diameter at breast height at 10 years ranges from 2.55 to 32.17 cm, and at 20 years, from 13.69 to 70.06 cm. These measurements reflect the relatively fast growth rate of mahogany. *S. mahagoni* thrives under supportive environmental conditions and grows rapidly in tropical areas with high rainfall and well-drained soils. This species has also been successfully planted in Sri Lanka as a fast-growing option for commercial forestry (Perera *et al*., 2012).

Principal component analysis biplot of tree associations and eco-physiological characteristics

Multivariate PCA biplot analysis was conducted based on the nine eco-physiological characteristics of the 16 roadside tree species in Malang. Biplot analysis is a descriptive statistical method that visually and simultaneously represents n objects (points) and *P* variables (vectors) in a two-dimensional data space. Thus, the characteristics of the variables and observation objects, as well as the relative positions of the observation objects and variables, can be analyzed more easily (Leleury & Wokanubun, 2015). The PCA biplot analysis of the relationship between the eco-physiological characteristics of roadside tree species and environmental factors resulted nine 9 principal components (Fig. 3). The first three principal components (PC1, PC2, and PC3) of the PCA showed eigenvalues of 4.45, 1.68, and 1.32, respectively, with a total variance of 83.03%. This indicates a high confidence level in the PCA results (Fig. 4). The longer the vector (variable) is from the PC origin, the higher the variation, and the greater the influence of the variable on the PC.

Eco-physiological characteristics such as SLA, LDMC, and LA are key determinants, with tree species positively associated with these characteristics being interpreted as having the best eco-physiological performance in sustainable urban greening programs. The PCA analysis was divided into three quadrants, with quadrants I (SLA and LDMC), II (LA), and III, including the additional characteristic WD. According to the research objectives of sustainable urban greening programs, which require strong and resilient wood quality, Quadrant III highlights the importance of WD. The sustainability of roadside trees can be achieved by ensuring stable growth, adaptation to water stress, and strong wood quality to consistently provide

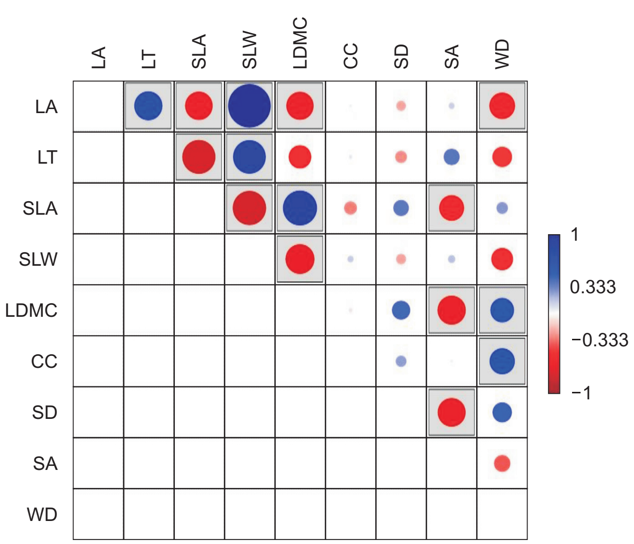


Fig. 3. Correlation among eco-physiological characteristics of roadside trees in Malang City. The size of the ellipse indicates the strength of the correlation, and the color indicates the direction of the correlation (blue for positive, red for negative). The intensity of the color correlates with the magnitude of the coefficient, with a range from −1 (dark red) to 1 (dark blue). LA, leaf area; LT, leaf thickness; SLA, specific leaf area; SLW, specific leaf weight; LDMC, leaf dry matter content; CC, chlorophyll content; SD, stomata density; SA, stomatal aperture; WD, wood density.

