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Determining Crown Mass Density of Decurrent Trees Based on Physical Characteristics Analysis

Penentuan Kerapatan Massa Tajuk Pohon Decurrent *Berdasarkan Analisis Keragaan Fisik*

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RESEARCH ARTICLE

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ABSTRACT

Self-weight calculation was identified as an essential step in tree structural analysis. In practice, this calculation included estimating stem weight based on wood density, while crown density was expressed as a percentage of crown area. However, previous research had not provided explicit methodologies for determining crown density as a function of crown mass and volume. Therefore, this research aimed to establish a proper method and corresponding conversion factors for translating area-based crown density estimates to those derived from crown weight and volume. A total of 15 healthy decurrent trees were selected to assess crown volume and density through physical attribute analysis. The new crown area density was calculated after pruning, where all pruned crown biomass was collected and weighed to determine crown mass. Mathematical analyses were developed to convert crown density values. The results showed that decurrent trees had a mean crown density of approximately 2.95 kg/m^3, exceeding the value reported in reference research for excurrent trees (1.9 kg/m^3). Since this research focused on tropical tree species, the results could serve as a reference for subsequent research on tropical tree structural characteristics.

KATA KUNCI
kerapatan tajuk,
presentasi tajuk,
volume tajuk,
decurrent, *pemangkasan*

INTISARI

Perhitungan beban berat sendiri merupakan tahapan terpenting dalam analisis struktur pohon. Pada umumnya, perhitungan berat batang dilakukan berdasarkan kerapatan massa kayu, sedangkan kerapatan tajuk dilakukan berdasarkan persentase luas area tajuk. Namun demikian, penelitian sebelumnya tidak menyediakan metode yang eksplisit untuk menentukan nilai kerapatan tajuk yang merupakan fungsi dari massa dan volume tajuk. Oleh karena itu, penelitian ini bertujuan untuk menyusun metode dan faktor konversi yang sesuai untuk menerjemahkan perkiraan kepadatan tajuk berbasis luas ke perkiraan kerapatan tajuk yang diperoleh dari berat dan volume tajuk. Lima belas pohon decurrent *yang sehat dipilih untuk dihitung volume dan kerapatan tajuk melalui analisis keragaan fisik. Massa tajuk yang dipangkas, dikumpulkan dan dihitung untuk mendapatkan bobot tajuk. Luas area kerapatan tajuk setelah pemangkasan dihitung dan dianalisis secara matematis untuk mengonversi nilai kerapatan tajuk. Hasil penelitian menunjukkan bahwa pohon* decurrent *memiliki kerapatan tajuk sekitar 2,95 kg/m^3. Nilai ini lebih tinggi daripada pohon* excurrent *yang memiliki nilai 1,9 kg/m^3, berdasarkan studi referensi. Penelitian ini berlaku menggunakan sampel spesies pohon tropis, sehingga hasil penelitian ini dapat digunakan sebagai rujukan untuk penelitian lain yang berkaitan dengan struktur pohon di daerah tropis.*

Introduction

Trees are important in urban landscapes, offering ecological, economic, sociocultural, and aesthetic functions (Saroh & Krisdianto 2020). Furthermore, trees function as both carbon stocks and carbon sequesters, which can be measured through carbon stock calculations (Febiriyanti et al. 2021), showing the importance of urban trees as assets for communities living in cities (Kadry et al. 2019). However, there are potential risks under certain conditions due to trees' failure caused by environmental stresses, such as wind, rain, storms, and pest attacks, including disease (Hui et al. 2022). Previous research has analyzed the stability of trees using biomechanical calculations based on tree structure analysis, developed with several load calculation methods (Brüchert et al. 2000; Karlinasari et al. 2023; Aini et al. 2024). From the calculations, a safety factor was obtained to estimate the safety condition (Karlinasari et al. 2023; Aini et al. 2024). This value is essential for determining the stability of standing trees and their sustainability in urban environments. In ecology, stability is defined as the ratio of tree height (branch-free height) to diameter at breast height (D_{bh}).

The most important stage in analyzing tree structure is to calculate the self-weight load (Kadry et al. 2019; Karlinasari et al. 2023; Aini et al. 2024), the live load due to external forces (external load), and the wind load (Kadry et al. 2019; Aini et al. 2024). Among the different parts of trees (Gul et al. 2017), trunk and crown are the main determinants of self-weight load (Kadry et al. 2019; Karlinasari et al. 2023; Aini et al. 2024), which is determined through crown density values based on weight and volume (kg/m^3) (Brüchert et al. 2000; Karlinasari et al. 2023; Aini et al. 2024). In the field of forest ecology, crown density is calculated as the percentage of crown area and the amount of sunlight blocked by crown biomass (leaves, stems, branches, and twigs), expressed as a percentage (%) (Bechtold & Randolph 2018). Previous research (Burger 1939; Brüchert et al. 2000; Karlinasari et al. 2023; Aini et al. 2024) has not clearly described the method of determining and obtaining crown density values based on weight and volume. Therefore, commonly used crown density values are often derived from Burger (1939) in Brüchert et al. (2000) of 1.9 kg/m^3 for subtropical tree species with an excurrent growth model.

