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Allometric models for non-destructive estimation of leaflet area of umbu-cajazeira (*Spondias* sp.)

Modelos alométricos para estimativa não destrutiva da área de folíolos da umbu-cajazeira (*Spondias* sp.)

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ABSTRACT

The umbu-cajazeira (*Spondias* sp.) is a fruit tree native to the semi-arid of Brazil, with significant environmental and agro-socioeconomic potential for the region. Determining leaflet area (LA) is essential for understanding the interactions between plant growth, physiology, nutrition, and environment. Thus, this research aims to construct allometric equations that non-destructively estimate the umbu-cajazeira (*Spondias* sp.) leaflet area, considering the leaflet dimensions (length and width). The leaflets were collected from mother plants of umbu-cajazeira (*Spondias* sp.) and individually measured for length (L), width (W), and LA using digitized images. These data were submitted for descriptive and regression analysis. The LA was estimated using, linear power, and exponential regression models based on the L and W of the leaflets. The best model and equation were chosen based on the following selection criteria: coefficient of determination, Willmott agreement index, root mean square error, and mean absolute error. The power model using LW presented the best equation $\hat{y} = 0.76 * LW^{0.98}$ to estimate the leaflet area of umbu-cajazeira (*Spondias* sp.). This study provides a reliable, accurate, fast, and non-destructive approach for agronomic researchers and growers to determine the LA of the species.

Index terms: Non-destructive method; leaflet dimensions; mathematical model; allometric equations; Anacardiaceae.

RESUMO

A umbu-cajazeira (*Spondias* sp.) é uma frutífera nativa do semiárido brasileiro, com grande potencial ambiental e agrossocioeconômico para região. A determinação da área foliar (LA) é importante para compreensão das interações entre o crescimento, fisiologia, nutrição das plantas e o ambiente. Assim, o objetivo desta pesquisa é construir equações alométricas que estime de forma não destrutiva a área foliar umbu-cajazeira (*Spondias* sp.), considerando as dimensões dos folíolos (comprimento e largura). Os folíolos foram coletados de plantas matrizes de umbu-cajazeira (*Spondias* sp.), e medidos individualmente quanto ao comprimento (L), largura (W) e LA por meio de imagens digitalizadas. Estes dados foram submetidos à análise descritiva e de regressão. A LA foi estimada utilizando os modelos de regressão linear, potência e exponencial, baseados no L e W dos folíolos. O melhor modelo e equação foi escolhido com base nos critérios de seleção: coeficiente de determinação, índice de concordância de Willmott, raiz do erro quadrático médio e erro absoluto médio. O modelo potência utilizando LW apresentou a melhor equação $0.76 * LW^{0.98}$ para estimar a área dos folíolos de umbu-cajazeira (*Spondias* sp.). Este estudo fornece uma abordagem confiável, precisa, rápida e não destrutiva para pesquisadores e produtores do meio agronômico determinarem a LA da espécie.

Termos para indexação: Método não destrutivo; dimensões foliares; modelo matemático; equações alométricas; Anacardiaceae.

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Introduction

The umbu-cajazeira (*Spondias* sp.), belonging to the Anacardiaceae family, is considered a natural hybrid between the cajazeira (*Spondias mombim* L.) and the umbuzeiro (*Spondias tuberosa* Arruda) (Santos et al., 2023). It is a fruit tree native to the semi-arid of Brazil, with great environmental, agro-socioeconomic, and phytotherapeutic potential (Mendes et al., 2019; Santos et al., 2020; Santos et al., 2023). The species is widely known for its nutritious fruits marketed in natura, pulps, sweets, ice creams, and juices. It is essential for the diversification of fruit agribusiness in the semi-arid region.

The leaf is a vital plant organ, participating in photosynthetic processes reflecting plant growth, development, and productivity (Zhang et al., 2022; Vieira et al., 2022). Leaf area determination is a valuable parameter for agronomic research, such as growth analyses, ecophysiological, plant nutrition, plant protection, plant-soil-water ratio, and plant adaptations to the environment

(Das et al., 2022; Gonçalves, Ribeiro & Amorim, 2022; Boyaci & Küçükönder, 2022). Thus, accurate leaf area assessment is necessary in several studies to understand the interactions between plant growth and the environment (Sabouri et al., 2021).