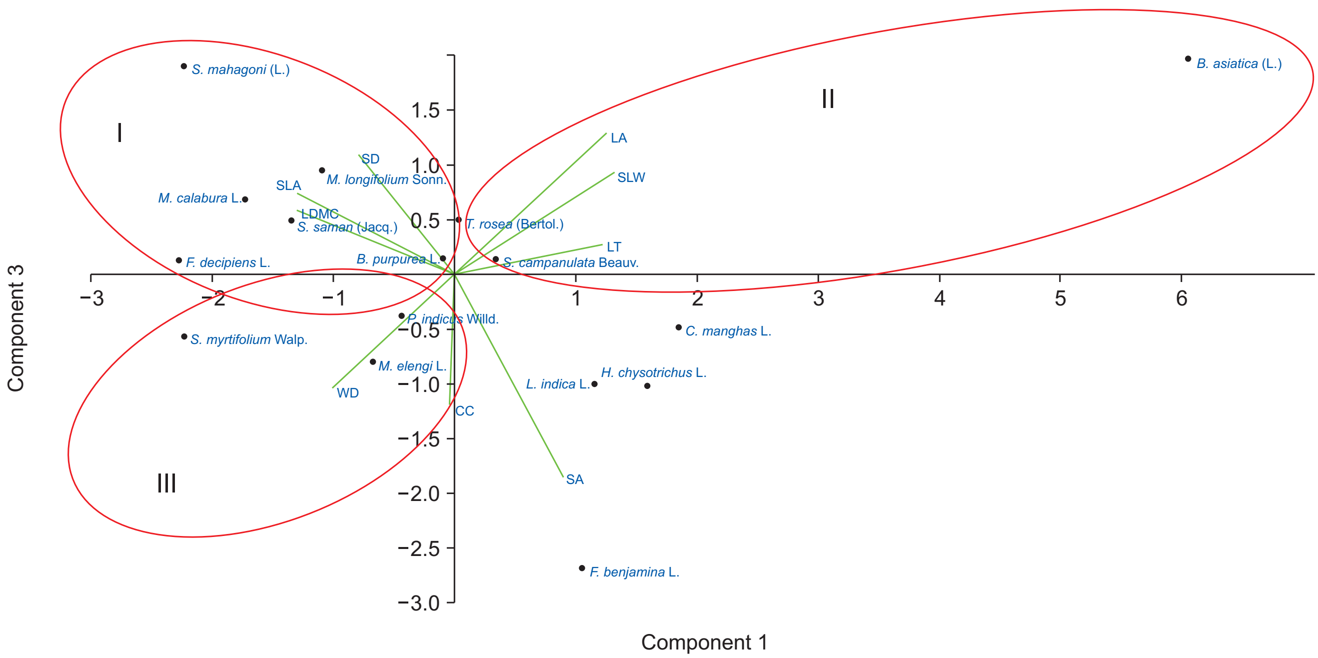


Fig. 4. Principal component analysis biplot of tree species associations and eco-physiological characteristics. LA, leaf area; SD, stomata density; SLW, specific leaf weight; SLA, specific leaf area; LDMC, leaf dry matter content; LT, leaf thickness; WD, wood density; CC, chlorophyll content; SA, stomatal aperture.

good environmental services, such as shading, temperature regulation, and pollution reduction, especially CO_2.

Tree species that showed positive associations with all four ecophysiological characteristics were considered to have the best ecophysiological performance. In Quadrant I, the tree species that were positively associated with SLA and LDMC included *B. purpurea, F. decipiens, S. saman, M. longifolium*, and *M. calabura*. Quadrant II highlights that LA was positively associated with *B. asiatica, Tabebuia rosea*, and *Spathodea campanulata*. Quadrant III showed that tree species that were positively associated with WD included *S. myrtifolium, M. elengi*, and *P. indicus* (Fig. 4).

Relationship of roadside tree eco-physiological characteristics with abiotic factors in Malang City

The measurements of abiotic factors from 16 tree species locations along the streets of Malang City include temperature ranging from 30°C to 33.3°C, air humidity from 48.0% to 66.3%, light intensity from 1,225 to 2,309 lx, soil pH from 7.1 to 7.6, and CO_2 concentration from 426.2 ppm to 557.3 ppm (Table 2). The results show an increase in CO_2 concentration, which in 2016 ranged from 388.38 ppm to 413.56 ppm (Herlina *et al*., 2017). PCA analysis of abiotic factors from the 16 tree species in Malang City indicated that temperature, CO_2 concentration, and air humidity were the most important abiotic factors (Fig. 5). Temperature has a strong negative correlation with air humidity (RH) and a strong positive correlation with CO_2 concentration. The CO_2 concentration has a strong negative correlation with air humidity and a strong positive correlation with humidity.