In contrast, tropical trees generally exhibit a decurrent growth pattern. Decurrent trees have many lateral branches that grow equally spaced at the same level, leading to the absence of a single central axis and a spreading crown shape (Li et al. 2022), which varies significantly (Zhu et al. 2021). However, referring to Karlinasari et al. (2023) and Aini et al. (2024), crown shape is considered paraboloid-duo. This is because the planes at the bottom of the decurrent trees' crown are not equal. For accurate characterization, calculation must be performed using a combination of several methods to determine the characteristics of the tree crown based on weight (Karlinasari et al. 2023), volume (Karlinasari et al. 2023; Aini et al. 2024), and density in the form of area (%) (Bechtold & Randolph 2018). The calculations converted crown density values expressed as area into crown weight and volume. These values are required for the bio-mechanical analysis of trees through structural analysis calculations. Therefore, this research aimed to determine the method and obtain conversion values for crown density from area to weight and volume for decurrent trees in tropical regions.

Methods

Selection of Trees

This research used purposive sampling to select 15 trees out of 173 species of trees (woody plants) found at the Institut Pertanian Bogor, Bogor, West Java, Indonesia (Figure 1). The selection was based on specific criteria: decurrent growth type, presence of a single main stem, and health condition. The selected samples consisted of 11 species of cape trees, two umbrella sunshade trees, and one each of jackfruit and rain species.

Procedures

Tree Condition Evaluation

This research evaluated the condition of target trees using the Visual Tree Assessment (VTA) adopted from the International Society of Arboriculture (ISA) Tree Risk Assessment framework. The assessment analyzed potential failure by identifying defects in the crown, branches, trunk, roots, and root collar due to

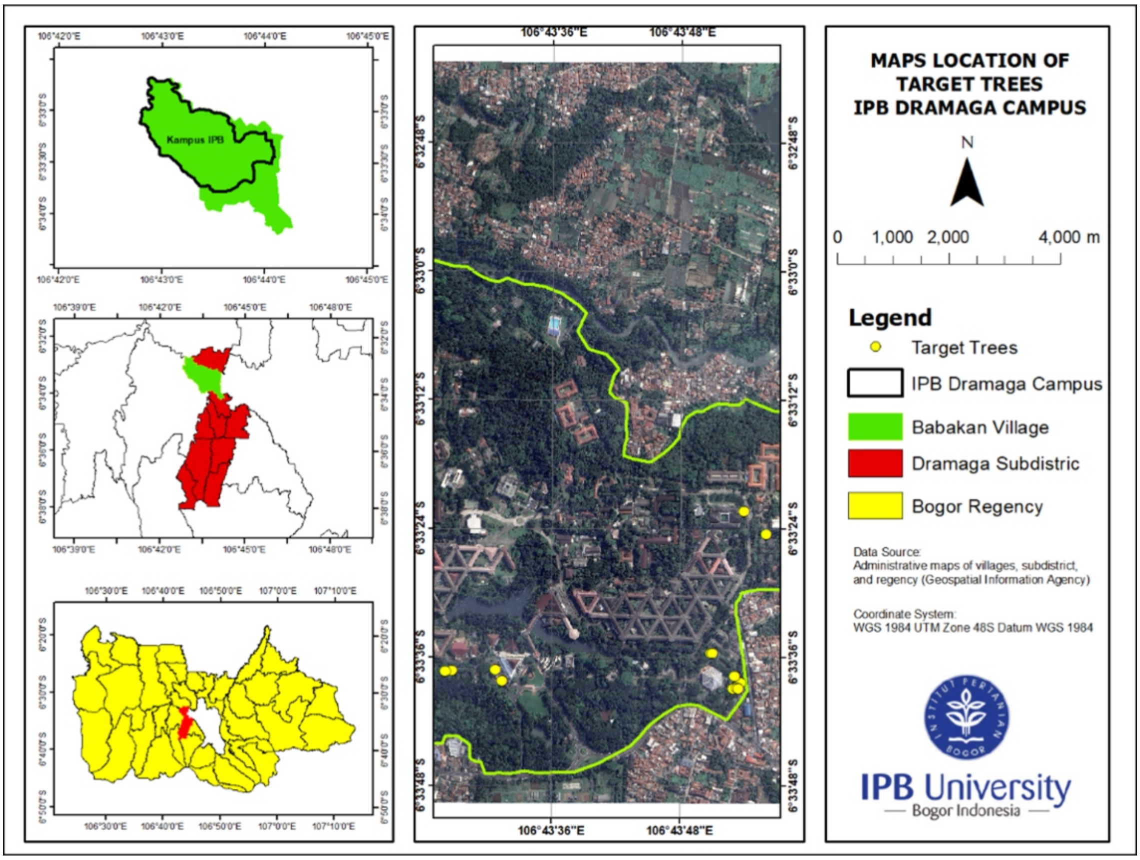


Figure 1. Map of observed trees distribution

Table 1. Quantification tree conditions based on potential failure, tree trunk circumference, and target presence

Potential Failure	Value	Tree Trunk Circumference (cm)	Value	Target Presence	Value
Very Low	1	< 45	1	Occasionally	1
Low	2	45 – 135	2	Intermittent	2
High	3	135 – 225	3	Often	3
Very Endanger	4	> 225	4	Permanent	4

Hazard rating = Potential failure + Tree trunk circumference + Target presence ....*Equation 1*

VTA. Additionally, this research analyzed target areas, including the presence of people, buildings, and properties, as well as other activities. The evaluation categorized the potential for tree failure based on observed conditions. Healthy trees showed a very low risk, while minor defects or open scars were in the low-risk category. The risk was high when signs of infestation by organisms such as fungi, termites, and beetles were present. Meanwhile, very endangered indicated decayed, hollow, or cankered trees, with yellowing leaves that eventually fell off. The assessment also classified the presence of the target based on exposure frequency. These included occasional areas such as parking areas with nearby trees, intermittent representing activity near trees in open green, and often where vehicles regularly passed under the roadside. Permanent targets included houses, buildings, sidewalks, or other structures and activities near unrelocated trees. Subsequently, Table 1 presents the quantified assessment of tree conditions. The values were accumulated to calculate the hazard rating according to Equation 1. Tree risk conditions, based on tree hazard rating values, were categorized as shown in Table 2.

