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Stem Longitudinal Gradient for Basic Density, Carbon, Nitrogen, and CN Ratio in *Khaya* spp.: Improved Correlation Using Diameter Instead of Commercial Height

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Abstract: The basic wood density influences the carbon stock, playing a crucial role in climate-changing global mitigation through carbon sequestration. Understanding wood carbon release depends on the Nitrogen assessment and CN ratio. Therefore, our research aimed to: (i) Compare basic density, organic carbon, nitrogen, and C/N ratio among the *Khaya grandifoliola*, *K. ivorensis*, and *K. senegalensis*; (2) Analyze the gradient along positions and diameter of the commercial stem; (3) Recommend the most representative sampling position for each species based on the diameter. The experimental area is located in Southeastern Brazil. Twelve average-diameter trees per species were cut down, and wood disc samples were collected at 0, 25, 50, 75, and 100% commercial height. Our results show statistical differences in wood basic density among the species, and *K. senegalensis* has the highest basic density, 592 kg m^3. There was no statistical difference in organic carbon between species and along the stem. Stem diameter instead of commercial height improved the variable studied, confirming the research hypothesis. Sampling at 17% of the commercial height, ranging to 18–22 cm stem diameters, is recommended for greater representativeness.

Keywords: properties of wood; *Khaya senegalensis*; *Khaya ivorensis*; *Khaya grandifoliola*; carbon sequestration; nitrogen

1. Introduction

African mahogany wood, belonging to the genus *Khaya* spp. Of the Meliaceae family, is internationally known for its high commercial value [1]. It stands out for its superior phenotypic properties, such as straight stems and rapid growth, which are important commercially [2–4]. The basic density of its wood allows for mechanical resistance and dimensional stability, and it is used for fine woodworking, shipbuilding, and the production of musical instruments and decorative items [5–7].

The *Khaya* spp. Reforestation contributes to mitigating climate change by storing carbon in its biomass during growth and transforming the soil into a carbon pool by decomposing roots and aboveground biomass. Additionally, wood products act as long-term carbon sinks. Nitrogen is required in large amounts for forest growth, and the decomposition rate is inversely related to its CN ratio. Understanding biogeochemical cycles and plant adaptation mechanisms to different environmental conditions depends on nitrogen assessment. Based on the Kyoto Protocol and the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, the quantification of carbon credits in reforestation projects considers the balance between carbon storage in biomass and the release of carbon through wood decomposition litter, among others [8,9].

Often, scientific papers use generalized carbon concentration in wood, resulting in imprecise estimates due to age, geographical location, species, or variations along the stem [9–11]. In the methodology for estimating carbon in forest biomass, the recommendation is to use a conversion value of 47% carbon for biomass. However, negligence factors such as planting spacing, forest management practices, soil chemical and physical properties, genetic improvement, stand maturity, climate, and topography interact to varying degrees with these variables [12–17].

Given forests' critical role in mitigating climate change, identifying patterns in wood basic density is essential for assessing forest stands. Furthermore, accurate carbon stock estimates are based on wood's basic density due to its direct relationship with biomass [9,18]. Therefore, wood density integrates the effects of these factors, making it a crucial parameter for biomass estimation based on volumes obtained from forest inventory data [12,19,20].

In addition to the factors mentioned, the basic wood density varies substantially along the stem. Among the trends in the base-top variability of wood density, there is a decrease in density from the base of the stem to half the total height, followed by an increase to the top of the tree [16,21]. However, only some studies have evaluated populations of *Khaya* spp. Outside of their original geography. Furthermore, much data on basic density and organic carbon originate from native forests, making it impractical to use them for estimates in commercial plantations.

In this context, this research aims to (1) compare basic density, organic carbon, nitrogen, and CN ratio among the *Khaya grandifoliola*, *Khaya ivorensis*, and *Khaya senegalensis* species; (2) analyze the gradient along five positions of the commercial stem; and (3) recommend the most representative sampling position for each species based on diameter.

2. Materials and Methods

2.1. Study Area

The present study was conducted in an experimental area at the Reserva Natural Vale in the municipality of Sooretama—ES, Brazil, at the geographic coordinates of 19°09′01.2″ S and 40°04′48.7″ W. The region's topography is predominantly flat, with slopes ranging from 0% to 3%.

According to the Köppen classification, the climate is classified as Aw, characterized by a humid, warm tropical climate with a rainy season in summer and a dry season in winter [22]. The warmest months occur between December and March, with average temperatures exceeding 25 °C. The months with milder temperatures are from May to September, with averages between 20 and 23 °C (Figure 1). Data from [23] showed that the average annual rainfall was 906 mm, with the lowest levels recorded in the second and third quarters of the year. According to [24], considering the climate zones, *Khaya grandifoliola* and *Khaya senegalensis* are classified as having high climate suitability, while *Khaya ivorensis* has medium climate suitability.

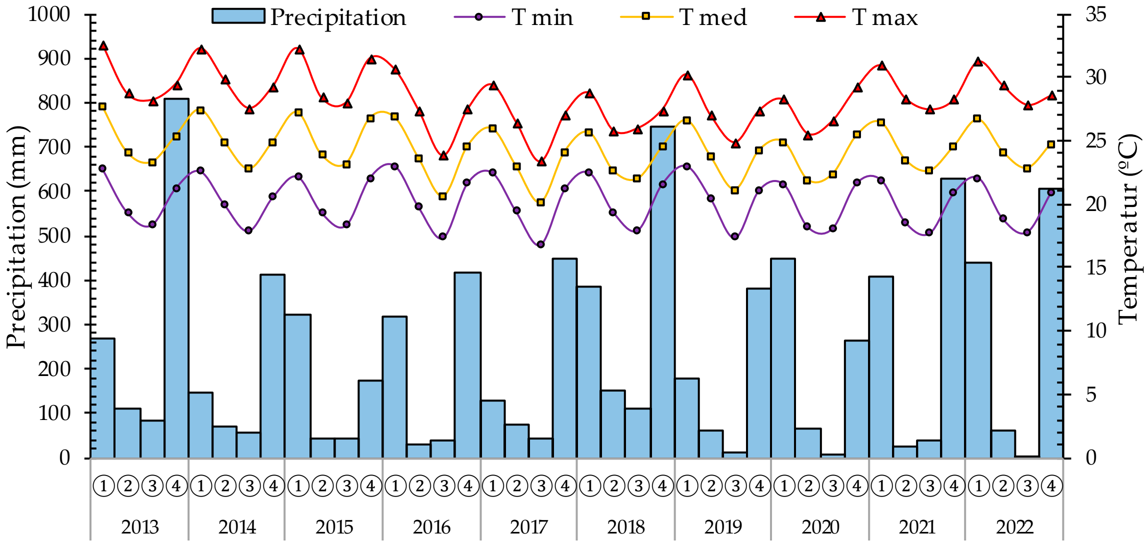

Figure 1. Meteorological variables during the study period for the experimental region. Precipitation; Tmin = minimum temperature; Tmed = median temperature; Tmax = maximum temperature. Source: data obtained from [18]. Where ①, ②, ③ and ④ refer to the year's quarters.

The soil is classified as the Yellow Dystrocohesive Argisol type, with moderate horizon A and textural horizon B [8]. Table 1 presents the chemical characteristics of the soil.

Table 1. Soil chemical attributes at 0–20 cm and 20–40 cm depths within the experimental area in Sooretama, ES.