The increase in the CO_2 concentration in Malang City is a significant concern. Higher CO_2 concentrations lead to higher air temperatures (Herlina *et al*., 2017). According to McPherson (1998), trees have greater potential for long-term CO_2 storage than non-woody vegetation. CO_2 from the surrounding air enters the leaf cells through the stomata. Then, CO_2 interacts with water (H_2O) and chlorophyll in the chloroplasts in a process called photosynthesis. After photosynthesis, the stomata close to reduce water loss through evaporation (Sukmawati *et al*., 2015). Therefore, tree species with high stomatal densities can absorb CO_2 from the air. Trees with dense and broad canopies and sturdy wood that are less likely to fall also help lower air temperatures and CO_2 concentrations (Andini, 2016). The denser the stomata, the better the ability of the plant to absorb CO_2 (Syafaati & Mangkoedihardjo, 2021).

Temperature and humidity are the primary determinants of vegetation suitability for urban parks. These factors are interrelated and an increase in air temperature can cause a decrease in humidity. Changes in humidity can affect various aspects of plant growth including plant height, leaf area, leaf length, flowering, and other metabolic processes. Parks play a significant role in controlling the environmental temperature (Hirai *et al*., 2000). Another important factor in urban park vegetation is light intensity,

Table 2. Results of abiotic factor measurements at 16 roadside tree locations in Malang City

Species	Temperature (°C)	Relative humidity (rH%)	Light intensity (Cd)	Air CO_2 (ppm)
Barringtonia asiatica	31.4±0.602[abcd]	58.0±626.6[cd]	1,389±2.645[bc]	446.0±12.16[ab]
Bauhinia purpurea	30.6±0.709[ab]	66.3±604.2[g]	1,760±2.081[bc]	490.3±7.09[ab]
Cerbera manghas	32.6±1.006[cde]	53.7±167.0[bc]	2,223±3.511[c]	475.2±17.34[ab]
Ficus benjamina	30.2±0.550[ab]	60.7±562.3[de]	1,444±4.041[ab]	426.2±6.00[a]
Filicium decipiens	31.3±1.527[abc]	52.0±524.4[ab]	1,745±1.000[ab]	490.3±34.12[ab]
Handroanthus chysotrichus	33.2±0.950[e]	53.3±828.2[bc]	2,170±3.785[abc]	482.4±2.64[ab]
Lagerstromia indica	30.0±1.081[a]	63.0±430.9[ef]	1,562±1.000[ab]	462.3±66.50[ab]
Mimusops elengi	31.8±0.800[bcde]	54.7±350.7[bc]	1,478±1.527[ab]	443.5±18.61[ab]
Muntingia calabura	33.3±0.556[e]	54.3±520.7[bc]	1,706±3.605[ab]	491.5±68.82[b]
Monoon longifolium	33.1±0.680[bc]	53.0±676.7[bc]	2,021±1.527[abc]	556.6±18.87[c]
Pterocarpus indicus	31.4±0.014[abc]	55.7±216.1[bc]	1,897±1.527[abc]	489.4±42.01[ab]
Samanea saman	31.9±0.351[bcde]	56.0±509.3[bcd]	2,067±3.000[abc]	458.3 ±14.57[ab]
Spathodea campanulata	31.8±0.400[bcde]	55.3 ±447.7[bc]	1,931±2.516[abc]	450.3±9.29[ab]
Swietenia mahagoni	30.4±0.953[ab]	58.0±245.2[cd]	2,024±4.000[abc]	458.3±29.02[ab]
Syzygium myrtifolium	33.2±1.276[e]	48.0±361.7[a]	2,309±2.000[bc]	557.3±52.78[c]
Tabebuia rosea	32.6±0.808[bcde]	53.3±399.8[bc]	1,225±2.081[bc]	502.4±15.01[bc]

Values are presented as mean±standard deviation. [a-e]Values are not significantly different based on Duncan's test at a 5% significance level (n=3).