Table 2. Tree risk condition categories based on hazard rating value

Category	Hazard Rating Value	Target Tree Risk Condition Estimation
1	0 – 3	Low
2	4 – 6	Medium
3	7 – 9	High
4	10 – 12	Extreme

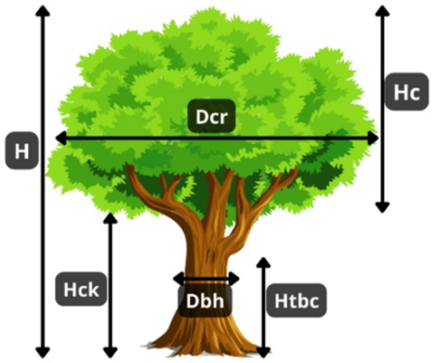


Figure 2. Variables for measuring tree morphometry include diameter at breast height (D_{bh}), crown diameter (D_{cr}), total tree height (H), height to the first branch (H_{tbc}), height of the lowest crown point (H_{ck}), and overall crown height (H_c)

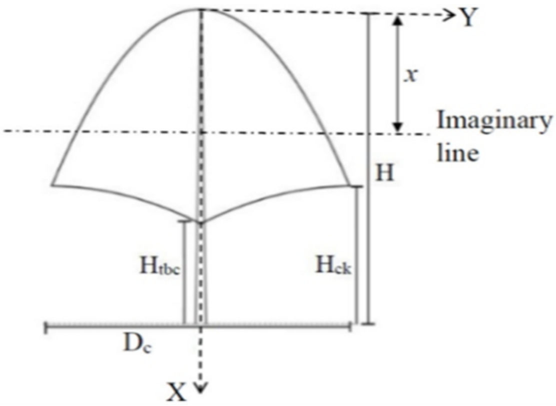


Figure 3. Shape geometry of the paraboloid-duo crown (Karlinasari et al. 2023)

Tree Morphometry Measurement

The tree morphometric parameters measured and observed in this research included diameter at breast height (D_{bh}), crown diameter (D_{cr}), tree height (H), branch-free height (H_{tbc}), lowest crown height (H_{ck}), and crown height (H_c), as shown in Figure 2. A compass and measuring tape were used to measure the crown diameter (D_{cr}) by first determining the longest crown radius and its direction. Subsequently, seven other directions were measured with an increase of 45° from the previous angle in each direction through the center of the tree trunk. Crown diameter was calculated from the total length of the crown in each direction divided by four. Measurements of the lowest crown height (H_{ck}) and the height of the branch-free stem (H_{tbc}) were taken using a Nikon Forestry Pro II laser rangefinder, which applied trigonometry to directly target the desired height. For H_{ck}, the target was the lowest part of the crown, while the stem was aimed for H_{tbc} before branching. Live Crown Ratio (LCR) was calculated as the ratio of the length of the tree trunk covered by live crown (crown height or H_c) to the total tree height (H) (Putra et al. 2023). All methods followed the procedures of the research by Aini et al. (2024).

Determination of Crown Volume

Crown volume (V_c) of trees with the decurrent growth model showed a paraboloid-duo shape (Figure 3), as expressed in Equation 2 (Karlinasari et al. 2023; Aini et al. 2024).

$$V_c = \mu \frac{D_{cr}^2}{24}(3H - 2H_{ck} - H_{tbc}) \text{ .... } \textit{Equation 2}$$

Remarks: V_c = Crown volume (m^3); D_{cr}^2 = Crown diameter (m); H = total tree height (m); H_{ck} = height of the lowest crown point (m); H_{tbc} = branch-free height (m)

Determination of Crown Density Based on Area

Crown density was defined as the amount of sunlight blocked by crown biomass (branches, twigs, leaves, buds, and seeds) from reaching the soil surface and was expressed as a percentage (Bechtold &

Randolph 2018; Putra et al. 2023). This research determined crown density as an area (%) using the direct observation method and compared it with card density. Observations were conducted 4–8 times according to the cardinal direction at a distance of 0.5 *Dc* (crown diameter). The card density method was adopted from one of the crown quality assessment indicators in Forest Health Monitoring (FHM). Further observation was carried out by standing under the tree crown and directly comparing the area blocked by crown biomass with the card density (Figure 4). For measurement accuracy, this research conducted vertical observation of the physical structure. Based on the results, any missing part of the crown was associated with a reduction in the calculated density value (Figure 5).

Crown Pruning

Crown pruning activities were aimed at tidying up the crown's shape (aesthetics) to reduce hazard (safety). These activities were conducted to obtain crown biomass weight (W_c) and to control changes in crown diameter and height, thereby determining differences in volume and crown density (%). After pruning, all crown biomass (branches, twigs, and leaves) was weighed (Figure 4), followed by morphometric measurements of dendrometric variables, volume calculations, and determination of density (%). Furthermore, this research assessed changes in crown density (ρ_{cd}, %) using the card density method through the back (Figure 5b). This was because pruning caused missing trees, which reduced the density value in the area after pruning (ρ'_{cd}) compared to before pruning (ρ_{ocd}) (Bechtold & Randolph 2018). Mathematically, the density value was expressed by Equation 3.