Specie	Depth	pH	P	K	Ca	Mg	Al	H + Al	SB	CTC (T)	V	MO
	cm	H_2O	mg dcm^{-3}				cmolc dm^{-3}				%	g kg^{-1}
K. grandifoliola	0–20	5.91	2.33	26.00	1.66	0.51	0.00	2.19	2.25	4.44	50.57	24.4
	20–40	5.81	1.33	19.78	1.12	0.36	0.02	2.01	1.54	3.55	43.12	19.3
K. ivorensis	0–20	5.76	2.33	23.67	1.33	0.43	0.00	2.22	1.84	4.06	45.17	22.4
	20–40	5.74	1.33	16.78	1.02	0.30	0.01	1.91	1.37	3.28	41.44	16.7
K. senegalensis	0–20	6.07	2.67	26.11	2.29	0.60	0.00	1.73	2.97	4.71	62.15	26.1
	20–40	6.00	1.44	19.00	1.40	0.42	0.00	1.67	1.88	3.55	52.48	18.6

Where pH in water, sum of bases (SB), cation exchange capacity (CEC) phosphorus (P), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), aluminum (Al^{3+}), hydrogen + aluminum (H + Al). Determination of pH in aqueous solution 1:2.5; potassium and sodium using the Mehlich-1 extractant; H + Al using the SMP pH method; organic matter by oxidation with $Na_2Cr_2O_7 \cdot 2H_2O + H_2SO_4$ 10 mol L^{-1} and calcium, magnesium, and aluminum using a KCl^{-1} mol L^{-1} extractant. Source: [8].

2.2. Stand Characterization and Experimental Design

Khaya species were planted in 2013 by manually digging pits with dimensions of 30 cm × 30 cm × 30 cm. The seedlings received base fertilizer with 150 g of yoorin thermophosphate and 15 g of FTE BR 12. The seedlings were sourced from different regions in Brazil and represented three species: *K. grandifoliola* (Belém, Pará state), *K. ivorensis* (Sooretama, Espírito Santo state), and *K. senegalensis* (Poranguatu, Goiás state) [25]. The plantation uses a monoculture system. Each species was planted in three randomized blocks with 3 plots of 1250 m^2, spaced 5 m × 5 m apart. The effective study area in each plot was 750 m^2 (15 m × 50 m), surrounded by a simple border, resulting in 30 primary trees per replication.

2.3. Biomass Quantification

The forest inventory was conducted at 9.5 years of age, and diameter at breast height (DBH), total height (Ht), and commercial height (Hm) were measured using a diameter tape and a Vertex hypsometer. The Hm was measured up to the first branch bifurcation. The average DBH was 21.3, 22.6, and 21.7 cm for *K. grandifoliola*, *Khaya ivorensis*, and

K. senegalensis, respectively (Figure 2). The total heights (Ht) and commercial heights (Hm) were 14.3, 14.1, and 11.1 m, and the average commercial heights (Hm) were 5.7 and 5.9 m for *Khaya grandifoliola* and *Khaya ivorensis*. *Khaya senegalensis* had the lowest total and commercial heights, 11.1 and 4.9 m, respectively.

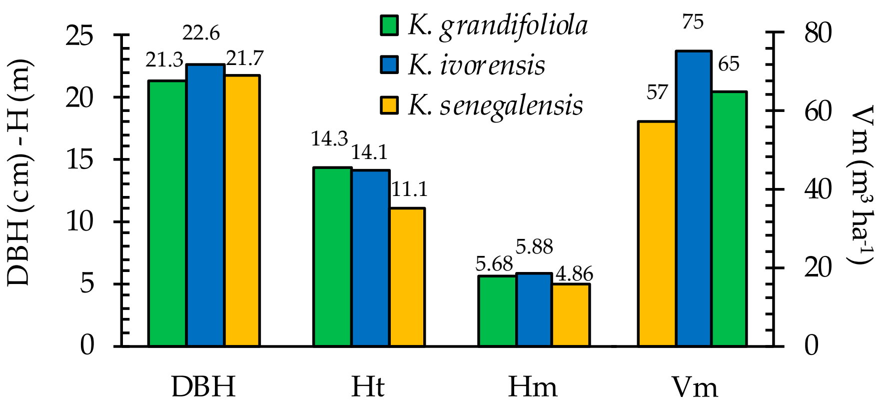

Figure 2. Average values of the dendrometric parameters of *Khaya grandifoliola*, *Khaya ivorensis*, and *Khaya senegalensis* at 9.5 years old. Where—Diameter at breast height (DBH); Total height (Ht); Merchantable height (H_m); Merchantable volume per hectare (V_m).

The merchantable height was defined as the distance from the trunk's base to the canopy's first branch or the point at which the wood remained straight and commercially viable. Each trunk was divided into five equal sections, and a disc approximately 3 cm thick was extracted at 0%, 25%, 50%, 75%, and 100% of the merchantable height.

All samples were weighed in the field using a precision scale to measure the wet weight. They were then packed in paper bags and dried in the laboratory in an air circulation oven at 105 °C until they reached a constant weight. After determining the dry weight, the moisture percentage was calculated using the formula below. The biomass of each tree was determined indirectly based on the moisture percentage of the samples of each component.

$$Mo\ (\%) = \frac{Mw\ - Dw}{Dw}\ \times\ 100 \quad (1)$$

where:

Mo = moisture (%);
Mw = moist weight (grams);
Dw = dry weight (grams).

2.4. Determination of Basic Density, Organic Carbon, Nitrogen, and C/N Ratio

The Brazilian Regulatory Standard determined the basic wood density—NBR 11941 [26]; which consisted of the relationship between the dry mass of the wood and its saturated volume. For the test, two opposite wedges obtained from the discs at 0, 25, 50, 75, and 100% of the merchantable height in twelve trees of each species were used.

Organic carbon concentration was determined through potassium dichromate oxidation $K_2Cr_2O_7$. Nitrogen was extracted via sulfuric acid digestion followed by titrimetric determination [27].

2.5. Statistical Analyses

The data were subjected to normality and homoscedasticity assumptions, followed by variance analysis (ANOVA). Tukey's test ($p < 0.05$) was employed to analyze the variation in basic density, carbon, nitrogen, and the CN ratio in the *Khaya grandifoliola*, *Khaya ivorensis*, and *Khaya senegalensis* species and longitudinal position on the stem (0, 25, 50, 75, 100%). Subsequently, Pearson's analysis was performed to identify correlations between the variables DBH (diameter at breast height), Ht (total height), Hm (merchantable height), Sd (stem diameter), Bd (basic density), C (carbon), N (nitrogen), CN (carbon-nitrogen ratio), Sp (relative position on the stem), and soil chemical attributes.

Given the highest correlation between stem diameter (Sd) and the variables Bd, C, N, and CN, a second-degree polynomial regression analysis was conducted for each species to define the diameter of the stem in (cm) ± standard deviation that represents the mean of each variable. In the regression analysis of each species, the sample diameters were ordered into seven classes (regression points), according to Sturges' formula.

$$K = 1 + 3.3 \times \log N$$

where: K = number of classes per species (regression points); log = logarithm; N = number of samples per species (diameters).

Additionally, a principal component analysis (PCA) was performed [28] to relate the variables according to common factors, reducing the dimensionality of the data and ordering them in a single graph based on similarities and contrasts between the variables. The data were normalized using Z-score statistics in R software, followed by PCA using the "FactoMineR" package [29] and "FactoExtra" [30]. The selection of principal components followed the criterion of including eigenvalues > 1 [31].

3. Results

3.1. Basic Density

There was a statistically significant difference in the basic wood density among the forest species. The highest basic density was observed for *Khaya senegalensis*, with an average value of 592 kg m^3, 15.6% and 30.7% higher than *Khaya grandifoliola* and *Khaya ivorensis*. In turn, the basic density of *Khaya grandifoliola* wood was 13.0% higher than *Khaya ivorensis*, differing according to the Tukey test ($p < 0.05$) (Figure 3B).