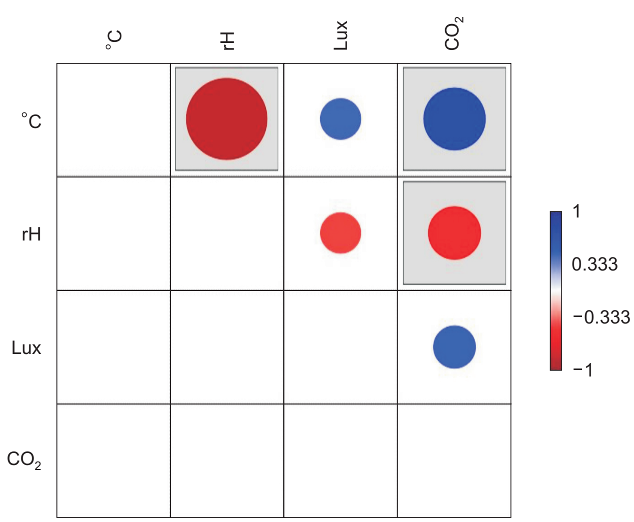


Fig. 5. Correlation between abiotic factors in Malang City. The size of the ellipse indicates the strength of the correlation, and the color indicates the direction of the correlation (blue for positive, red for negative). The intensity of the color correlates with the magnitude of the coefficient, with a range from −1 (dark red) to 1 (dark blue).

which affects plant photosynthesis. High light intensity can cause the stomata to open wider and affect the ability of plants to absorb environmental pollutants (Mansur & Pratama, 2014). The more plants absorb pollutants, the more they play an important role in the form of ecosystem services (Molnár *et al*., 2020).

The PCA biplot analysis of the relationship between the ecophysiological traits of roadside tree species and environmental factors resulted in 14 principal components. The first two principal components (PC1 and PC2) of the PCA showed Eigenvalues of 5.03 and 2.41, respectively, with a total variance of 53.22%. This indicates a good level of confidence in the PCA results of this study. The longer the vector (variable) from the origin of the PC, the higher the variation and the greater the influence of the variable on that PC (Fig. 6).

The PCA produced four quadrants. Quadrant I shows that the ecophysiological traits LA, LT, and SLW were related to the environmental factor of soil pH. Tree species positively associated with these three traits included *S. campanulata*, *C. manghas*, *H. chrysotricus*, and *B. asiatica*. Quadrant II indicated that the environmental factors of CO_2 concentration, temperature, and light intensity were related to the ecophysiological traits of SD and CC. The tree species positively associated with these environmental factors were *M. calabura*, *M. longifolium*, and *S. myrtifolium*. Quadrant III showed that the ecophysiological traits SLA, LDMC, and WD were not significantly associated with environmental factors. The tree species that were positively associated with this quadrant included *S. saman*, *T. rosea*, *P. indicus*, *M. elengi*, *F. decipiens*, and *S. mahagoni*. Finally, Quadrant IV shows that the ecophysio-