$$\rho_{cd} = (\rho_{ocd} - \rho'_{cd})\% \quad \textit{Equation 3}$$

Remarks: ρ_{cd} = Crown density based on area (%); ρ_{ocd} = Crown density before pruning (%); ρ'_{cd} = Crown density after pruning (%)

Determination of Crown Density Based on Crown Weight and Volume

The determination of crown density based on crown weight and volume (ρ, kg/m^3) followed the same fundamental principle, namely by dividing the mass or weight by the volume of an object (ASTM

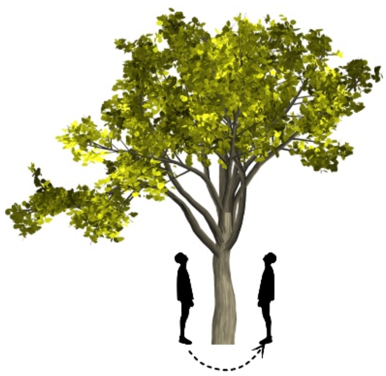
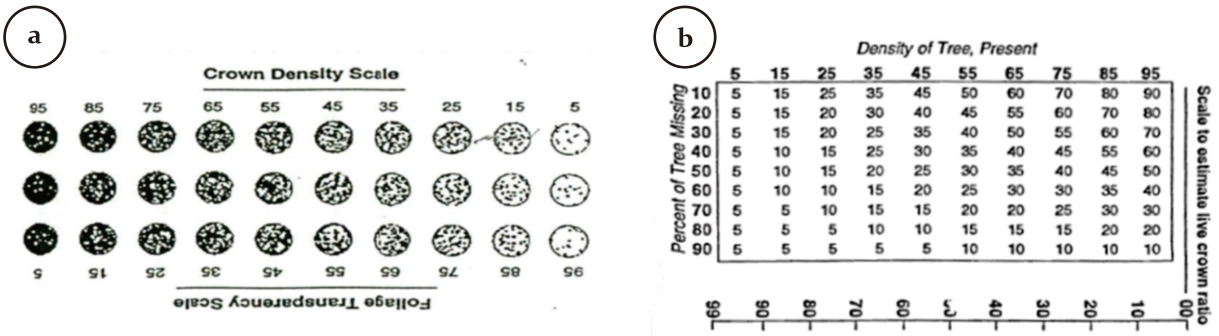


Figure 4. Position of crown density observation using card density



Percent of Tree Missing	5	15	25	35	45	55	65	75	85	95
10	5	15	25	35	45	50	60	70	80	90
20	5	15	20	30	40	45	55	60	70	80
30	5	15	20	25	35	40	50	55	60	70
40	5	10	15	25	30	35	40	45	55	60
50	5	10	15	20	25	30	35	40	45	50
60	5	10	10	15	20	25	30	30	35	40
70	5	5	10	15	15	20	20	25	30	30
80	5	5	5	10	10	15	15	15	20	20
90	5	5	5	5	5	10	10	10	10	10

Figure 5. Card crown density (a) front section and (b) back section (Bechtold & Randolph 2018)

2017). Specifically, this research obtained the weight of crown biomass (W_c) from the trimmed crown portion and weighed it. Crown volume (V_c) was obtained from the difference between the calculated crown volume before (V_{co}) and after (V_{c1}) pruning. Mathematically, Equation 4 expresses the formula for calculating crown density.

$$\rho_{ob} = \left(\frac{W_c}{V_c}\right)\frac{kg}{m^3}$$

$$\rho_{ob} = \left(\frac{W_c}{(V_{co} - V_{c1})}\right)\frac{kg}{m^3} \quad \text{.......... Equation 4}$$

Remarks: ρ_{ob} = Crown density based on crown weight and volume (kg/m³); W_c = Crown weight (kg); V_c = Crown volume (m³); V_{co} = Crown volume before pruning (m³); V_{c1} = Crown volume after pruning (m³)

Equalization of Crown Density Values

Equalization of inner crown density values based on area (%) to crown weight and volume (kg/m³) used the mathematical conversion principle, as expressed in Equation 5. The analysis yielded a crown density value in the form of area (%) as the difference between crown density before (ρ_{ocd}) and after (ρ'_{cd}) pruning (Equation 3). Furthermore, this research calculated crown density (kg/m³) using crown weight and volume, based on the weight of the weighed part (W^c) divided by the difference in volume before (V^{co}) and after (V^{c1}) pruning (Equation 4).

$$\rho_{cd}(\%) = \rho_{ob}\left(\frac{kg}{m^3}\right)$$

$$(\rho_{ocd} - \rho'_{cd})\% = \left(\frac{W_c}{(V_{co} - V_{c1})}\right)\frac{kg}{m^3} \quad \text{.......... Equation 5}$$

Tree Self-Load Mechanical Structure Analysis

The evaluation process analyzed the mechanical structure of trees to determine the safety factor by comparing the corrected allowable compressive stress with the actual value, following the procedures of Karlinasari et al. (2023) and Aini et al. (2024). The allowable compressive stress was calculated using the structural analysis method in American Wood Council or AWC (2018). Karlinasari et al. (2023) reported that the Euler and Ylinen compressive formulas produced similar values. Therefore, this research adopted the Ylinen formula recommended by AWC (2018) for buckling analysis. The corrected fiber-parallel compressive allowable stress (L(x)) was calculated using Equation 6, with the variables detailed in AWC (2018).

$$L_{(x)} = F_C C_D C_M C_t C_{cs} C_{ls} C_{ct} C_i C_F C_P \quad \text{.......... Equation 6}$$