Determining leaf area can be done by direct and indirect methods as well as destructive and non-destructive methods (Marshall, 1968). However, despite being more accurate and practical, direct and destructive methods make it challenging to make successive measurements of the same leaves throughout plant development (Gonçalves, Ribeiro & Amorim, 2022) since they extract the leaves from the plants. On the other hand, indirect and non-destructive methods can be applied, such as modelling, which involves a group of different statistical techniques that use regression models (Basak et al., 2019). This method is based on foliar measurements that can be obtained without destructive sampling techniques (Suárez, Casanoves & Di Rienzo, 2022) for the development of allometric models and equations and appears to be more reliable and feasible under limited conditions and budgets due to the need for a simple tool (Budiarto et al., 2021; Sousa et al., 2024). In this way, it emerges as a fundamental and easy-to-predict solution, offering a means to comprehensively understand continuous LA during phenological stages throughout the plant cycle (Rodriguez-Páez et al., 2023).

Allometric equations to estimate LA as a function of leaf length and width have been developed for several crops, e.g., in *Chrysanthemum morifolium* (Fanourakis, Kazakos & Nektarios, 2021), *Vitis vinifera* (Junges & Anzanello, 2021), *Salvia hispanica* L. (Goergen et al., 2021), *Citrus hystrix* (Budiarto et al., 2021), Apple cultivars (Boyaci & Küçükönder, 2022), *Phaseolus vulgaris* L. (Suárez, Casanoves & Di Rienzo, 2022), *Psidium guajava* L. (Gonçalves, Ribeiro & Amorim, 2022), *Musa* spp (Vieira et al., 2022), *Manilkara zapota* L. (Ribeiro et al., 2023a), *Coffea arabica* (Mielke et al., 2023), *Dendranthema grandiflora* (Silva et al., 2023), *Spondias tuberosa* Arruda (Amorim et al., 2024), sweet potato cultivars (Ribeiro et al., 2024) and *Euterpe oleracea* (Sousa et al., 2024). Therefore, we hypothesize that models constructed using leaflet length and width are the most reliable for the prediction leaf area of umbu-cajazeira. However, during the literature search, no studies were found on the species, suggesting that our study is a pioneer in estimating the leaflet area of umbu-cajazeira (*Spondias* sp.) and one of the few species of the genus *Spondias*. Thus, this research aims to construct allometric equations that non-destructively estimate the umbu-cajazeira (*Spondias* sp.) leaflet area, considering the leaflet dimensions (length and width).

Material and Methods

The study was carried out with leaflets of mother trees of umbu-cajazeira (*Spondias* sp.) from the Federal Rural University of the Semi-Arid (Mossoró campus) (5°12'19.8" S, 37°19'23.6" W) and from the Rafael Fernandes Farm of UFERSA in the municipality of Mossoró, Rio Grande do Norte, Brazil (5° 03' 39" S, 37° 24' 07" W). The climate of the region is BSh (dry and very hot) (Alvares et al., 2013), with an average annual rainfall of 555 mm and an average annual temperature of 27.8 °C (Climate-Data, 2024).

To perform the allometric measurements, healthy leaflets of a diversity of sizes and shapes and free of damage by diseases, pests, or environmental stresses were randomly collected. Four hundred sixty-four leaflets were collected and stored in plastic bags to prevent water loss through transpiration and then taken to the Fruit Growing Laboratory of UFERSA, Mossoró, RN.

The leaflets were scanned with a flatbed scanner (model Samsung Xpress SL-C480FW) at a resolution of 600 dpi. After obtaining the images, they were processed and analyzed using the ImageJ® software and transformed into black-and-white scales for the analysis of leaflet dimensions and area.

In each leaflet, the maximum length (L) (measured from the tip of the limb to the point of intersection between the leaflet and the petiole), maximum width (W) (measured from end to tip between the widest part of the blade precisely perpendicular to the central rib of the limb) (Figure 1), considered independent variables, and leaflet area (LA), were measured and considered as a dependent variable. Subsequently, the product of length by width (LW), product of length by length (LL), and product of width by width (WW) were calculated.

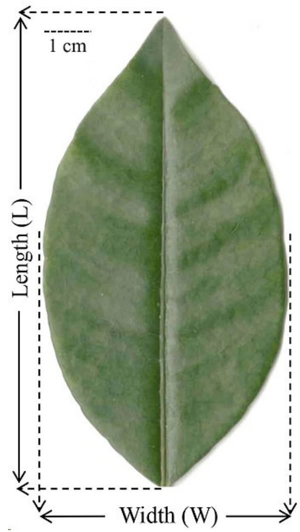

Figure 1: Leaflet of umbu-cajazeira (*Spondias* sp.) used to estimate leaflet area.

