Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252026v3915230rc

Scientific Article

Allometric models for non-destructive estimation of leaf area of abieiro (*Pouteria caimito*)

Modelos alométricos para estimativa não destrutiva da área foliar do abieiro (*Pouteria caimito)*

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ABSTRACT - Abieiro (*Pouteria caimito*) is an essential native fruit tree of the Amazon, with several bioactive compounds beneficial to health. Estimating leaf area is crucial for evaluating the growth, development, and productivity of *P. caimito* plants. Therefore, this work aimed to develop regression models to construct allometric equations that accurately and non-destructively estimate *P. caimito* leaf area. We collected 222 leaves of diverse sizes and shapes from parent trees in São Luís, MA, Brazil, to determine maximum length (L), maximum width (W), and leaf area (LA). We fitted linear, power, and exponential regression models using single dimensions and products (LW, LL, WW) and evaluated them with multi-criteria statistical diagnostics. Models using LW yielded the best leaf area estimates, with $\hat{y} = 0.50 + 0.65 * LW$ (linear model) and $\hat{y} = 0.76 * LW^{0.97}$ (power model) being the most suitable and accurate. Thus, these allometric equations provide a non-destructive, accurate, and low-cost method for estimating *P. caimito* leaf area.

Keywords: Sapotaceae. Abieiro. Biometry. Leaf sizing. Regression models.

RESUMO - O abieiro (Pouteria caimito) é uma importante árvore frutífera nativa da Amazônia, que contém diversos compostos bioativos benéficos à saúde. A estimativa da área foliar é crucial para avaliar o crescimento, o desenvolvimento e a produtividade das plantas de P. caimito. Portanto, objetivou-se desenvolver modelos de regressão para construir equações alométricas que estimem, de forma precisa e não destrutiva, a área foliar de P. caimito. Foram coletadas 222 folhas de diferentes tamanhos e formatos, coletadas de árvores matrizes em São Luís, MA, Brasil, para determinar o comprimento máximo (C), a largura máxima (L) e a área foliar (AF). Ajustaram-se modelos de regressão linear, de potência e exponencial, utilizando dimensões isoladas e produtos (CL, CC, LL), e avaliaram-se por meio de diagnósticos estatísticos multicritério. Os modelos que utilizaram LW apresentaram as melhores equações para estimar a área foliar, sendo as equações $\hat{y} = 0{,}50 + 0{,}65 * LW$ (modelo linear) e $\hat{y} = 0{,}76 * LW0{,}97$ (modelo de potência) as mais adequadas e precisas. Assim, o uso dessas equações alométricas constitui um método não destrutivo, preciso e de baixo custo para estimar a área foliar de P. caimito.

Palavras-chave: Sapotaceae. Abieiro. Biometria. Dimensionamento de folhas. Modelos de regressão.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

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Received for publication in: December 15, 2025.
Accepted in: September 29, 2026.

Editor in Chief: Aurélio Paes Barros Júnior

Data Availability: The data that support the findings of this study can be made available, upon reasonable request, from the corresponding author.

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INTRODUCTION

Among the native fruit species of the Amazon with market, nutritional, and medicinal potential is abieiro [*Pouteria caimito* (Ruiz & Pav.) Radlk.] which belongs to the Sapotaceae family and is popularly known as abiu, apple, and yellow star; it is widely cultivated worldwide, especially in Brazil (ZHAO et al., 2024). The plant possesses antibacterial, antifungal, antitumor, antioxidant, bioherbicide, antimicrobial, and acetylcholinesterase-inhibitory properties (SUSANTO et al., 2023). Its leaves contain compounds that inhibit alpha-amylase, alpha-glucosidase, and tyrosinase, and that scavenge free radicals. Its fruits are sweet and nutritious, containing significant amounts of protein, calcium, vitamins A and C, iron, and thiamine (ALSAIF et al., 2023). Despite its commercial and nutritional value, expanding its agronomic management and understanding its ecophysiological behavior require accurate, non-destructive methods to continuously monitor plant growth.

Non-destructive leaf area estimation enables continuous quantification of plant growth, light interception, and physiological processes without removing photosynthetic tissue (SOYSAL, 2024). Although direct destructive methods provide accurate measurements, they require destructive leaf harvesting, preventing sequential evaluations on the same plant and increasing experimental error in long-term studies (VERMA; VERMA; SINGH, 2021). Consequently, indirect non-destructive methods based on allometric regression models linking leaf area to linear dimensions, length (L) and width (W), have become cost-effective and essential tools for agronomic and ecological research across various

fruit and perennial crops (GOERGEN et al., 2021; DAS et al., 2022; SOUSA et al., 2024).