Remarks: $L_{(x)}$ = The corrected fiber-parallel compressive allowable stress (MPa); F_c = The fiber-parallel compressive allowable stress (MPa); C_D = Correction factor of load duration; C_M = Correction factor of wet service; C_{cs} = Correction factor of critical section; C_{ls} = Correction factor of load sharing; C_{ct} = Correction factor of condition treatment; C_i = Correction factor of incising; C_P = Correction factor of column stability

The actual compressive stress ($G_{(x)}$) was calculated using Equation 7. The compressive load acting on trees consisted of an internal compressive load (trunk weight (P_{bx}) (Equation 8), crown weight (P_{cx}) (Equation 9), and external compressive weight (P)). The crown density value (ρ_c) used in the tree structural analysis calculation was used to calculate the crown weight load value (P_{cx}). Descriptions of the other variables used in the calculations were provided by Karlinasari et al. (2023) and Aini et al. (2024). The analysis calculated the safety factor of the tree as the ratio of the corrected allowable compressive stress (*L(x)*) to the actual compressive stress (*G(x)*), as defined by Equation 10.

$$G_{(x)} = \frac{P + P_{bx} + P_{cx}}{A_{ef}} \quad \text{.......... Equation 7}$$

Remarks: $G_{(x)}$ = The actual compressive stress (MPa); P = External load (N); P_{bx} = Stem weight (N); P_{cx} = Crown weight (N); A_{ef} = Effective surface area (m²)

$$P_{bx} = \rho\, g\, V_{bx} \quad \text{.......... Equation 8}$$

Remarks: P_{bx} = Stem weight (N); ρ = Wood density (kg/m³); g = Gravitational acceleration (m/s²); V_{bx} = Stem volume (m³)

$$P_{cx} = \rho_c\, g\, V_{cx} \quad \text{.......... Equation 9}$$

Remarks: P_{cx} = Crown weight (kg); ρ_c = Crown density (kg/m³); g = Gravitational acceleration (m/s²); V_{cx} = Crown volume (m³)

$$S_f = \frac{L_x}{G_x} \quad \text{.......... Equation 10}$$

Remarks: L(x) = The corrected fiber-parallel compressive allowable stress (MPa); G(x) = The actual compressive stress (MPa)

Brüchert et al. (2000) proposed another method for determining the safety factor of previously developed trees using the ratio of critical height (H_{cr}) to the actual height (H), as expressed in Equation 11. This critical height indicated the buckling capacity of trunks and could be obtained through a graphical-mathematical analysis using the Desmos Graphic Calculator software, as conducted by Karlinasari et al. (2023) and Aini et al. (2024).

$$S_f = \frac{H_{cr}}{H} \quad \text{...... Equation 11}$$

Remarks: H_{cr} = Critical tree height (m); H = Actual tree height (m)

The safety condition was determined using a safety factor. Previous research by Kadry et al. (2019) developed the safety factor (Sf), with Sf = 1.5 indicating very safe conditions. This value could exceed three (Sf > 3) in an ideal scenario for healthy trees. Karlinasari et al. (2023) and Aini et al. (2024) developed a classification of tree safety conditions based on the critical height of the trunk, using buckling analysis, and divided it into three groups, as shown in Table 3.

Table 3. Classification of tree safety conditions

No.	Safety Factor (SF) Value	Tree Condition
1	SF ≤ 1	Not safe
2	1 < SF ≤ 1.645	Safe
3	SF ≥ 1.645	Very safe

Result and Discussion

Visual Condition of Trees

This research observed 15 decurrent trees, comprising 11 species of cape, two umbrella sunshades, and one each of jackfruit and rain trees, functioning as shade with minor asymmetrical shapes. The results of the tree risk condition assessment, based on the adopted ISA Tree Risk Assessment form, indicated that 5 trees were at medium risk and 10 at high risk (Figure 6).

Further analysis determined risk conditions using a tree hazard rating assessment, considering potential failure, trunk circumference, and the presence of targets in the surrounding area. These targets included living things (humans, animals, and other plants), buildings, parking lots, and other properties that could affect tree failure (broken branches and fallen trees) (Latifah et al. 2020) (Figure 7). Based on the results, branches and twigs were more prone to failure due to dieback, open wounds from pruning, and decay, as well as dryness and a hollow condition (Figure 8). This contributed to the abundance of broken branches and fallen trees, particularly when exposed to external forces, such as wind. Meanwhile, the trunk and roots required further examination to determine their internal condition. Several cracks, wounds, decay, cavities, and termites were found on certain trees (Figure 9).