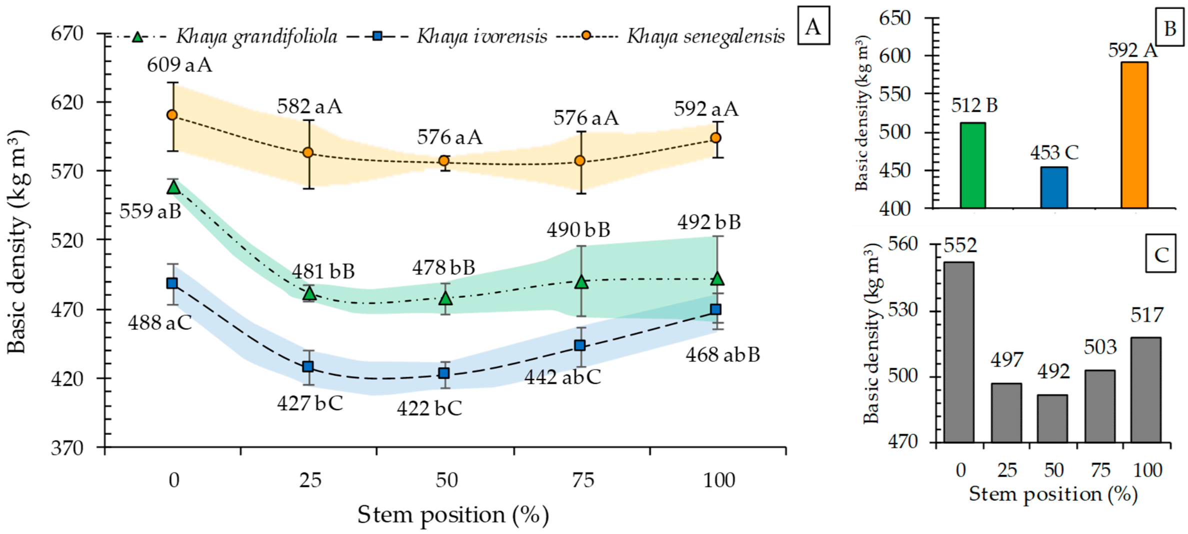

Figure 3. Basic density (kg m^3) in *Khaya grandifoliola*, *Khaya ivorensis*, and *Khaya senegalensis* along different stem positions. Where: (**A**) = Basic wood density of each species along the stem; (**B**) = Average Basic wood density of the species; (**C**) = Average basic wood density along the stem. Means followed by the same letter, lowercase between the positions along the stem and uppercase between species, do not differ at 5% significance using the Tukey test. Error bars denote the standard deviation.

As shown in Figure 3A, *Khaya senegalensis* has a density greater than 570 kg m^3 at all positions along the stem, differing statistically from the other species at all five evaluated positions. Between the species *Khaya grandifoliola* and *Khaya ivorensis*, there was a statistical difference at positions 0, 25, 50, and 75% of the commercial height, with no difference only at position 100% of the stem.

The highest basic wood density occurred at the 0% portion of the stem: 609 kg/m^3 for *Khaya senegalensis*, 559 kg m^3 for *Khaya grandifoliola*, and 488 kg m^3 for *Khaya ivorensis*. Conversely, the lowest basic density was observed at the 50% portion of the stem: 576 kg m^3 for *Khaya senegalensis*, 478 kg m^3 for *Khaya grandifoliola*, and 422 kg m^3 for *Khaya ivorensis*.

The basic wood density of *Khaya senegalensis* at the base of the commercial stem was 24.9% higher than that of Khaya ivorensis. This difference is more pronounced when comparing the stem's 25% and 50% positions, representing an increase in basic density of up to 36%.

The three forest species showed variations from the base to the top of the stem, with similar behavior between the positions. Basic density decreased from the base to the 50% position of the commercial height and then increased until the 100% height of the stem. The density gradient along the stem was significant for the *Khaya grandifoliola* and *Khaya ivorensis species*.

The most significant variations in basic density along the stem occurred for the species *Khaya grandifoliola* and *Khaya ivorensis*, with decreases of 14.5% and 13.5%, respectively, between the tree's 0% and 50% positions. This variation was subtle for *Khaya senegalensis* at only 5.5%. The average coefficient of variation for each species was 6.7%, 6.2%, and 2.4% for *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*, respectively.

As shown in Figure 3C, the average basic density among the species at each position was as follows: 0% > 100% > 75% > 25% > 50%, with values of 552, 517, 503, 497, and 492 kg m^3, respectively.

3.2. Organic Carbon

The African mahogany species exhibited similar levels of organic carbon (g kg^{-1}), as demonstrated by the absence of statistically significant differences identified by the Tukey test, with a significance level of $p \leq 0.05$, at different positions along the stem, as illustrated in Figure 4B. However, considering the relative positions of 0, 25, 50, and 75% of the stem, the species *Khaya ivorensis* showed a lower organic carbon concentration trend. At the same time, *Khaya grandifoliola* exhibited a trend towards higher values (Figure 4A).

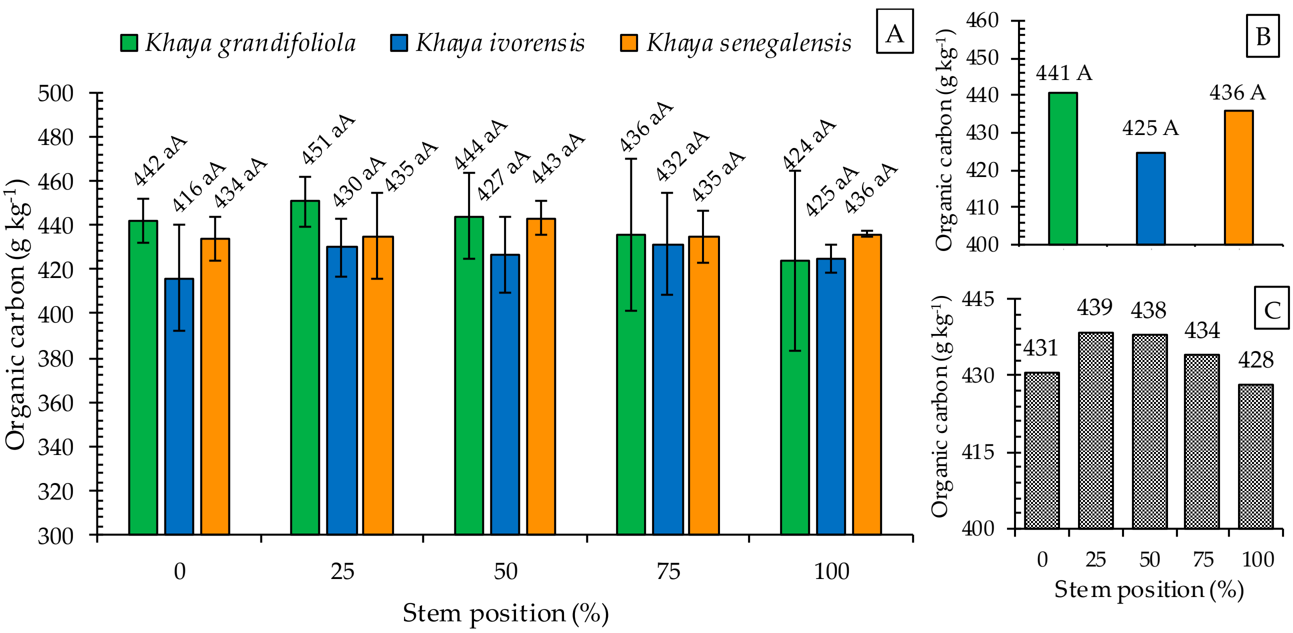

Figure 4. Organic carbon (g kg^{-1}) in *Khaya grandifoliola*, *Khaya ivorensis*, and *Khaya senegalensis* along different stem positions Where: (**A**) = Organic carbon of each species along the stem; (**B**) = Average organic carbon of the species; (**C**) = Average organic carbon along the stem. Means followed by the same letter, lowercase between the positions along the stem and uppercase between species, do not differ at 5% significance using the Tukey test. Error bars denote the standard deviation.