Models have been reported to predict leaf area in crops such as *Theobroma cacao* L. (SALAZAR et al., 2018), *Eugenia uniflora* L. (POMPELLI; FIGUEIRÔA; LOZANO-ISLA, 2018), *Salvia hispanica* L. (GOERGEN et al., 2021), *Congea tomentosa* (DIAS et al., 2022), and *Dendrobium nobile* L. (DAS et al., 2022), *Manilkara zapota* L. (RIBEIRO et al., 2023), *Euterpe oleracea* (SOUSA et al., 2024), *Cenostigma pyramidale* (POMPELLI et al., 2024), *Spondias* sp. (AMORIM et al., 2024), *Euterpe oleracea* and *Euterpe precatoria* (DELGADO et al., 2024), and cultivars of *Ricinus communis* L. (RIBEIRO et al., 2025), for which the best allometric equations to estimate leaf area were developed as a function of the length and width of leaves or leaflets. Although Silva et al. (2014) previously developed allometric equations for *P. caimito*, their study analyzed 80 leaves collected from 10 trees and evaluated linear, polynomial, logarithmic, and exponential regression models using leaf length (L), width (W), and their product (L × W) as predictor variables. Model selection was based on equation simplicity and the coefficient of determination (R^2), without reporting complementary prediction-error metrics or residual diagnostic analyses. These methodological considerations highlight the relevance of a more comprehensive assessment of model fit and predictive performance (POMPELLI et al., 2024; RIBEIRO et al., 2025).

To overcome these limitations, a comprehensive study with a larger sample size, multiple mathematical model structures (linear, power, and exponential), and multi-criteria error diagnostics is needed to establish robust, generalizable equations. Therefore, the objective was to develop regression models to construct allometric equations that accurately and non-destructively estimate the leaf area of *Pouteria caimito*.

MATERIAL AND METHODS

The study was conducted using, on average, 22.2 leaves collected from 10 healthy *P. caimito* mother trees from the São Luís Teaching Farm of the State University of Maranhão (UEMA), São Luís *campus* (2° 35' 09.7" S, 44° 12' 27.4" W) in the municipality of São Luís, Maranhão, Brazil. To capture intra- and inter-canopy structural variation and avoid sampling bias, we randomly collected leaves from different canopy levels (lower, middle, and upper thirds) and orientations (north, south, east, and west). According to Köppen, the region's climate is Aw, characterized as tropical, hot, and humid, with summer and autumn rainfall. Average annual rainfall is 2,156 mm, and average annual temperature is 26.8 °C (CORRÊA; CARVALHO; MENDES, 2023).

We collected 222 *P. caimito* leaves of various sizes, shapes, and developmental stages from different parts of the mother trees, free from mechanical damage or deformations caused by biotic and abiotic stresses. Sampling leaves across diverse insertion points and expansion stages provided broad biological variability, ensuring sample independence and model accuracy across different leaf size spectra. After collection, the leaves were packed in plastic bags and kept in the shade to preserve turgidity and reduce water loss through transpiration. The sample size (exceeding 200 per plant) is considered ideal and sufficiently representative to avoid biased estimates with low reliability (TRACHTA et al., 2020; RIBEIRO et al., 2023).

The adaxial surfaces of the leaves were photographed on a white EVA (Ethylene-Vinyl Acetate) sheet (40 x 60 cm) using a Motorola G30S smartphone (Motorola, Jaguariúna, Brazil). The images acquired included a millimeter-graduated ruler as a reference scale indicator. The images were processed using the ImageJ software (National Institutes of Health, United States of America), and the maximum length (L) (measured from the leaf tip to the leaf blade base at the petiole insertion point), maximum width (W) (measured from end to end at the broadest part of the leaf blade), and actual leaf area (LA) (cm^2) were determined in each leaf collected (Figure 1). We then calculated the products of length and width (LW) (cm^2), length and length (LL) (cm^2), and width and width (WW) (cm^2).

We derived the allometric equations for leaf area estimation using simple linear, power, and exponential regression (Table 1).

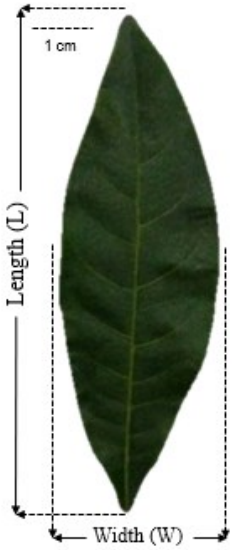


Figure 1. *Pouteria caimito* leaves used to estimate leaf area using linear dimensions of leaves [length (L) and width (W)].

Table 1. Regression models used to estimate *Pouteria caimito* leaf area from leaf dimensions.

Model	Statistical model
Linear	$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$
Power	$y_i = \beta_0 x_i^{\beta_1} + \varepsilon_i$
Exponential	$y_i = \beta_0 \beta_1^{x_i} + \varepsilon_i$

γ_i : observed leaf area (cm²) of the ith leaf; χ_i : predictor value for the ith leaf, corresponding to length (L), width (W), or the products LW, LL, and WW; β_0 and β_1: model parameters; ε_i : random error associated with the ith observation; i = 1, ..., n, where n is the number of observations.
LW = L × W; LL = L²; WW = W².

The precision and choice of the best equations for estimating the LA of *P. caimito* were based on the following criteria: higher coefficients of determination (R^2) (Equation 1), Pearson's correlation coefficients (r) (Equation 2), Willmott's agreement index (d) (WILLMOTT, 1981) (Equation 3), and lower Akaike's information criterion (AIC) (AKAIKE, 1974) (Equation 4), mean squared error (MSE) (Equation 5), root mean squared error (RMSE) (JANSSEN; HEUBERGER, 1995) (Equation 6), mean absolute error (MAE) (JANSSEN; HEUBERGER, 1995) (Equation 7) and mean absolute percentage error (MAPE) (Equation 8).