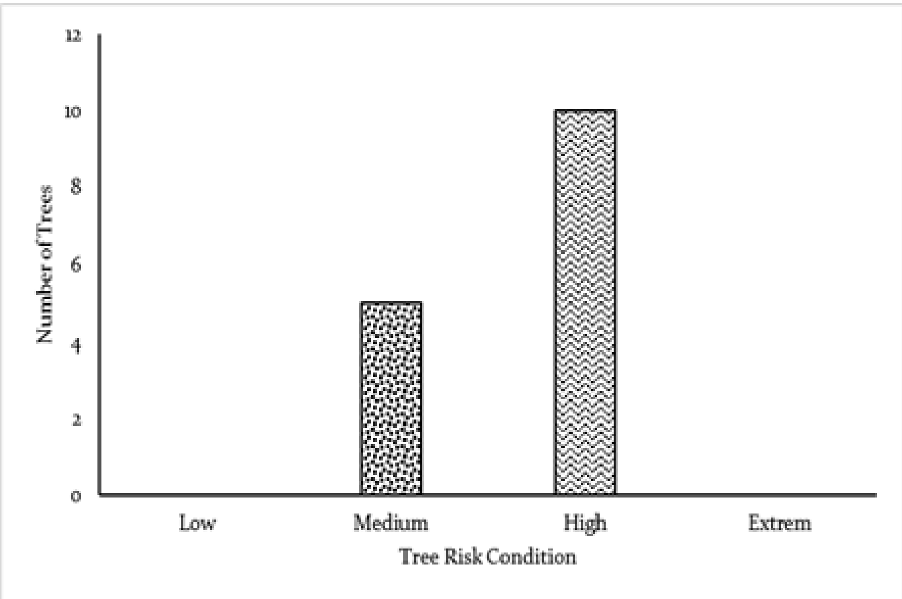


Figure 6. Tree risk condition based on visual assessment

Figure 7. Targets around trees: (a) motorcycle and car, (b) campus bus, (c) sidewalk, people, and car

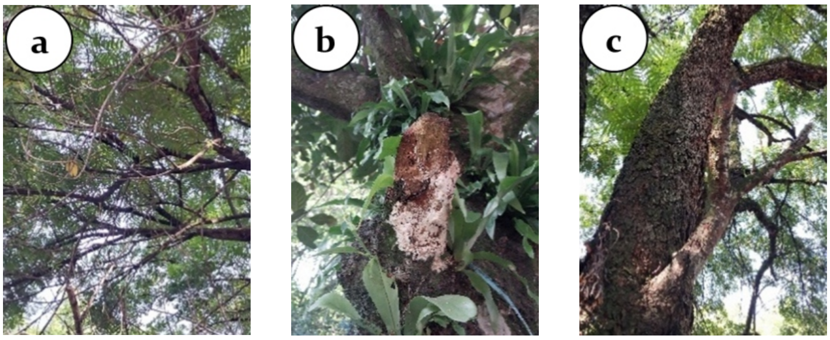


Figure 8. Tree defects in the branches and twigs: (a) dieback, (b) pruning injury, (c) dry and brittle branches

Figure 9. Tree defects in the trunk and roots: (a) decay, (b) cavity and termite nest, (c) termites

The presence of targets, including motorcycles and cars, campus bus, sidewalk, and people around trees, was relatively frequent due to the location in open spaces, such as parking lots and roadsides. Other surrounding structures were sidewalks, gutters, streetlights, and buildings. Trees in the medium-risk condition category showed a very low potential failure value and a medium trunk circumference of 45-70 cm. Meanwhile, high-risk trees had higher and more varied potential failure rates and circumferences. Observing the visual condition using the ISA Tree Risk Assessment method provided a guideline for evaluating tree structures, such as pruning or felling recommendations, to reduce risk levels (Coelho-Duarte et al. 2021).

Morphometric Characteristics of Trees

Tree morphometry played an important role in determining the dynamics of tree form (de Carvalho Maria et al. 2020). Natural tree characteristics (morphometry) could serve as an auxiliary tool for afforestation planning and management (Bobrowski & Biondi 2017). Similarly, tree morphometry was an important aspect of tree biomechanics, particularly in structural analysis (Karlinasari et al. 2023; Aini et al. 2024). The morphometric characteristics of trees were listed in Table 4.

Based on the results, the average values of parameters that remained unchanged due to pruning were diameter at breast height (D_{bh}) 0.35 m, total tree height (H) 11.33 m, and branch-free height (H_{tbc}) 1.41 m.

Table 4. Morphometric characteristics of trees

Parameter	Units	Decurrent (n=15)			
		Before Pruning		After Pruning	
		Avg	St. Dev	Avg	St. Dev
Diameter at breast height (D_{bh})	m	0.35	0.14	0.35	0.14
Crown diameter (D_{cr})	m	9.38	3.74	8.56	3.56
Tree height (H)	m	11.33	3.78	11.33	3.78
Branch-free height (H_{tbc})	m	1.41	0.64	1.41	0.64
Lowest crown height (H_{ck})	m	2.34	1.26	3.78	1.61
Crown height (H_c)	m	8.99	3.34	7.55	3.26
Live Crown Ratio (LCR)	%	78.84	9.71	65.27	11.81

Meanwhile, the average parameters that changed due to pruning were crown diameter (D_{cr}) at 9.38 m, lowest crown height (H_{ck}) at 2.34 m, and crown height (H_c) at 8.99 m. The average parameters that changed due to pruning were crown diameter (D_{cr}) at 9.38 m, lowest crown height (H_{ck}) at 2.34 m, and crown height (H_c) at 8.99 m for conditions before pruning. The average parameters for conditions after pruning included crown diameter (D_{cr}) of 8.56 m, lowest crown height (H_{ck}) of 3.78 m, and crown height (H_c) of 7.55 m. This research reported a lower value than previous reports on morphometric measurements of decurrent trees (Karlinasari et al. 2023; Aini et al. 2024). The variation in results occurred because the D_{bh} was smaller than in previous research. Similarly, Hardjana (2013) stated that D_{bh} size affected crown diameter and tree height. The average values of morphometric characteristics of trees were in line with the criteria for decurrent trees according to Li et al. (2022).

LCR was calculated as the ratio of the length of the tree trunk covered by live crown (crown height) to the total tree height (Putra et al. 2023). The results showed that the average LCR value was 78.84% before and 65.27% after pruning. Based on the classification by Anderson & Belange (1987), the value obtained was assigned to the good category because it exceeded 40%, which could be used to estimate the photosynthetic capacity of trees. Putra et al. (2023) reported that *LCR* indicated the number of active (living) leaves used for photosynthesis. Therefore, this value indicated tree crown health and vitality. Higher values indicated a faster growth process and stronger resilience, which contributed to improving health (Latifah et al. 2020).