From the leaflet dimensions (L, W, LW, LL and WW) and leaflet area (LA), descriptive analyses were performed, determining the minimum, maximum, mean, amplitude, median, variance, standard deviation, standard error and coefficient of variation (CV). The allometric equations were constructed using simple linear regression, power regression and exponential regression models (Table 1).

Table 1: Models and descriptions of the models used to estimate the leaflet area of the umbu-cajazeira (*Spondias* sp.) through the linear dimensions of the leaflets.

Model	Description
Linear	$\hat{y} = \beta_0 + \beta_1 * x + \varepsilon_i$
Potência	$\hat{y} = \beta_0 * x^{\beta}{}_1 + \varepsilon_i$
Exponencial	$\hat{y} = \beta_0 * \beta_1{}^x + \varepsilon_i$

$\hat{y}$: Leaflet area; x: linear dimensions of leaflets; β_0, β_1: Model coefficients; ε_i: Random error.

The best model and equation were selected using the following criteria: highest coefficient of determination (R^2) (Equation 1), Willmott agreement index (d) (Equation 2), lowest root mean square error (RMSE) (Equation 3) and mean absolute error (MAE) (Equation 4).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{n}\left(y'_i\right)^2} \quad (1)$$

$$d = 1 - \frac{\sum_{i=1}^{n}\left(\hat{y}_i - y_i\right)^2}{\sum_{i=1}^{n}\left(|\hat{y}'_i| + |y'_i|\right)^2} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{y}_i - y_i\right)^2}{n}} \quad (3)$$

$$MAE = \frac{\sum_{i=1}^{n}|\hat{y}_i - y_i|}{n} \quad (4)$$

where: $\hat{y}_i$ = estimated values of leaflet area; y_i = values of the observed leaflet area; $\bar{y}_i$ = mean of the observed values; = $\hat{y}_i - \bar{y}$; $y'_i = y_i - \bar{y}$; n = number of observations; x_i e y_i observations of variables y and x; $\bar{y}$ and = mean of the variables y and x.

The data were submitted to descriptive and regression analysis to clarify relationships between leaflets area and the independent variables and to adjust the appropriate statistical model. The normality of the data was verified using the Shapiro-Wilk test (Shapiro & Wilk, 1965). The observed leaflet area and estimated leaflet area were compared using Student's t-test for paired samples ($p \leq 0.01$). The analyses were performed using the R software (R Core Team, 2024).

Results and Discussion

Leaf area is critical in assessing physiological, ecological, evolutionary, and anatomical traits affecting plant survival and growth. This study describes the application of modeling as a tool to allow accurate, practical, and easy non-destructive estimation of leaflet area. Notably, our study is the first to estimate the leaflet area of umbu-cajazeira (*Spondias* sp.) and one of the few carried out with species of the genus *Spondias*.

The descriptive analysis with the values of length (L), width (W), product of length by width (LW), product of length by length (LL), product of width by width (WW), and leaflet area (LA) are described in Table 2. The L of the leaflets ranged from 1.49 cm to 17.36 cm, with a mean of 6.69 cm and an amplitude of 15.87 cm. The minimum and maximum W were 0.94 cm and 8.29 cm, with a mean of 3.63 cm and a range of 7.33 cm (Table 2). Similar results of the mean values of L and W were obtained by Amorim et al. (2024) in *Spondias tuberosa* Arruda, who found values of 5.20 cm (L) and 3.25 cm (W).

The product of length by width (LW) ranged from 1.51 cm^2 to 133.76 cm^2, with a mean of 30.06 cm^2 and amplitude of 132.24 cm^2. The product's length by length (LL) values ranged from 2.22 to 301.61 cm^2, with a mean of 57.46 cm^2 and amplitude of 299.38 cm^2. The product of width by width (WW) ranged from 0.89 cm^2 to 68.75 cm^2, with a mean of 15.97 cm^2 and an amplitude of 67.85 cm^2. The leaflet area (LA) ranged from 1.10 cm^2 to 68.75 cm^2, with a mean of 15.97 cm^2 and an amplitude of 67.85 cm^2 (Table 2).