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

$$r = \frac{\sum_{i=1}^{n}(y_i - \bar{y})\left(\hat{y}_i - \bar{\hat{y}}\right)}{\sqrt{\left[\sum_{i=1}^{n}(y_i - \bar{y})^2\right]\left[\sum_{i=1}^{n}\left(\hat{y}_i - \bar{\hat{y}}\right)^2\right]}} \quad (2)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{\sum_{i=1}^{n}(|\hat{y}_i - \bar{y}| + |y_i - \bar{y}|)^2} \quad (3)$$

$$AIC = -2\ln(\hat{L}) + 2k \quad (4)$$

$$MSE = \frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n} \quad (5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \quad (6)$$

$$MAE = \frac{\sum_{i=1}^{n}|\hat{y}_i - y_i|}{n} \quad (7)$$

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{\hat{y}_i - y_i}{y_i}\right| \quad (8)$$

Where:
y_i = observed leaf area for the ith observation;
$\hat{y}_i$ = estimated leaf area for the ith observation;
$\bar{y}$ = mean of the observed leaf area values;
$\bar{\hat{y}}$ = mean of the estimated leaf area values;
n = number of observations;
$\hat{L}$ = maximized likelihood of the fitted model;
k = number of parameters estimated in the likelihood function, including residual variance when applicable;
i = index of each observation (from 1 to n).

We performed descriptive data analysis to determine the minimum, maximum, mean, range, median, variance, standard deviation, standard error, coefficient of variation, skewness, and kurtosis of L, W, LW, LL, and WW (independent variables) and LA (dependent variable). We assessed variable distributions using the Shapiro–Wilk test. Given the relatively large sample size (n = 222), we interpreted the test results as a complementary diagnostic rather than an absolute criterion for model adequacy, since small departures from normality may become statistically detectable in large samples. For the regression models, adequacy was evaluated primarily using the statistical performance criteria described. Residual normality was considered mainly in relation to the reliability of statistical inference on model parameters rather than as a strict requirement for model fitting. We quantified parameter uncertainty using the standard errors and 95% confidence intervals of the estimated regression coefficients, and assessed statistical significance at 5% probability level. We compared observed and estimated leaf area values using a paired Student's t-test ($p \leq 0.05$). All statistical analyses were performed using R software version 4.4.1 (R CORE TEAM, 2024).

RESULTS AND DISCUSSION

Validating allometric models for estimating leaf area is essential for accurate, non-destructive analyses of plant development. In this study, the results enabled a consistent evaluation of the accuracy of models proposed for *P. caimito*,

highlighting their strong predictive performance using easily measurable morphological variables, such as leaf length (L) and width (W). Figure 2 presents descriptive statistics for length (L), width (W), the product of length and width (LW), the product of length and length (LL), the product of width and width (WW), and leaf area (LA). The leaves showed variations in length (L) between 1.555 and 25.895 cm, with a mean of 9.884 cm and range of 24.340 cm (Figure 2A); the minimum and maximum width (W) values were 0.426 and 6.947 cm, with a mean of 3.012 cm and range of 6.521 cm (Figure 2B).

The product of length and width (LW) ranged from 0.748 to 179.893 cm², with a mean of 40.173 cm² and a range of 179.144 cm² (Figure 2C). The product between length and length (LL) ranged from 2.418 to 670.551 cm², with a mean of 134.844 cm² and a range of 668.133 cm² (Figure 2D); the product between width and width (WW) ranged from 0.181 to 48.261 cm², with a mean of 12.405 cm² and a range of 48.079 cm² (Figure 2E). Leaf area (LA) ranged from 0.533 to 116.024 cm², with a mean of 26.918 cm² and a range of 115.491 cm² (Figure 2F). The highest coefficients of variation (CV) were found for the products LW (98.9%), LL (97.1%), WW (95.1%), and LA (96.2%), while L and W obtained the lowest coefficients (61.6 and 60.6%), respectively (Figure 2). The descriptive analysis in Figures 2A and 2B showed mean values for L and W lower than those reported by Silva et al. (2014), who evaluated the leaf area of *P. caimito* and observed averages of 14.48 cm for L and 5.12 cm for W.