Crown Density Conversion

Crown density values based on area (%) were converted to crown weight and volume (kg/m^3). The results are shown in Table 5.

In line with the results, crown density value based on the area (%) before pruning (column a) was categorized as good with more than 55% (Anderson & Belange 1987). After pruning (column b) was included in the moderate category, with percentages ranging from 25 to 50% (Pertiwi et al. 2020). As a growth indicator, a high crown density value indicated faster tree growth (Putra et al. 2023). Asriyanti et al. (2015) also reported that a crown with lush biomass (leaves, twigs, and branches) optimized photosynthesis and supported growth. According to Morin et al. (2015), crown density could be used as an indication of healthy plants. This suggested that trees with high density were considered healthier.

Crown density was expressed in units of weight per crown volume, according to Burger (1939) in Brüchert et al. (2000), as required for tree-structure analysis (Karlinasari et al. 2023; Aini et al. 2024). The value of crown density, as measured by the area-to-weight ratio and crown volume, could be equated using mathematical equations. The results showed that the average crown density conversion rate from area to weight and volume for decurrent trees was 0.06 (Table 3, column i). Furthermore, the conversion results showed that the average decurrent tree crown density, based on weight and volume, before and after pruning was 3.36 kg/m^3 (Table 3, column j) and 2.54 kg/m^3 (Table 3, column k), respectively. The values were greater than the calculation results for the weight and volume of excurrent trees reported by Burger (1939) in Brüchert et al. (2000) which amounted to 1.9 kg/m^3. The higher density in decurrent trees was attributable to their wider crown diameters. This was consistent with Putra et al. (2023), who reported a positive correlation between crown diameter and

Table 5. Crown characteristics

No.	Tree ID	ρ_{ocd}* (%)	ρ'_{cd}* (%)	$\Delta\rho_{cd}$* (%)	W_c (kg)	V_{co} (m^3)	V_{c1} (m^3)	ΔV_c (m^3)	ρ_{ob}** (kg/m^3)	Conversion Rate	ρ_{co}*** (kg/m^3)	$\rho_{c'}$*** (kg/m^3)
		a	b	c (a-b)	d	e	f	g (e-f)	h (d/g)	i (h/c)	j (a×i)	k (b×i)
1	SR01	15	10	5	86.68	561.88	305.78	256.10	0.34	0.07	1.02	0.68
2	SR02	95	90	5	31.42	917.60	767.57	150.04	0.21	0.04	3.98	3.77
3	SR03	35	25	10	117.78	740.09	610.77	129.32	0.91	0.09	3.19	2.28
4	SR04	45	35	10	25.96	343.04	307.95	35.10	0.74	0.07	3.33	2.59
5	SR05	35	25	10	78.32	1240.54	976.87	263.66	0.30	0.03	1.04	0.74
6	SR06	65	55	10	23.96	115.90	82.03	33.86	0.71	0.07	4.60	3.89
7	SR07	55	45	10	51.86	488.57	414.40	74.16	0.70	0.07	3.85	3.15
8	SR08	55	40	15	116.38	831.51	606.76	224.75	0.52	0.03	1.90	1.38
9	SR09	45	30	15	77.39	404.90	296.52	108.38	0.71	0.05	2.14	1.43
10	SR10	55	40	15	93.12	449.34	345.53	103.81	0.90	0.06	3.29	2.39
11	SR11	75	60	15	39.52	247.68	188.63	59.05	0.67	0.04	3.35	2.68
12	SR12	85	60	25	15.36	113.79	75.90	37.89	0.41	0.02	1.38	0.97
13	SR13	95	70	25	14.96	21.98	14.07	7.91	1.89	0.08	7.19	5.30
14	SR14	85	60	25	20.32	30.85	19.80	11.05	1.84	0.07	6.26	4.42
15	SR15	95	60	35	17.26	27.71	15.66	12.05	1.43	0.04	3.89	2.46
Avg		62.33	47.00	15.33	54.02	435.69	335.22	100.47	0.82	0.06	3.36	2.54
St. Dev		25.20	20.68	8.55	37.43	368.45	294.64	88.27	0.52	0.02	1.77	1.38

Remarks: * = Crown density value based on card density table (area); ** = Crown density value based on observation (crown weight and volume); *** = Crown density value based on conversion rate (crown weight and volume). Column c is the result of subtracting columns a and b, column g is the result of subtracting columns e and f, column h is the result of dividing columns d and g, column i is the result of dividing columns h and c, column j is the result of multiplying columns a and i, and column k is the result of multiplying columns b and I.

density. Crown weight and volume were identified as important tree characteristics due to their strong relationships with forest biomass production and ecosystem functions, such as carbon sequestration and air pollution reduction (Zhu et al. 2021). Moreover, volume could serve as a surrogate variable to estimate leaf area, biomass, transpiration, and fine-particle filtration (Pretzsch et al. 2015).

Safety Factor

Engineering science traditionally evaluates mechanical reliability by calculating the safety factor as the ratio of load-bearing capacity to the actual load of a structure. In tree biomechanics, the safety factor is determined objectively to assess the mechanical load on a tree (Niklas 2002; Helmanto et al. 2022). It is also defined as the ratio of allowable stress to actual stress, serving as a dimensionless parameter. Beyond stress-based calculations, the safety factor may be determined by comparing distances or heights, provided the numerator and denominator share the same units (Niklas 2002; Kadry et al. 2019). Regardless of the specific quantities or units employed, the safety factor typically indicates the probability of mechanical failure in a structure (Niklas 2002). Therefore, trees, as structural entities, should maintain a safety factor greater than one due to potential exposure to unpredictable events such as rain, wind, storms, and mechanical fatigue. The safety factor should be calculated separately for each organ, including the crown, trunk, and roots (Niklas 2002). In this research, the safety factor was calculated based on the stresses acting on trees and categorized in Table 3. The results for decurrent trees are presented in Tables 6 and 7, corresponding to allowable stress and critical height calculations, respectively.