The lowest coefficient of variation (CV) was observed in L (53.12%) and W (46.12%), and the highest CV was found in LL (108.08%), LW (99.99%), LA (98.52%) and WW (92.66%) (Table 2). Our results indicate high variability in the data of the variables LL, LW, WW, and LA, possibly due to the different shapes and sizes of the leaflets, which is essential for the constitution of reliable and accurate models and equations, as it covers small, medium, and large leaves (Goergen et al., 2021). This ensures the representativeness of the conditions found in the field, in addition to the possibility of carrying out measurements in different leaflets from the beginning to the end of the plant life cycle (Junges & Anzanello, 2021; Ribeiro et al., 2023b).

Linear and nonlinear association patterns between the values of the independent and dependent variables were used to construct the regression models to estimate the LA (Figure 2). Linear patterns were observed between LW and LA, LL and LA, and WW and LA, while L and LA and W and LA indicate a nonlinear pattern (Figure 2). These results revealed the need to use linear and nonlinear patterns, suggesting that to estimate the leaflet area of the umbu-cajazeira (*Spondias* sp.), it is essential to use different regression models to adjust and validate the data (Ribeiro et al., 2023a).

The equations obtained are presented in Table 3, based on linear, power, and exponential regression models. The power model was the best model to estimate leaflet area according to the selection criteria, with the independent variable between the product of length and width (LW). This model presented the highest R^2 (0.9980) and d (0.9995), and lower RMSE (0.9250) and MAE (0.4922), thus being more precise and accurate.

Table 2: Descriptive analysis of length (W), width (L), product of length by width (LW), product of length by length (LL), product of width by width (WW) and leaflet area (LA) of umbu-cajazeira (*Spondias* sp.).

Descriptive statistic	L	W	LW	LL	WW	LA
Minimum	1.493	0.948	1.5184	2.229	0.8987	1.107
Maximum	17.367	8.292	133.7606	301.6127	68.7573	92.238
Amplitude	15.874	7.344	132.2423	299.3836	67.8586	91.131
Median	5.6445	3.3005	19.4033	31.8604	10.8933	13.8185
Mean	6.6963	3.6304	30.0632	57.4654	15.9771	21.1385
Variance	12.6519	2.803	903.6045	3857.549	219.1841	433.7355
Standard deviation	3.557	1.6742	30.06	62.1092	14.8049	20.8263
Standard error	0.1651	0.0777	1.3955	2.8833	0.6873	0.9668
Coefficient of variation	53.12%	46.12%	99.99%	108.08%	92.66%	98.52%