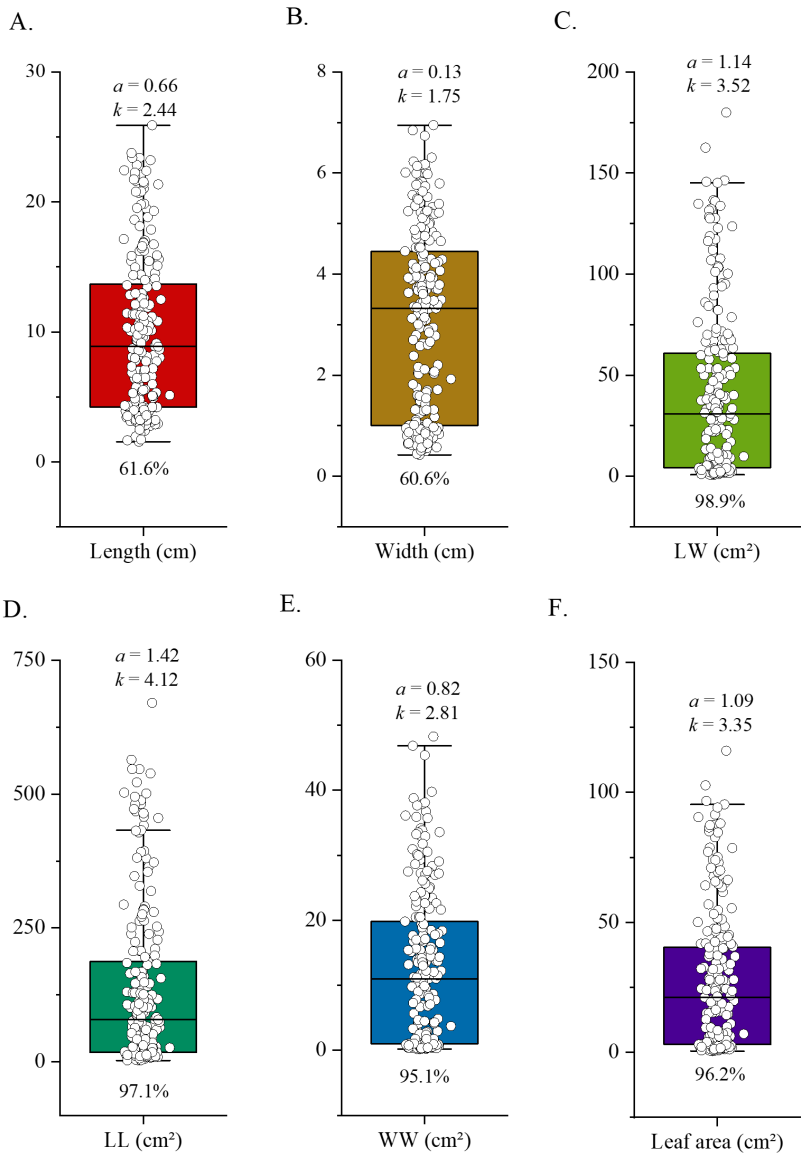


Figure 2. Descriptive analysis of length (A), width (B), product between length and width (C), product between length and length (D), product between width and width (E), and leaf area (F) of *Pouteria caimito* leaves. The top and bottom ends of each box represent the 1/4 and 3/4 quartiles, respectively. The horizontal line within each box refers to the median. The top and bottom points of the boxes represent the extreme minimum and maximum values of the data. The numbers above the distribution refer to the coefficients of skewness (*a*) and kurtosis (*k*). The numbers below the distribution refer to the coefficient of variation (CV).

The wide variability in LW, LL, WW, and LA data (Figure 2), resulting from the sampling of leaves with different sizes and shapes, contributed to data diversity, which is highly recommended for studies that use modeling to estimate the LA of species (GOMES et al., 2020; RIBEIRO et al., 2023; AMORIM et al., 2024). This high variability suggests greater representativeness of the regression models and higher precision of the constructed equations, as the collected leaves encompass different stages of morphological development (RIBEIRO et al., 2025). Studies by Donato et al. (2020) and Silva and Gheyi (2024) on *Musa* spp., and *Cucumis anguria* L., respectively, also found high variability in leaf dimensions, including LW, LL, WW, and LA.

The most significant skewness coefficients (*a*) were observed in LW, LL, WW, and LA (Figure 2). The kurtosis coefficients (*k*) for LW, LL, and LA indicated leptokurtic distributions, with the data more peaked and concentrated around the mean (k > 3). In contrast, the kurtosis coefficients (*k*) for L, W, and WW indicated platykurtic distributions (k < 3), with more dispersed and flattened data (Figure 2). The percentage distribution of leaf area size classes showed that 48.65% fell between 0.50 and 20.00 cm² and 25.22% between 20.01 and 40.00 cm², indicating that most of the leaves collected from this species were small (Figure 3).