Due to differences in the safety factors of the two methods, the results varied. However, both methods indicated that pruning activities increased the safety factor of trees. The analysis results based on allowable stress (Table 6) showed that, before pruning, the average safety factor was 35.21 and increased to 82.10 after pruning. When calculated using the critical height (Table 7), the safety factor increased from 1.36 before to 1.44 after pruning. According to the categorization presented in Table 3, 13 trees were classified as safe and two as very safe before pruning. Following pruning, 11 trees were categorized as safe and four as very safe. These changes occurred in SR14 and SR15, indicating that pruning affected the safety factor value. Based on the categorization, a comparative factor was required to equalize the two safety calculation methods.

Safety factor is generally related to the imbalance

Table 6. Tree condition based on the safety factor through allowable stresses

No.	Tree ID	Decurrent (n=15)			
		Before Pruning	After Pruning	Different	Percentage* (%)
1	SR01	309.49	824.53	515.04	73.4
2	SR02	5.95	7.74	1.79	0.25
3	SR03	0.02	0.04	0.02	0.00
4	SR04	0.01	0.01	0.00	0.00
5	SR05	129.64	229.05	99.41	14.14
6	SR06	10.60	17.89	7.29	1.04
7	SR07	0.06	0.08	0.03	0.00
8	SR08	0.01	0.02	0.01	0.00
9	SR09	65.49	136.17	70.68	10.05
10	SR10	0.05	0.10	0.05	0.01
11	SR11	0.02	0.04	0.02	0.00
12	SR12	0.04	0.08	0.05	0.01
13	SR13	3.13	6.92	3.80	0.54
14	SR14	3.66	8.64	4.98	0.71
15	SR15	0.05	0.15	0.10	0.01
Sum		62.33	528.22	1231.48	703.25
Avg		62.33	35.21	82.10	46.88
St. Dev		25.20	83.86	215.51	132.90

Remarks: * = The percentage value of the safety factor is obtained by dividing the difference value by the total difference value and then multiplying by 100.

Table 7. Tree condition based on the safety factor through critical height

No.	Tree ID	Safety factor (SF)				Tree condition**	
		Before Pruning	After Pruning	Different	Percentage* (%)	Before Pruning	After Pruning
1	SR01	1.69	1.76	0.07	5.58	Very safe	Very safe
2	SR02	1.28	1.29	0.01	1.19	Safe	Safe
3	SR03	1.16	1.25	0.09	7.48	Safe	Safe
4	SR04	1.39	1.47	0.08	6.78	Safe	Safe
5	SR05	1.17	1.21	0.04	3.55	Safe	Safe
6	SR06	1.04	1.08	0.04	3.40	Safe	Safe
7	SR07	1.14	1.18	0.04	3.47	Safe	Safe
8	SR08	1.42	1.51	0.09	7.56	Safe	Safe
9	SR09	1.27	1.35	0.08	6.43	Safe	Safe
10	SR10	1.33	1.42	0.08	6.76	Safe	Safe
11	SR11	1.21	1.26	0.05	4.52	Safe	Safe
12	SR12	1.31	1.41	0.09	7.70	Safe	Safe
13	SR13	1.85	1.99	0.14	11.39	Very safe	Very safe
14	SR14	1.61	1.74	0.12	10.19	Safe	Very safe
15	SR15	1.53	1.70	0.17	14.01	Safe	Very safe
Sum		20.41	21.62	1.21	100.00	-	-
Avg		1.36	1.44	0.08	6.67	-	-
St. Dev		0.23	0.25	0.04	3.35	-	-

Remarks: * = The percentage value of the safety factor is obtained from the division between the difference value and the total difference value, then multiplied by 100; ** = Tree condition is determined based on the safety factor value developed based on critical height (Karlinasari et al. 2023; Aini et al. 2024).

between trunk and crown dimensions. Dahle et al. (2017) stated that tree safety increased alongside trunk size, while stability improved with smaller crown diameter (Mușat & Ciubotaru 2015). This condition was demonstrated by changes in tree safety factor values resulting from pruning. The data obtained showed that tree pruning activities could increase the safety factor by 6.67% based on calculations using allowable stress and critical height. Ciftci et al. (2013) identified pruning as an effective method to increase stability by reducing the mechanical load of the crown. These results showed that tree morphometry strongly influenced tree safety (stability), although pruning must account for *LCR* to avoid excessive reduction in crown size. The crown functioned as the "engine" of tree growth and development (Pretzsch et al. 2015; Zhu et al. 2021), underscoring the need to maintain adequate size to optimize photosynthesis.

Conclusion

This research shows that using card density and analyzing the physical characteristics of the crown can be used to estimate crown density from weight and volume by applying a conversion rate. The average crown density is converted from area to weight and volume at a rate of 0.06, which improves tree structural stability calculations. The results show that the safety factor value after pruning increases by 6.67% compared to before pruning. This indicates that changes in tree morphometric conditions due to pruning activities are useful for crown shape (aesthetics), reducing hazards (safety), and increasing the safety value (stability) of trees.

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