No influence of stem position on organic carbon values for the same species was observed for the base-to-top variability. The lowest value found was 416 g kg^{-1} for the species *Khaya ivorensis* at the base of the stem, and the highest value reported was 451 g kg^{-1} for *Khaya grandifoliola* at 25% of the stem. As shown in Figure 4C, the average organic carbon concentration for *Khaya* spp. Ranges from 428 to 439 g kg^{-1} between stem positions.

3.3. C/N Ratio

The highest averages for the CN ratio were observed at 25% of the stem height in all species, where a significant gradient was detected using the Tukey mean test at $p \leq 0.05$ for the species *Khaya grandifoliola* and *Khaya senegalensis* (Figure 5A). For all species, the lowest CN ratios were recorded at the 100% position. The variation was subtler for *Khaya ivorensis*, with no significant differences along the stem. There was a statistical difference between the species at all relative stem positions. *Khaya senegalensis* had the lowest C/N ratio at all positions, while at 0%, 75%, and 100%, *Khaya ivorensis* exhibited the highest values.

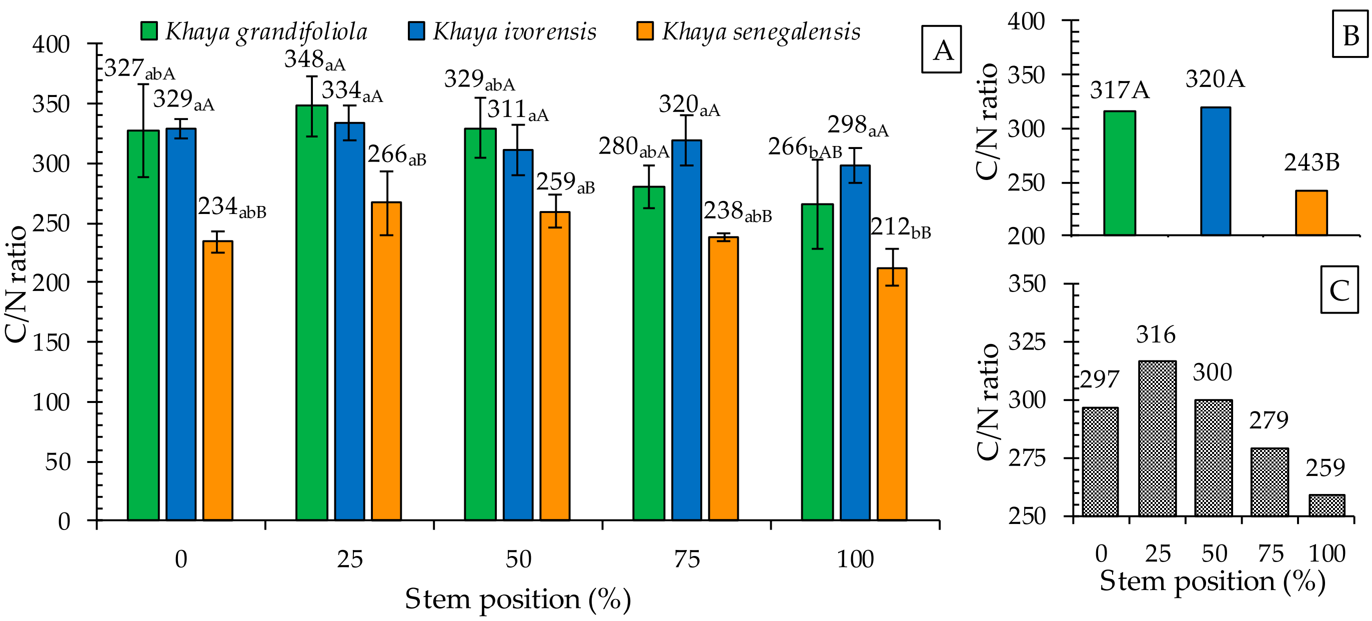

Figure 5. C/N ratio in *Khaya grandifoliola*, *Khaya ivorensis*, and *Khaya senegalensis* along different stem positions. Where: (**A**) = CN ratio of each species along the stem; (**B**) = Average CN ratio of the species; (**C**) = Average CN ratio along the stem. Means followed by the same letter, lowercase between the positions along the stem and uppercase between species, do not differ at 5% significance using the Tukey test. Error bars denote the standard deviation.

The highest average C/N ratio was observed for *Khaya ivorensis* and *Khaya grandifoliola*, with ratios of 320 and 317, respectively (Figure 5B). Both differed from *Khaya senegalensis* according to the Tukey test ($p < 0.05$). As shown in Figure 5C, the average C/N ratio among the species at each position was as follows: 25% > 50% > 0% > 75% > 100%, with values of 316, 300, 297, 279, and 259, respectively.

3.4. Nitrogen Concentration

The species *Khaya senegalensis* exhibited the highest nitrogen concentration at all stem positions, differing statistically via the Tukey test ($p < 0.05$) (Figure 6A). Additionally, there was a concentration gradient for this species along the stem, with increased levels observed at the stem ends, differing from the 0% and 25% positions. The average nitrogen concentrations among the species were 1.86, 1.46, and 1.36 g kg^{-1} for *Khaya senegalensis*, *Khaya grandifoliola*, and *Khaya ivorensis*, respectively (Figure 6B). The species *K. senegalensis* showed an increase of approximately 37% and 27% compared to *K. ivorensis* and *K. grandifoliola*.