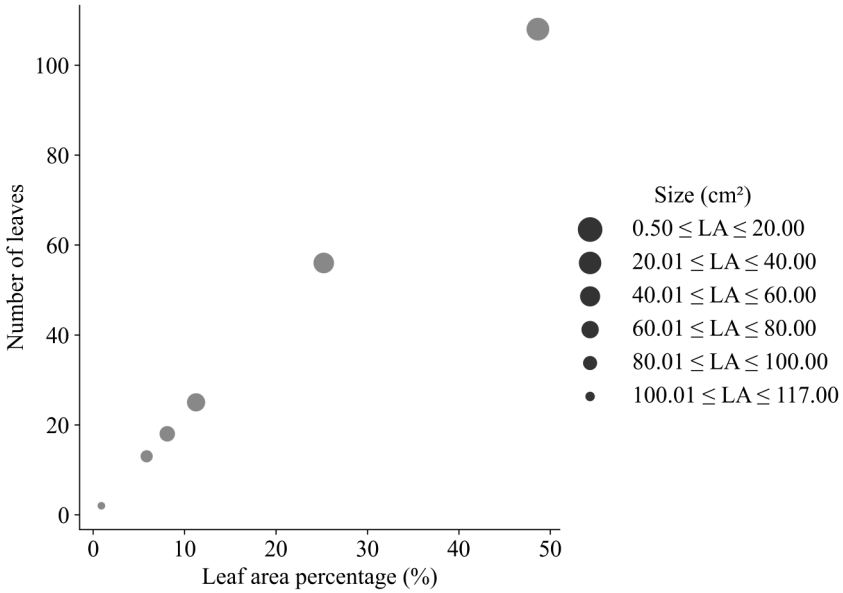


Figure 3. Relationship between the number of *Pouteria caimito* leaves and the percentage of leaf area classified into size classes.

The data showed both linear and nonlinear associations across L, W, LW, LL, WW, and LA in the regression models (Figure 4). Linear associations were observed between LW and LA, LL and LA, and WW and LA. In contrast, nonlinear patterns were identified between L and LA, and between W and LA (Figure 4).

The dispersion analysis (Figure 4) suggests that, to construct allometric equations for estimating leaf area in *P. caimito*, it is essential to apply different regression models for data generation, adjustment, and validation (RIBEIRO et al., 2023). Based on the selection criteria, linear regression and power models produced more reliable and interpretable results (POMPELLI et al., 2024). The simple linear model was also more suitable for predicting leaf area in other species, such as *Eugenia uniflora* L. (POMPELLI; FIGUEIRÔA; LOZANO-ISLA, 2018), *Salvia hispanica* L. (GOERGEN et al., 2021), and *Cenostigma pyramidale* (POMPELLI et al., 2024). The power model, on the other hand, was more effective in species such as *Psidium guajava* L. (VITÓRIA et al., 2018), *Theobroma cacao* L. (SALAZAR et al., 2018), *Manihot esculenta* (TRACHTA et al., 2020; PHONCHAROEN et al., 2022), *Thevetia peruviana* (RODRIGUEZ-PAEZ et al., 2024), *Manilkara zapota* L. (RIBEIRO et al., 2023), and *Spondias* sp. (AMORIM et al., 2024).

The exponential models performed consistently worse than the linear and power models, particularly when LW was used as the predictor, as shown by the lower R^2 and agreement indices (d) and substantially higher AIC and prediction errors (Table 2).

Table 2 presents the most appropriate and accurate regression models and equations for estimating *P. caimito* leaf area, based on the selection criteria. The linear regression and power models, as a function of LW, showed the highest R^2, r, and d, and the lowest AIC, MSE, RMSE, MAE, and MAPE (Table 2).

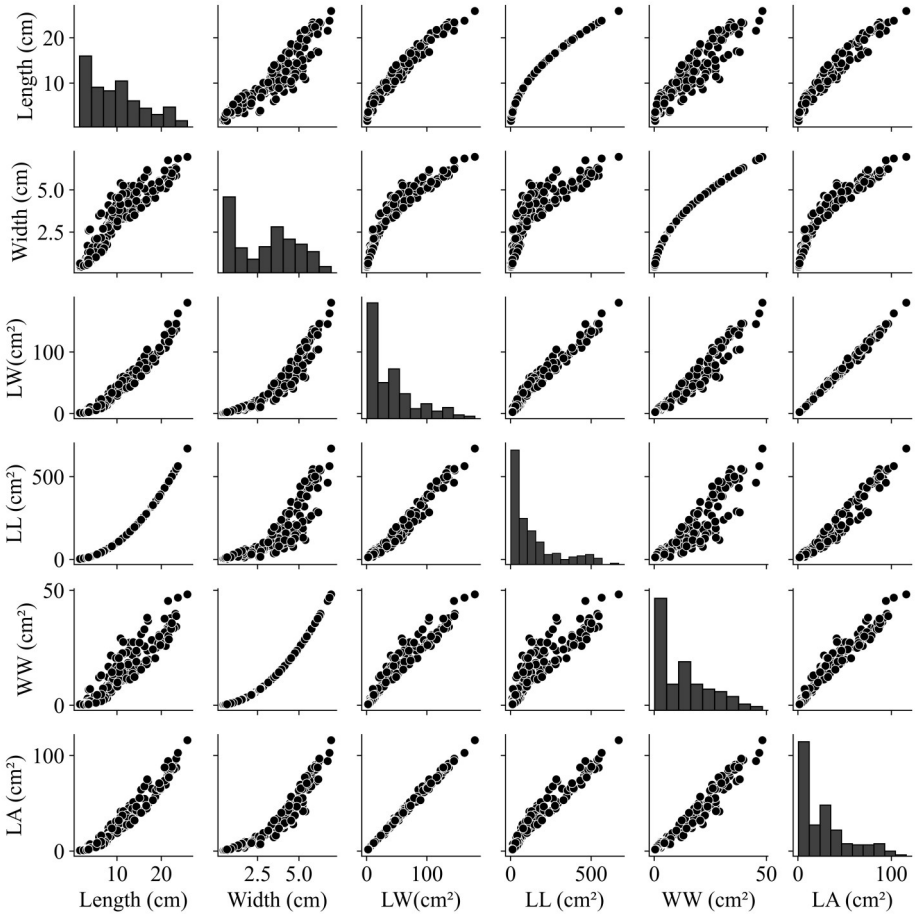


Figure 4. Frequency histogram (diagonally) and data dispersion between length (L), width (W), length and width product (LW), length and length product (LL), width and width product (WW), and leaf area (LA), of *Pouteria caimito* leaves.