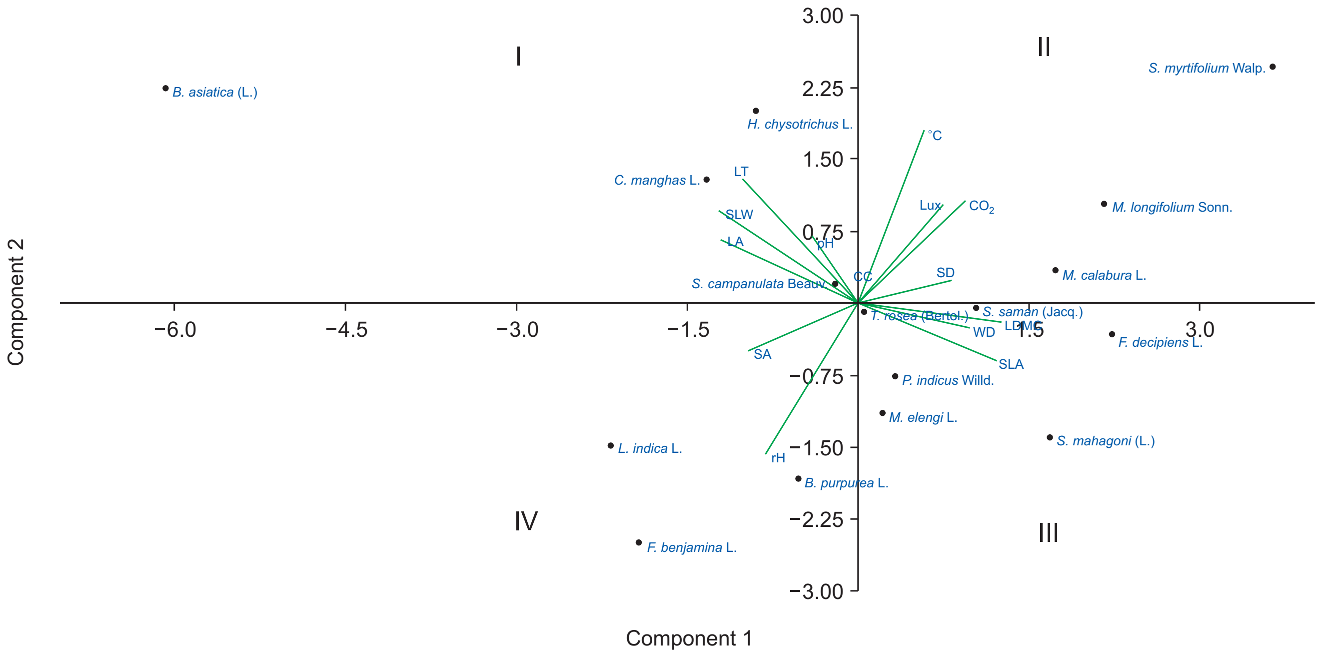


Fig. 6. Relationship between ecophysiological traits and environmental factors in Malang City. LT, leaf thickness; SLW, specific leaf weight; LA, leaf area; CC, chlorophyll content; SD, stomata density; LDMC, leaf dry matter content; WD, wood density; SA, stomatal aperture; SLA, specific leaf area.

logical trait SA is related to air humidity, with tree species being positively associated with *B. purpurea*, *L. indica*, and *F. benjamina* (Fig. 6).

Discussion

Implications for sustainable urban greening strategies

Research on plant ecophysiology, which involves the interactions between plants and their environment, can provide valuable insights for evaluating and guiding urban greening programs. Understanding the ecophysiological mechanisms that allow plants to grow and thrive in disturbed environments can enhance the effectiveness of revegetation efforts (Junita *et al*., 2022). This study showed that several tree species, including *S. mahagoni*, *S. saman*, *M. elengi*, *M. longifolium*, *P. indicus*, *F. benjamina*, *M. calabura*, and *S. myrtifolium*, exhibited better adaptation and ecophysiological performance, supporting the effectiveness of urban greening programs. Four of these species, namely *M. calabura*, *M. longifolium*, *S. mahagoni*, and *S. saman*, are exotic species that tend to adapt easily, but can be invasive and inhibit the growth of surrounding plants. This is consistent with Mukaromah *et al*.'s (2016) findings, which showed that mahogany has an inhibitory effect on the growth of surrounding plants, owing to allelopathic substances produced in its leaves. Mahogany leaf litter contains compounds, such as limonoids, essential oils, and polyphenols, that can inhibit plant growth (Moghadamtousi *et al*., 2013; Paritala *et al*., 2015).