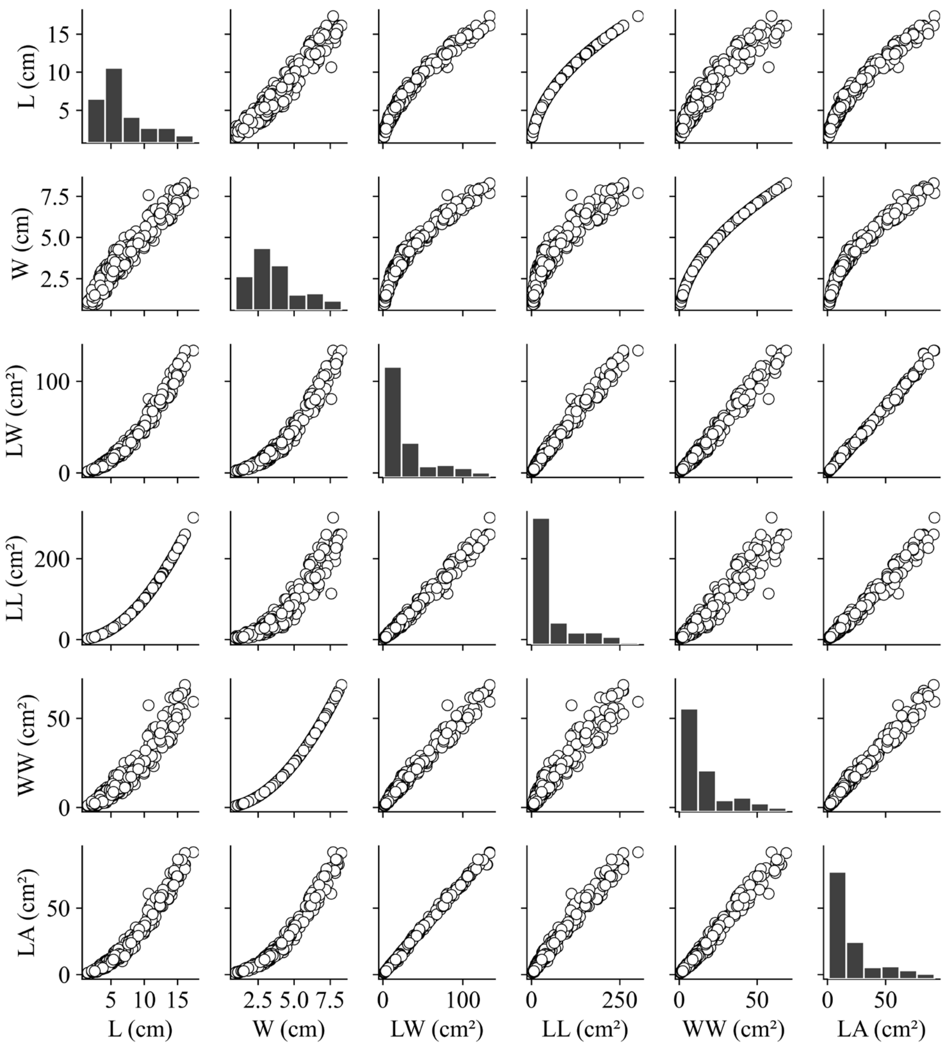

Figure 2: Histogram of frequency (diagonal) and dispersion of data between length (L), width (W), product of length and width (LW), product of length between length (LL), product of width and width (WW), and leaflet area (LA) of umbu-cajazeira (*Spondias* sp.).

Table 3: Regression model, equations, coefficient of determination (R^2), Willmott agreement index (d), root mean squared error (RMSE), and mean absolute error (MAE) obtained as a function of size measurements leaflet of umbu-cajazeira (*Spondias* sp.).

Model	x[1]	R^2	d	RMSE	MAE	Equation
Linear	L	0.9527	0.9877	4.5190	3.5180	$\hat{y} = -17.13 + 5.71*L$
Linear	W	0.9286	0.9812	5.5518	4.4795	$\hat{y} = -22.38 + 11.99*W$
Linear	LW	0.9979	0.9994	0.9600	0.5327	$\hat{y} = 0.33 + 0.69*LW$
Linear	LL	0.9803	0.9950	2.9177	2.0032	$\hat{y} = 2.06 + 0.33*LL$
Linear	WW	0.9830	0.9957	2.7109	1.8709	$\hat{y} = -1.14 + 1.39*WW$
Power	L	0.9824	0.9955	2.7585	1.8175	$\hat{y} = 0.58 * L^{1.79}$
Power	W	0.9830	0.9956	2.7136	1.7915	$\hat{y} = 1.15 * W^{2.09}$
Power	LW	0.9980	0.9995	0.9250	0.4922	$\hat{y} = 0.76 * LW^{0.98}$
Power	LL	0.9824	0.9955	2.7585	1.8174	$\hat{y} = 0.58 * LL^{0.90}$
Power	WW	0.9824	0.9955	2.7584	1.8174	$\hat{y} = 0.58 * WW^{1.80}$
Exponential	L	0.9528	0.9863	4.6765	3.5016	$\hat{y} = 4.98 * 1.20^{L}$
Exponential	W	0.9547	0.9867	4.6003	3.5310	$\hat{y} = 3.92 * 1.49^{W}$
Exponential	LW	0.9029	0.9698	6.7244	5.4412	$\hat{y} = 10.76 * 1.02^{LW}$
Exponential	LL	0.8748	0.9604	7.5962	5.8759	$\hat{y} = 11.54 * 1.01^{LL}$
Exponential	WW	0.8838	0.9632	7.3473	5.8543	$\hat{y} = 10.49 * 1.04^{WW}$

x: independent variables (L, W, LW, LL, and WW).

The chosen model is a good fit and is considered a simple and high-precision model (Gonçalves, Ribeiro & Amorim, 2022). Similar results have been demonstrated in other plants, such as *Capsicum annuum* L. (Basak et al., 2019), *Khaya senegalensis* (Adji et al., 2021), *Citrus hystrix* (Budiarto et al., 2021), *Vitis vinifera* (Junges & Anzanello, 2021), *Musa spp* (Vieira et al., 2022), *Psidium guajava* L. (Gonçalves, Ribeiro & Amorim, 2022), Apple cultivars (Boyaci & Küçükönder, 2022) and *Cassia fistula* L. (Ribeiro et al., 2023b).