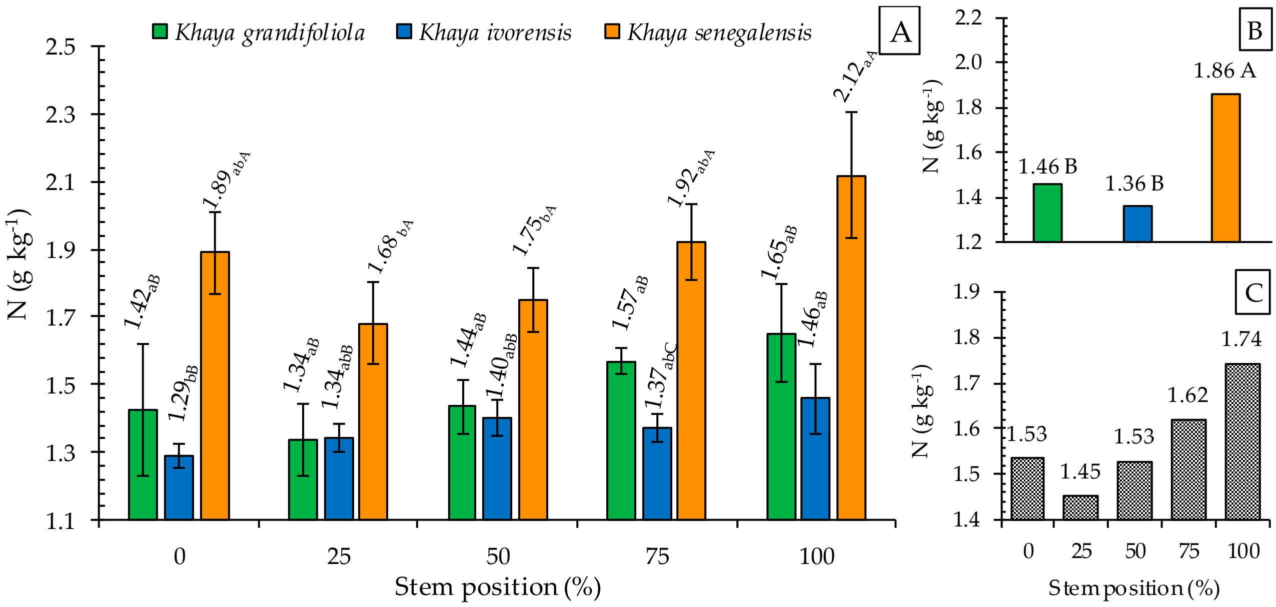

Figure 6. Nitrogen concentration in *Khaya grandifoliola*, *Khaya ivorensis*, and *Khaya senegalensis* along different stem positions. Where: (**A**) = Nitrogen concentration of each species along the stem; (**B**) = Average nitrogen concentration of the species; (**C**) = Average nitrogen concentration along the stem. Means followed by the same letter, lowercase between the positions along the stem and uppercase between species, do not differ at 5% significance using the Tukey test. Error bars denote the standard deviation.

According to the analysis of the nutritional gradient along the stem, differences in nitrogen from the base to the end of the commercial log were in the order of 16.2%, 13.2%, and 12.2% for *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*, respectively.

Overall, *Khaya ivorensis* exhibited the lowest nitrogen concentration at all evaluated positions. The nitrogen concentration pattern along the stem shows a substantial increase in nitrogen at 100% of the stem, with an average value of 1.74 g kg^{-1}. This position represented a 20% increase compared to the 25% position of the stem (Figure 6C).

3.5. Correlation Analysis

The stem's diameter and relative longitudinal position were significantly and inversely correlated, with values of −0.79 *, −0.95 **, and −0.86 * for *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*, respectively. The stem diameter and nitrogen were significantly correlated for all species: −0.93 **, −0.87 *, and −0.78 * for *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*, respectively. On the other hand, the correlation between the relative position in the stem and nitrogen was significant only for *K. grandifoliola* and *K. ivorensis*: 0.70 *, 0.82 * (Figure 7). The C/N ratio is explained by nitrogen (−0.96 ***, 0.93 **, and 0.99 ***) but not by carbon concentration due to the constancy of carbon levels along the stem. The basic wood density and nitrogen were inversely correlated for the three species, although not significantly (−0.66, −0.67, and −0.20).

Our analyses suggest that the stem diameter in the sampled region more accurately explains the parameters of basic density (BD), carbon (C), nitrogen (N), and C/N ratio when compared to the values of relative height in the stem (0%, 25%, 50%, 75%, and 100%). This better performance of the diameter can be explained by the crown architecture and morphology of the *Khaya* genus, which presents substantial variation in commercial height for individuals with the same diameter at breast height (DBH).

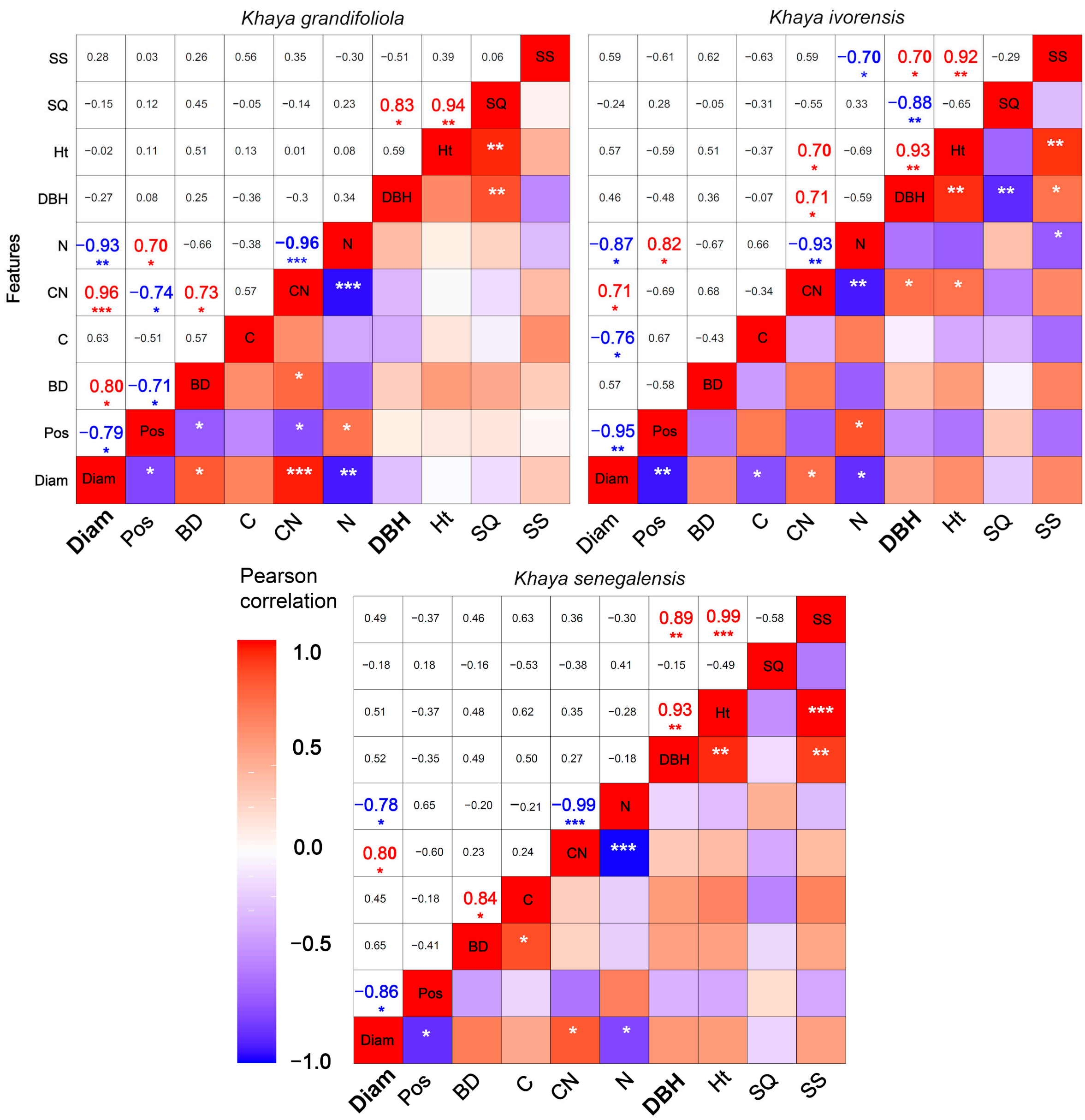

Figure 7. Pearson correlation between basic density (BD), carbon (C), C/N ratio (CN), nitrogen (N), and dendrometric measurements of felled trees: stem diameter (Diam), relative position (Pos), diameter at breast high (DBH), total high (Ht), stem quality (SQ), sanity status (SS), along the commercial stem in *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*. * Significant at the level of 0.05; ** Significant at the level of 0.01; *** Significant at the level of 0.001.

The marked heterogeneity in branch insertion height among trees with the same DBH can be observed in the descriptive analysis of the 36 felled trees. The coefficients of variation were 20.7%, 18.8%, and 32.9% for DBH, total height (Ht), and commercial height (Hc), respectively. The DBH/Ht ratio was 1.55 ± 21%, while the DBH/Hc ratio was 3.8 ± 32%. As can be seen, for the same sample group of 36 trees, the data dispersion was more significant when the Hc variable was present, indicating that the branching behavior of the genus generates wide variation in commercial height and, consequently, distortions in relative heights.