M. calabura exhibits variable growth rates depending on environmental conditions and management practices. This plant is known for its relatively fast growth rate, reaching heights of 10-12 meters within a few years under favorable conditions (Horstman *et al*., 2018). Its adaptability includes its ability to grow in various soil types, withstand high temperatures, resist pests and diseases, and tolerate drought and flooding. However, the wood quality of *M. calabura* is poor because of its softness, lightness, and lack of durability, limiting its use for construction and other purposes (Rahman *et al*., 2010). *M. longifolium*, or glodokan tiang, is an exotic tree species with a relatively fast growth and the ability to absorb Pb; however, it is sensitive to air pollution. This high resilience makes them a good choice for street greening (Hardiyanti, 2017).

Local tree species with good ecophysiological performances are required for urban roadside planting. The four recommended local tree species are *F. benjamina*, *P. indicus*, *M. elengi*, and *F. decipiens*. *F. benjamina* is known for its high environmental service value, particularly as a shaded tree. In addition, *F. benjamina* plays a role in maintaining groundwater quality and slope stabilization because of its natural soil-binding roots. With its dense canopy, this plant significantly absorbs CO_2 and other air pollutants because of its efficient SA (Fig. 2D, 6; Hadi *et al*., 2024). According to the results of this study, *P. indi-*

cus had good growth rates because of its high SLA (Fig. 2B). Moreover, this tree species is drought tolerant (Syahbudin *et al*., 2018). Additionally, the wood of *P. indicus* has Class II strength and long-term durability, making it widely used in construction materials, furniture, bridges, and boats (Yuliah *et al*., 2020).

Based on the result of this study, *S. myrtifolium* is a local species with relatively good WD, allowing it to absorb more CO_2 than other tree species and thrive in high-temperature environments (Table 2). This is based on the results of the study that *S. Myrtifolium* is a type of tree with quite good CC, SD, and SA character values (Fig. 2C, D). *S. myrtifolium* helps to prevent landslides and stores water because of its strong taproot structure. The stem of *S. myrtifolium* can reach a height of 5 m if grown under nutrient-rich and fertile conditions (Tsan, 2023). Additionally, secondary metabolites were found in some parts of the red shoots of the plant. This plant is beneficial as an antioxidant, natural dye, and anti-tumor, antiangiogenic, and cytotoxic agent (Aini & Chairul Saleh, 2015).

Conclusion

The ecophysiological performances of LA, LT, SLA, SLW, LDMC, CC, SD, SA, and WD of the 16 roadside tree species in Malang City showed a pattern of variation in adaptation to their environment. The most important ecophysiological traits were LA, SLA, and LDMC, which were positively correlated with tree species, including *B. asiatica, P. indicus*, *S. mahagoni*, and *M. longifolium*. WD was the next determining factor, with positively correlated species, including *S. myrtifolium*, *F. decipiens*, and *M. elengi*. Some tree species, such as *M. calabura*, *M. longifolium*, and *S. myrtifolium*, are closely related to environmental factors such as temperature and CO_2 concentration. Air humidity was significantly correlated with *B. purpurea*, *L. indica*, and *F. benjamina*.

The recommended trees for roadside greening programs include exotic species such as *S. mahagoni*, *S. saman*, *M. calabura*, and *M. longifolium*, as well as local species such as *M. elengi*, *P. indicus, F. benjamina*, and *S. myrtifolium*. These species exhibited good adaptation capabilities and superior ecophysiological performance, particularly in SLA, LDMC, WD, and SD. In addition to their rapid growth rates, these tree species can withstand water stress and produce durable wood. Trees with a high SD are more effective at absorbing CO_2 during stomatal opening periods, both in the morning and afternoon.

Author Contributions

Aisyah Raihan Fadillah, as the lead author, was responsible for data collection, data analysis, result interpretation, manuscript drafting, and editing. Vivi Novianti (corresponding author) and Lia Hapsari supervised the research to ensure adherence to ethical standards and proper procedures, while also providing corrections and suggestions to address conceptual errors, inaccuracies in the scientific names of plants, and other mistakes.

Conflict of Interest

The authors declare that they have no competing interests.

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