The allometric equation obtained using the power model ($\hat{y} = 0.76 * LW^{0.98}$) using LW is the most suitable for estimating the leaflet area of umbu-cajazeira (*Spondias* sp.) (Table 3), showing a coefficient of determination greater than 0.99. This information states that this equation explained at least 99% of the variations in leaflet area. This means that the product of leaf length and width is an important parameter to accurately calculate leaf area (He et al., 2020). This result is consistent with studies on *Moringa oleifera* (Macário et al., 2020), Magnoliaceae species (He et al., 2020), *Chrysanthemum morifolium* (Fanourakis, Kazakos & Nektarios, 2021), *Salvia hispanica* L. (Goergen et al., 2021), *Phaseolus vulgaris* L. (Suárez, Casanoves & Di Rienzo, 2022), Apple cultivars (Boyaci & Küçükönder, 2022), *Psidium guajava* L. (Gonçalves, Ribeiro & Amorim, 2022), *Dendranthema grandiflora* (Silva et al., 2023), *Manilkara zapota* L. (Ribeiro et al., 2023a) and *Euterpe oleracea* (Sousa et al., 2024).

It is noteworthy that the simple linear regression and power models with single linear dimensions (L and W) also showed suitable adjustments to estimate the leaflet area of umbu-cajazeira (*Spondias* sp.) (Table 3). Such models would facilitate and provide speed, practicality, and more straightforward analyses and would be considered suitable alternatives for different cultures (Junges & Anzanello, 2021; Suárez, Casanoves & Di Rienzo, 2022; Vieira et al., 2022). However, applying single-dimensional models leads to overburdened validation, low precision, and unrepresented leaf area (Fanourakis, Kazakos & Nektarios, 2021; Amorim et al., 2024). In addition, when incorporating both dimensions, the determination coefficients are higher than those involving only one dimension (Rodrigues-Paez et al., 2023), which can be proven in our study.

The equation proposed to estimate the LA of umbu-cajazeira (*Spondias* sp.) using LW showed a high relationship and good fit of the data, with a coefficient of determination ($R^2 = 0.9980$) (Figure 3A). In addition, there was a homogeneous residual variance and little dispersion of the data (Figure 3B), which makes this equation very reliable for predicting the LA of umbu-cajazeira (*Spondias* sp.).

It should be noted that the choice of this equation ($\hat{y} = 0.76 * LW^{0.98}$) confirms that length and width are strongly correlated with leaf area (Gomes et al., 2020). In addition, the evaluation of the residuals serves as a complementary approach to examine the overall adequacy of the model (Rodrigues-Paez et al., 2023), which in our study was considered appropriate (Figure 3B) since there was homoscedasticity in the distribution of the residual error, which indicates that the distribution of the data met the expected standard of normality (Sousa et al., 2024).

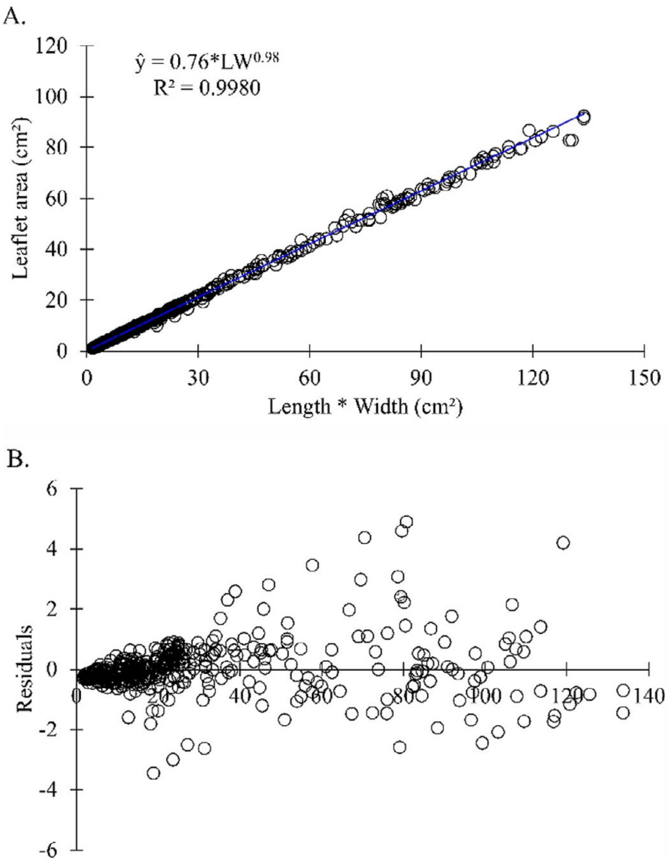

Figure 3: Relationship between the actual leaflet area and the product between length and width of the leaflets of umbu-cajazeira (*Spondias* sp.), based on the power model (A). The dispersion analysis of the residues is presented in insert (B).