Table 2. Regression model, equations, coefficient of determination (R^2), Pearson's correlation coefficient (r), Akaike's information criterion (AIC), Willmott's agreement index (*d*), mean squared error MSE (cm^4), root mean squared error RMSE (cm^2), mean absolute error MAE (cm^2), and mean absolute percentage error MAPE (%), obtained as a function of leaf dimensions.

Model	x[1]	R^2	r	*d*	AIC	MSE	RMSE	MAE	MAPE	Equation
Linear	L	0.9489	0.9742	0.9867	1438.0	37.06	6.08	4.75	1.08	$\hat{y} = -15.71 + 4.31*L$
Linear	W	0.8693	0.9326	0.9641	1646.3	94.72	9.73	7.93	1.13	$\hat{y} = -14.58 + 13.78*W$
Linear	LW	0.9966	0.9983	0.9991	836.9	2.47	1.57	0.98	0.07	$\hat{y} = 0.50 + 0.65*LW$
Linear	LL	0.9535	0.9765	0.9880	1416.8	33.69	5.80	4.46	0.31	$\hat{y} = 3.21 + 0.17*LL$
Linear	WW	0.9563	0.9780	0.9887	1402.8	31.63	5.62	3.92	3.26	$\hat{y} = -0.82 + 2.23*WW$
Power	L	0.9652	0.9824	0.9907	1356.8	25.71	5.07	3.81	0.26	$\hat{y} = 0.51 * L^{1.65}$
Power	W	0.9609	0.9802	0.9899	1382.0	28.80	5.36	3.68	0.49	$\hat{y} = 1.50 * W^{2.23}$
Power	LW	0.9968	0.9984	0.9992	821.3	2.30	1.51	0.87	0.03	$\hat{y} = 0.76 * LW^{0.97}$
Power	LL	0.9652	0.9824	0.9907	1356.8	25.71	5.07	3.81	0.26	$\hat{y} = 0.51 * LL^{0.82}$
Power	WW	0.9609	0.9802	0.9899	1382.0	28.80	5.36	3.68	0.49	$\hat{y} = 1.50 * WW^{1.11}$
Exponential	L	0.9227	0.9605	0.9765	1547.7	60.76	7.79	6.36	0.38	$\hat{y} = 6.84 * 1.12^{L}$
Exponential	W	0.9475	0.9734	0.9846	1460.8	41.07	6.40	5.02	0.31	$\hat{y} = 4.39 * 1.63^{W}$
Exponential	LW	0.8784	0.9372	0.9593	1653.9	98.01	9.90	8.43	0.41	$\hat{y} = 13.55 * 1.01^{LW}$
Exponential	LL	0.8784	0.9362	0.9503	1659.9	99.79	9.99	8.49	0.44	$\hat{y} = 14.50 * 1.00^{LL}$
Exponential	WW	0.8759	0.9359	0.9585	1657.8	99.78	9.98	8.22	0.40	$\hat{y} = 12.20 * 1.05^{WW}$

x[1]: between length (L), width (W), length and width product (LW), length and length product (LL), and width and width product (WW).

This poor fit occurs because leaf blade surface expansion is inherently a two-dimensional geometric process that scales proportionally with the product of orthogonal linear axes (L × W), as observed in other woody and perennial species (POMPELLI; FIGUEIRÔA; LOZANO-ISLA, 2018; RIBEIRO et al., 2023). Exponential functions assume an accelerating multiplicative rate of surface expansion as linear dimensions increase, which overestimates area in larger leaves and distorts predictions across smaller size classes, thereby failing to reflect the morphological scaling of *P. caimito* (SILVA et al., 2014; POMPELLI et al., 2024).

Notably, the best-performing models employed LW, demonstrating that leaf length and width are crucial for accurate leaf area estimation (GOERGEN et al., 2021; MUDA et al., 2023). The superior performance of LW is also morphologically consistent because it incorporates the two main dimensions that define leaf blade expansion. Thus, it captures changes in both longitudinal and transverse leaf growth, whereas models based solely on L or W may fail to account for variations in leaf shape. From an ecophysiological perspective, reliable leaf area estimation matters because leaf surface area determines the interface available for light interception, gas exchange, and transpiration. Consequently, LW-based equations enable repeated monitoring of leaf expansion without removing leaves, which is particularly useful in growth and physiological studies requiring successive measurements on the same plants. This result corroborates Silva et al. (2014), who also found that LW models are more suitable for estimating the leaf area of *P. caimito* because of the strong correlation. Sousa et al. (2024) reported similar results for *Euterpe oleracea*.