Although total or commercial height is widely used, it is worth noting that the *Eucalyptus* spp. And *Pinus* spp., which are conventional for the paper and wood industry, are employed in most studies. These genetic materials are improved to promote natural pruning and reduce crown biomass, resulting in homogeneity of commercial height. For the *Khaya* genus, as well as other species that have a substantial contribution of branches to biomass and whose commercial heights are strongly influenced by branch and crown height, it is recommended to use diameters (in cm) for estimating the parameters of basic density (BD), carbon (C), nitrogen (N), and C/N ratio instead of relative height.

3.6. Determination of Sampling Region

It was found that diameter is significantly more assertively correlated with basic density, carbon, nitrogen, and CN ratio. Therefore, regression analysis was conducted to determine the stem diameter representing the evaluated variables' average. The regressions were statistically significant for basic density in *K. grandifoliola*, carbon in *K. ivorensis*, nitrogen in all three species, and the CN ratio in *K. grandifoliola* and *K. senegalensis* (Figure 8).

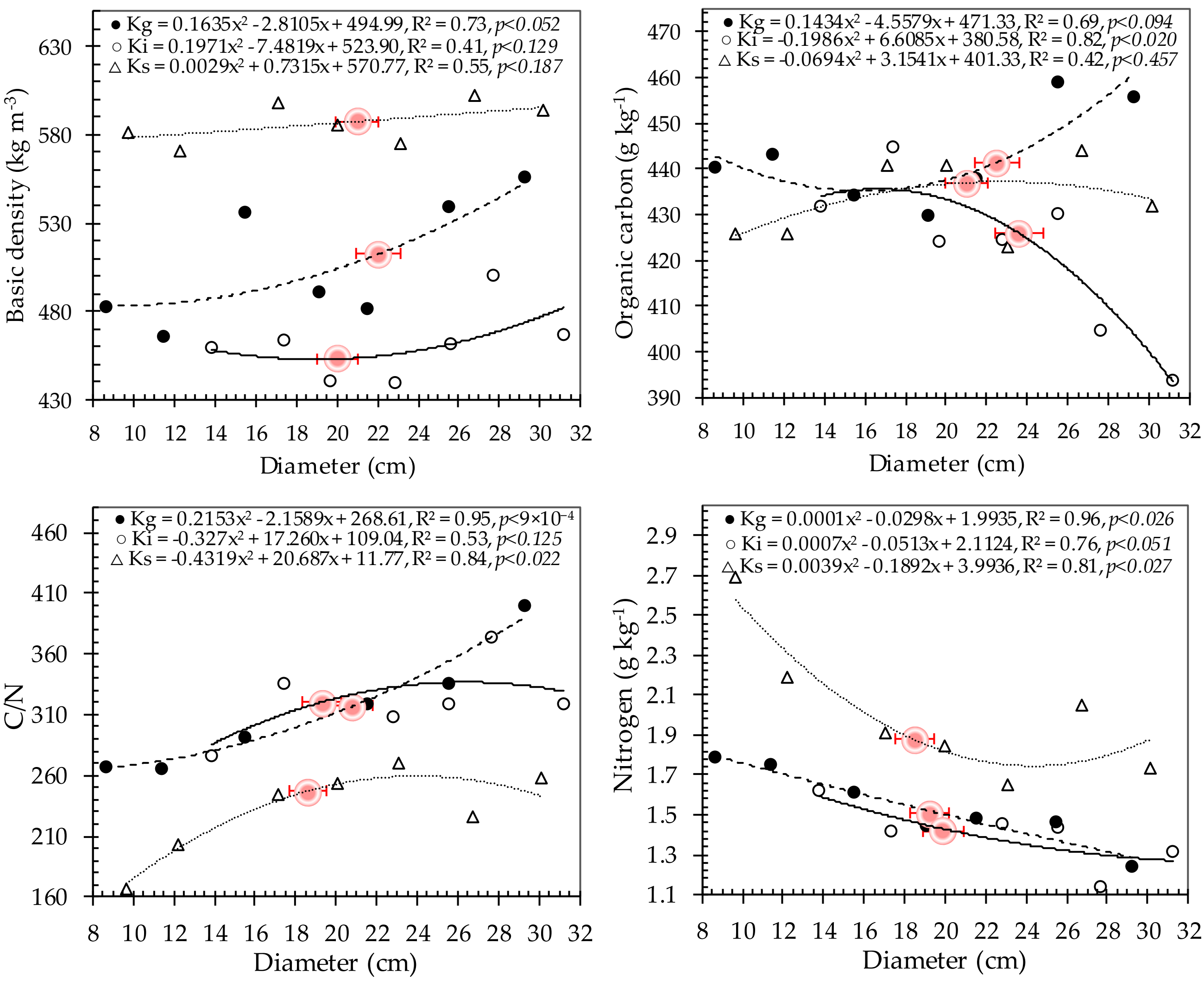

Figure 8. Regression analysis to determine the sample diameter in the commercial stem for the variables basic density, carbon, nitrogen, and CN ratio in *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis* stands. The markers and error bars (in red) in each regression analysis represent the diameter ± deviation (cm) to indicate the mean of each variable.

The average stem diameter for estimating the variables should be 21.23 ± 1.64 cm, 20.70 ± 1.95 cm, and 19.93 ± 2.53 cm for *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*, respectively. Analyzing the average for the *Khaya* genus, the diameter was 20.62 ± 1.96 cm. For the determination of basic density, carbon, nitrogen, and CN ratio, the average diameters were 21.67 ± 1.53 cm, 22.53 ± 1.36 cm, 19.03 ± 0.96 cm, and 19.23 ± 1.50 cm, respectively, according to the regression equations.

As observed in the mean tests and Pearson correlation, carbon was insignificant along the stem and among the species, reinforcing the modest, statistically insignificant linear coefficients. The regressions for nitrogen concentration concerning diameter for *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis* were well explained by a second-degree polynomial, with adjusted coefficients of determination of 0.96, 0.76, and 0.81, respectively.

The regression of basic density as a function of diameter was considered well-fitted for *K. grandifoliola* and *K. ivorensis*. The model was not significant for *K. senegalensis*, which could be attributed to the greater homogeneity of this variable along the stem for this species.

3.7. Principal Components Analysis

The PCA (Principal Component Analysis) formed three distinct groups, each corresponding to the species studied. The sum of components 1 and 2 explains 75.1% of the data variation, as shown in Figure 9. It is observed that basic density is associated with the species *K. senegalensis*, occupying the left side of the graph and belonging to component 2. This result is explained by the species exhibiting the highest basic densities at all evaluated positions. Additionally, according to the mean comparison test and the PCA, nitrogen concentrations were higher and aligned with *K. senegalensis* in PC2.