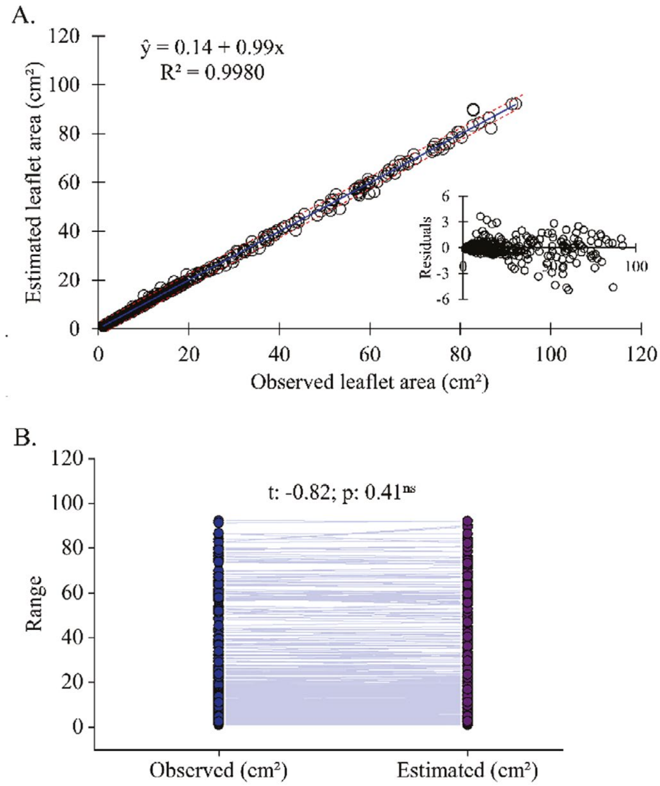

Figure 4: Relationship between observed leaflet area and estimated leaflet area using the LW power model (A) and comparison between observed leaflet area and estimated leaflet area of leaflets of umbu-cajazeira (*Spondias* sp.) using Student's t-test ($p < 0.01$) (B).

The relationship and comparison between the observed and estimated values are shown in Figure 4. It was found that the estimated LA showed a cheerful and very high correlation with the observed values, showing that it can be accurately estimated ($R^2 = 0.9980$) (Figure 4A). In addition, there were no significant differences between the observed and estimated LA in the chosen model, confirming similar values and significant relationships. Therefore, the power model can be used accurately to estimate the leaflet area of umbu-cajazeira (*Spondias* sp.) (Figure 4B).

Boyaci and Küçükönder (2022), when studying apple cultivars, also found coefficients of determination between predicted and estimated leaf area values close to 1.0 for the potency model, indicating that it is reliable and effective for estimating leaf area. This information is confirmed by authors who have studied the adjustment of regression models to estimate the leaf area of *Dendranthema grandiflora* species (Silva et al., 2023) and *Manilkara zapota* L. (Ribeiro et al., 2023a).

Conclusions

The allometric equation of the power model ($\hat{y} = 0.76 * LW^{0.98}$), using LW, was the best non-destructive modeling method for accurately and reliably estimating the leaflet area of umbu-cajazeira (*Spondias* sp.) plants. The equation is practical, precise, and accurate in obtaining the leaflet area without destroying the plants of umbu-cajazeira (*Spondias* sp.), contributing to current and future research in agronomy and the environment.

Author Contribution

Conceptual idea: Amorim, P. E. C.; Ribeiro, J. E. R. D.; Mendonça, V.; Methodology design: Ribeiro, J. E. R. D.; Amorim, P. E. C; Data collection: Amorim, P. E. C.; Oliveira. A. M. F. D.; Ribeiro, J. E. R. D.; Lima, J. L.; Data analysis and interpretation: Ribeiro, J. E. R. D.; Amorim, P. E. C.; Mendonça, V.; Sá, F. V. S.; and Writing and editing: Amorim, P. E. C.; Ribeiro, J. E. R. D.

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