All estimated parameters (β0 and β1) for the selected linear and power models were statistically significant ($p \leq 0.001$), with low standard errors and narrow 95% confidence intervals, confirming high statistical reliability.

Although the models with LW are the ones chosen because they show higher coefficients of determination among the selection criteria compared to those based on only one leaf dimension (VITÓRIA et al., 2018; RODRIGUEZ-PAEZ et al., 2024), models with single dimensions L or W also have good fits (GOMES et al., 2020). However, applying equations with only one dimension may, in some cases, result in lower precision and a less optimal fit (RIBEIRO et al., 2025).

The proposed models demonstrated a strong relationship between LA and LW, as indicated by the equations $\hat{y} = 0.50 + 0.65*LW$ (simple linear model) and $\hat{y} = 0.76 * LW^{0.97}$ (power model), with R^2 values of 0.9966 and 0.9968, respectively. These results indicate that the proposed equations explain at least 99% of the variation in the species' leaf area (Figure 5). In addition, the analysis of residual dispersion shows good distribution and homogeneity (Figure 5), supporting the reliability of these equations for predicting *P. caimito* leaf area.

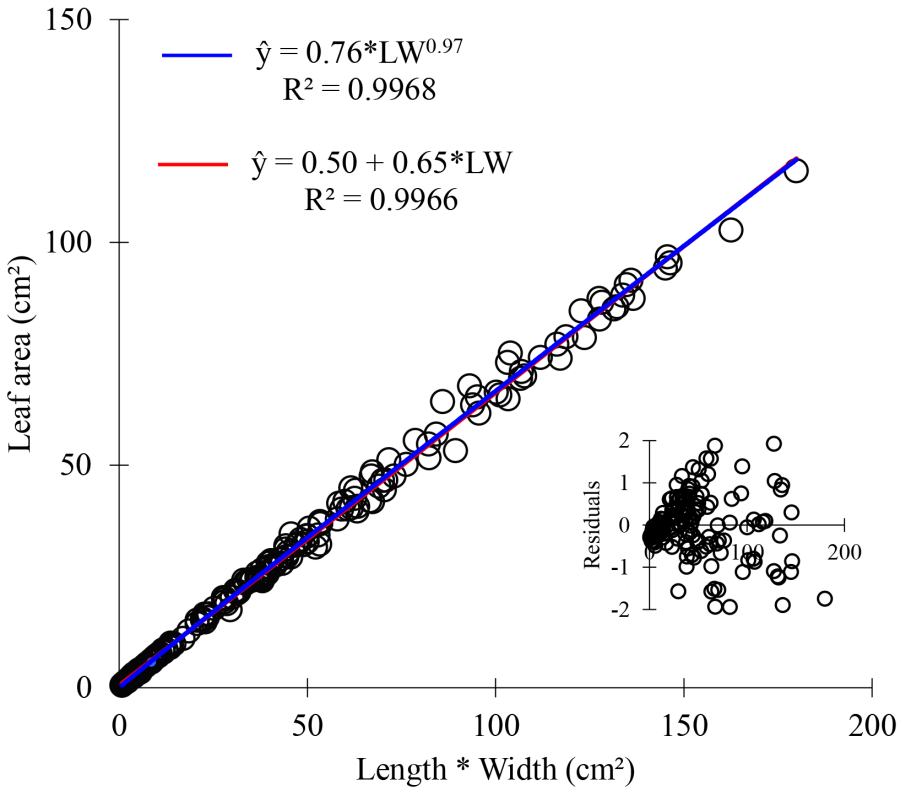


Figure 5. Relationship between the real leaf area and the product of the length and width of *Pouteria caimito* leaves, from the simple linear and power models. The insert shows the residual dispersion analysis.

The high R^2 values (0.9966 for the linear model and 0.9968 for the power model) indicate that more than 99.6% of the total variance in *P. caimito* leaf area is explained by the product of linear dimensions (LW) (DIAS et al., 2022). This high explanatory power, combined with Willmott's agreement indices close to unit ($d \geq 0.9991$) and exceptionally low prediction errors (RMSE $\leq$ 1.57 cm²; MAE $\leq$ 0.98 cm²; MAPE $\leq$ 0.07%), confirms the high predictive accuracy and stability of both the simple linear model and the power model based on LW (Table 2). In addition, graphical inspection of the standardized residuals revealed no evident systematic pattern or marked changes in dispersion across the fitted value range (Figure 5), suggesting adequate error variance homogeneity and an acceptable residual dispersion for the selected equations. Residual analysis is important for identifying possible departures from model assumptions, such as non-normality and heteroscedasticity, which may affect the reliability of statistical inference and model performance (POMPELLI et al., 2024).

The evaluation of the simple linear and power models comparing the observed leaf area (OLA) and estimated leaf area (ELA) is presented in Figure 6. For both models (simple linear and power), the relationship between OLA and ELA showed R^2 values above 0.99, indicating a strong positive correlation between these parameters (Figures 6A and 6B). Notably, OLA and ELA did not differ significantly ($p \geq 0.05$), confirming that ELA accurately represents OLA (Figures 6C and 6D).