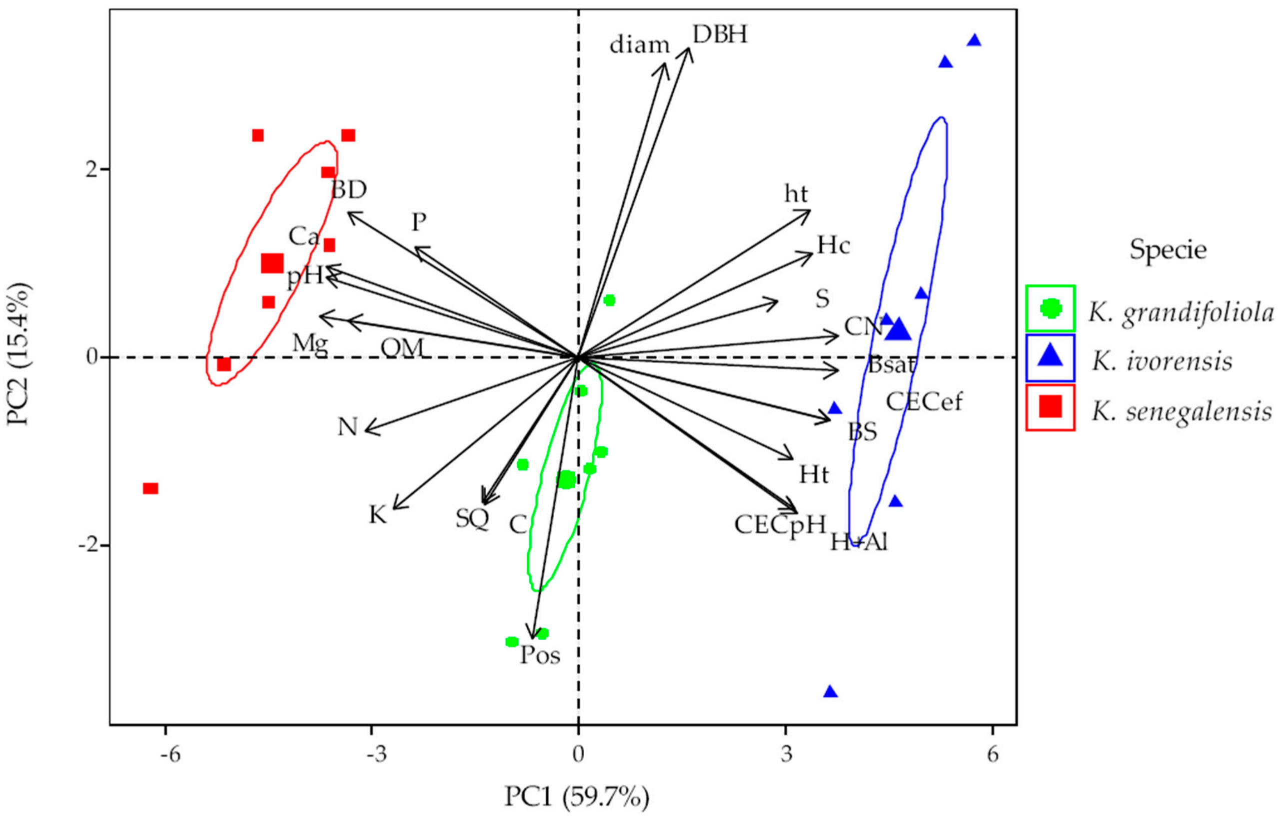

Figure 9. Relationship between principal component 1 (PC1) and principal component 2 (PC2) for parameters of the basic density, carbon, CN ratio, nitrogen, relative stem position, and stem diameter of *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis* stands. Where: BD = basic wood density, C = wood carbon, N = wood nitrogen, CN = carbon/nitrogen ratio, HS = tree health status, SQ = stem quality, DBH = stand diameter, diam = sampled tree diameter, Hc = commercial height of the trees, Ht = total height of the trees, pH = soil hydrogen potential, Pos = position at commercial height of the samples, K = soil potassium, Mg = soil magnesium, OM = soil organic matter, P = soil phosphorus, BS = soil base saturation, and Ca = soil calcium.

The species *K. grandifoliola* is associated with component 1, stem position, carbon concentration in wood, and stem quality. The C/N ratio was positively correlated with *K. ivorensis* and inversely correlated with the concentrations of C and N in the wood, as this metric is a function of the ratio between the two variables. Moreover, the PCA reinforces the mean tests presented in the previous sections, which indicated that *K. ivorensis* had the highest C/N ratio and the lowest concentrations of C and N compared to the other species. We can also infer that *K. ivorensis* generally shows the lowest values in basic density, positioning itself opposite to this variable.

The PCA analysis effectively summarized the differences between the species by forming three distinct groups categorized by species. The attributes of base sum, base saturation, and cation exchange capacity were plotted opposite to soil pH, reflecting the inverse correlation between these variables.

4. Discussion

4.1. Basic Density

Basic density is an essential parameter in evaluating wood quality, as it correlates with other wood properties directly impacting product quality [32,33]. Although it is a hereditary characteristic, its variation can also be influenced by tree age, growth rate, genotype, place of origin, and edaphoclimatic factors [34,35]. For *Khaya* species at 9.5 years of age, differences in basic density were observed. The wood of *K. ivorensis* was classified as low-density (<500 kg m^3), while *K. grandifoliola* and *K. senegalensis* were classified as medium-density wood (>500 kg m^3), according to the classification by [36].

This differentiation directly influences the final use of *Khaya* wood. Species with medium and high density are generally better suited for the solid wood sector, such as flooring and civil construction [37]. Therefore, since *Khaya* forests are planted with thinning planned throughout the rotation [38], young wood from *K. ivorensis* is recommended for uses that do not require high mechanical strength, such as furniture production, plywood, and surface finishing in civil construction [39]. Meanwhile, young wood from *K. grandifoliola* and *K. senegalensis* is more suitable when the pieces require greater mechanical strength.

It is observed that the values for the basic density of young *Khaya* wood are consistent with those in the literature for timber from plantations, ranging from 380 to 540 kg m^3 for *K. ivorensis* [40]; 460 to 590 kg m^3 for *K. grandifoliola* [41,42]; and 510 to 670 kg m^3 for *K. senegalensis* [39,40].

A study of *K. ivorensis* wood from planted and native forests in Ghana [43] found no statistical difference in basic density, with average values reported as 540 kg m^3 and 509 kg m^3, respectively. The authors also observed that the mechanical properties of *Khaya* trees grown in plantations were not inferior to those of natural trees and could be used for the same purposes. Thus, *Khaya* plantations can be recommended to ensure a sustainable species supply to the timber industry.

Basic wood density variability also occurs within the same tree, with the most significant variations observed along the stem from base to top [33]. This variation is primarily related to the anatomical structure of the wood and the tree's growth process. The literature reports various patterns of base-to-top variability in eucalyptus wood density [8,44]. Among these, a decrease in density of up to 50% by commercial height, followed by a further decrease towards the top, can occur [33], as observed in this study for *Khaya* species. [39], when evaluating 19-year-old adult trees of *K. ivorensis* and *K. grandifoliola*, we found this same density variability along the stem.

For 7-year-old young *K. ivorensis* trees, [45] also found a reduction in density from the base to the 50% commercial height position, followed by an increase up to the top of the tree, with minimum, average, and maximum densities of 350, 370, and 400 kg m^3, respectively. However, the average values found by the authors were lower than those in the present study, which is attributed to the age difference of the stands.

Generally, the more homogeneous the basic density within the stem, the better the wood performs in mechanical processing and drying operations. Thus, sawn wood pieces with less density variation, such as young *K. senegalensis* wood, are more suitable for applications requiring a denser and more uniform material regarding physical-mechanical properties [46].

Additionally, it is worth noting that the data presented on the base-to-top variability of the basic density of young *Khaya* wood are important for future research involving non-destructive evaluation studies similar to those currently conducted in Brazil for eucalyptus plantations. Non-destructive wood testing offers rapid data collection and evaluation of many samples [47].

4.2. Organic Carbon (OC)

The carbon tends to increase from the ends of the log towards the central region. This pattern is the opposite when analyzing the basic wood density, where values decrease from the ends to the central portion of the stem. Studying tropical tree species, Yeboah et al. [18] found the same pattern, with the base of the stem showing lower carbon concentrations and the central portion having the highest values. The authors reported carbon concentrations of 470, 475, and 471 g kg^{-1} for *K. ivorensis*, 12 years old, planted in the humid evergreen forest of Ghana.