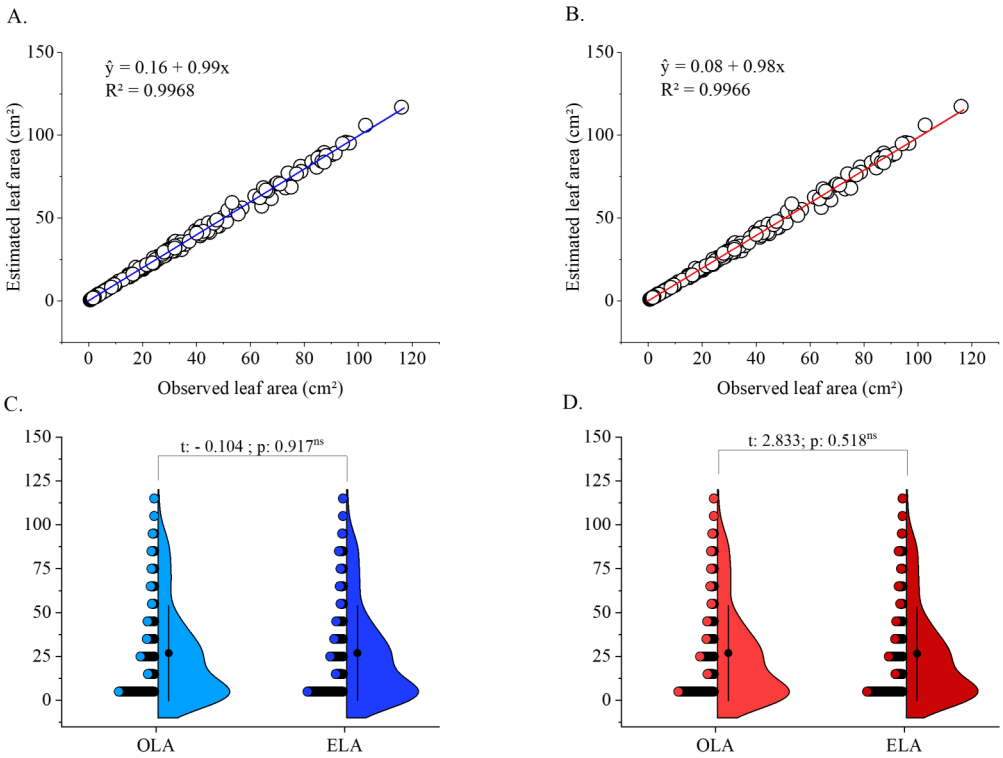


Figure 6. Relationship between observed leaf area (OLA) and estimated leaf area (ELA) for the power model (A) and simple linear model (B) as a function of the product of length and width (LW) of Pouteria caimito leaves. Comparison between OLA and ELA using a paired Student's t -test ($p \leq 0.05$) for the power model (C) and simple linear model (D).

Model validation, as evidenced by the comparison of observed leaf area (OLA) with estimated leaf area (ELA) (Figure 6), further supports the model's accuracy. Soysal (2024) states that the goal of regression analysis and modeling is to maximize the proportion of variation the model accounts for while minimizing non-attributable variation. In this way, the equation should accurately estimate leaf area and remain stable across leaves of different shapes and sizes (VERMA; VERMA; SINGH, 2021), as observed in the present research.

Thus, the allometric equations $\hat{y} = 0.50 + 0.65*LW$ and $\hat{y} = 0.76 * LW^{0.97}$ (Table 2) enable the evaluation of the evolutionary, ecophysiological, and morphological characteristics that influence plant survival, development, yield, and quality (AMORIM et al., 2024; SOYSAL, 2024). In addition, these equations greatly benefit researchers by enabling them to study plant growth phenomena, such as respiration, photosynthesis, and transpiration, without destructive leaf harvesting (GOMES et al., 2020). They also support agricultural management, such as plant spacing, irrigation, nutrition, and phytosanitary practices, based on leaf morphology and leaf area (DELGADO et al., 2024).

Despite the strong predictive performance of the proposed equations, some limitations remain. The models were developed using leaves collected from ten mother plants grown at a single location. They included only leaves without clear mechanical damage or deformation from biotic or abiotic stresses. Therefore, their performance should be further evaluated in plants grown under different environmental and management conditions and in leaves showing greater morphological variation. Independent

validation using additional populations would also strengthen the general applicability of the proposed equations.

CONCLUSION

Linear regression and power models, which account for the linear dimensions of the product of leaf length and width, proved efficient and appropriate for estimating the leaf area of *Pouteria caimito*. This non-destructive approach is practical and cost-effective for obtaining scientific data in agronomic, ecological, and biological research.

The equations $\hat{y} = 0.50 + 0.65*LW$ (linear model) and $\hat{y} = 0.76 * LW^{0.97}$ (power model) can accurately and reliably estimate *Pouteria caimito* leaf area. However, because the parent trees were evaluated in a single geographic location, the equations may reflect regional edaphoclimatic conditions and phenotypic plasticity in leaf morphology in response to environmental variation. Therefore, further validation of these models across distinct cultivation environments and regions is recommended to confirm their broader generalizability.

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