In an integrated system in the Brazilian Amazon, [48] reported carbon concentration at the base of the stem for *K. grandifoliola* of 490 g kg^{-1}, which is 10.9% higher than in the present study. Although both stands are around 9 years old, the dendrometric averages were higher than in our study, likely due to the larger tree spacing. The average DBH of *K. grandifoliola* in the integrated system was 26.3 cm, and the total height was 18.4 m [49]. In contrast, in the present study, the values were only 21.3 cm and 14.3 m, respectively. Additionally, the more significant growth of the species may have increased the proportion of heartwood relative to sapwood, thereby raising carbon concentration [50].

Exceptionally, comparing carbon for *Khaya* spp. with other studies is challenging, and more surveys are needed for this genus. Consequently, most research defines the conversion factor for carbon as 50% of the dry biomass [51–53]. In a 21-year restoration area with native species in Minas Gerais, Brazil, [54] found that using a generic carbon concentration factor (0.5) to estimate carbon stock led to an exaggerated estimate for the species present.

According to [18], the conversion of 50% of wood biomass to carbon was not confirmed, as they observed an average of 476 g kg^{-1} among species, with no species reaching 500 g kg^{-1}. Even in 38 native species from the Mixed Ombrophilous Forest, the carbon in wood, bark, foliage, and live and dead branches was 41.8%, 40.0%, 42.3%, 40.6%, and 41.2%, respectively, not reaching either 50% or 47% [55]. Approximately 38.8% of studies adopt a conversion factor of 0.5 for carbon concentration relative to dry biomass, and another 33.3% of studies do not report the conversion used, according to a review on biomass and carbon stock in the Amazon [56].

For *Eucalyptus* spp., different genetic materials and planting spacing show slight variations in carbon, ranging from 44.87% to 44.99% [56]. According to the authors, only the carbon stock in Mg ha^{-1} varied among treatments, with the highest accumulation observed in denser plantings, i.e., determined by the amount of biomass produced. Other studies reinforce the slight variation in carbon concentration, such as the study with different clones of *E. urophylla* planted at various sites, where wood carbon ranged from 45.8% to 48.6% [57], between 47.1% and 48.2% [58], and between 48.6% and 49.9% in an *E. urophylla* x *E. globulus* hybrid, 10 years old, in southeastern Brazil [59].

Various factors considerably influence the carbon concentration of wood. These factors include species, maturity stage, and planting density [60,61]. Evaluating natural forests and short-rotation plantations, [60] concluded that the biomass component, followed by genotype and species, explains carbon variation in wood by approximately 52%, 23%, and 17%, respectively.

The increase in atmospheric nitrogen deposition directly affects carbon stock but not the concentration [62]. In this context, nitrogen-fixing leguminous species play a crucial role, as they can significantly increase carbon stock compared to others. This evidence can be seen in the study by [60], which assessed carbon in leaves, branches, bark, and wood of *Acacia mearnsii*, *Mimosa scabrella*, and *Eucalyptus grandis*. The first two nitrogen-fixing species had 51.2% and 49% of carbon in leaves, differing from *E. grandis* at 48.2%. Bark and branch compartments also differed between species; however, there was no statistical difference in wood.

4.3. Nitrogen

The definition of sampling points along the stem is crucial to ensure sample representativeness and reduce time and costs in execution [62]. Additionally, the tree stem exhibits tapering, where the upper portion, comprising 20% of the log's length, accounts for only 2–8% of the volume. In comparison, the section corresponding to the base of the log represents about 43% of the volume. The weighted average concentration (WAC) is a function of the product of a given element's concentration and the section's volume. In this sense, the terminal segment of the stem, with a higher nutritional concentration, should not carry the same weight as the basal section [62].

In our study, the WAC of N was 1.46, 1.36, and 1.86 g kg^{-1} for *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*, respectively. Similar to [62], the lower portion of the stem, at 10% of the total height, has lower nutritional concentration compared to the 90% height position. According to the author, in a 17-year-old planting of *Pinus taeda* in southern Brazil, the N concentration increased from 1.15 to 2.1 g kg^{-1}, representing an 82.6% increase. In a 5.5-year-old plantation of *Platanus* × *acerifolia* in southern Brazil, [63] found N of 1.45 and 2.83 g kg^{-1} at 10% and 90% of stem height, respectively, representing a 95.2% increase.

Analyzing *Populus* spp. at 4 years of age, [64] found significant differences in N at different stem positions. The base and top N concentrations were 3.16 and 5.85 g kg^{-1}, representing an 85% difference. In our study, the base-to-top difference was not as pronounced as in other studies, representing 16.2%, 13.2%, and 12.2% difference for *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*, respectively. Our results are partly explained by sampling only the merchantable wood, disregarding the canopy stem, where higher photosynthetic activity occurs due to branches and leaves.

The stem is the central vascular structure connecting roots to lateral organs such as branches and leaves [65]. It temporarily acts as a storage site for photoassimilates by translocating mobile nutrients like N, which occur from the leaves and reproductive structures to the stem region [66]. In this sense, a nutritional gradient substantially increases from the basal region of the stem to the crown insertion area. According to [67], the translocation rate of N from senescent leaves is 28.7%.

Unlike carbon, for nitrogen, in addition to the gradient observed along the stem, there is variation among species as reported by [59], who found 6.0, 2.4, 2.2, 1.6, and 0.9 g kg^{-1} for *Populus* spp., *Quercus robur*, *Betula pubescens*, *Eucalyptus globulus*, and *Eucalyptus nitens*, respectively. The magnitude of this variation was up to 567% higher for *Populus* spp. compared to *Eucalyptus nitens*.

4.4. C/N Ratio

Several factors govern the CN ratio in biomass, which varies according to edaphoclimatic conditions, species, and developmental stage. N concentration strongly influenced the CN ratio found in our study, as C remained invariant among species and along the stem. The averages were 317, 320, and 243 for *K. grandifoliola*, *K. ivorensis*, and *K. senegalensis*, respectively. While *K. senegalensis* had the highest N concentration and the lowest CN ratio, *K. ivorensis* had the lowest and highest CN ratio. This highlights that plant nutrition and physiology influence the dynamics of this ratio.

Forest harvest management and soil preparation methods also determine the CN ratio. In a study conducted in southern Sweden [67], observed that removing wood and stumps during forest harvest, followed by subsoiling to a depth of 50–60 cm, resulted in a substantial N reduction in the wood biomass of the subsequent rotation and an increase in the CN ratio, with values of 661 and 750 in stands of *Pinus sylvestris* L. and *Picea abies* (L.) Karst. In contrast, in the conventional harvest system, with only wood removal and soil preparation through scarification, the CN ratios were 588 and 581 in *Pinus sylvestris* L. and *Picea abies* (L.) Karst. Thus, there was a 12% and 29% increase in the CN ratio of wood with unconventional harvest and soil preparation management. The values reported by the authors are 99.5% higher than those in our study, even in the conventional management system, explained by differences in stand age, intrinsic species characteristics, and edaphoclimatic conditions [68].

5. Conclusions

Basic density exhibited significant variations along the stem, with the lowest density observed in the central portion, increasing towards the ends. Significant differences in basic density were also noted between species of the same genus.

Our analyses confirm that diameter was a better predictor than stem position. It is recommended to use diameter for the genus *Khaya* and consider this hypothesis for other tree species, especially those with pronounced heterogeneity in commercial height or lacking natural pruning.

The IPCCs proposal with a carbon concentration of 47% leads to overestimations in carbon stock and, consequently, inaccuracies in generating carbon credits.

The species differed in basic density, nitrogen, and CN ratio but not in carbon concentration.

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