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ORIGINAL PAPER

Leaf area estimation of gherkin plants from linear leaf dimensions

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Abstract: The gherkin is a widely consumed species in the Northeast Brazil, where its production is mainly derived from naturally occurring or wild plants. The leaf area of plants plays a crucial role in their development and productivity, as it is directly related to photosynthetic capacity. Through their leaves, plants absorb sunlight and convert light energy into chemical energy, which is essential for growth and biomass production. Thus, the objective of this study was to propose regression models to estimate the leaf area of gherkin using linear dimensions of the leaves. Two experiments were conducted, one between January and April (summer-autumn) with two gherkin cultivars (‘Caipira do Norte’ and ‘Liso Calcutá’ for test and validation – dependent data) and other between May and August (autumn-winter) 2021 only with the cultivar ‘Caipira do Norte’ (for validation – independent data). In the summer-autumn experiment, the relationships between individual leaf area (LA), as the dependent variable, and leaf length (L), width (W), or the L×W product, as independent variables, were analyzed using both linear and power regression models. These models were developed individually for each cultivar, as well as for the two cultivars jointly (grouped data). Statistical indicators, including the Pearson’s linear correlation coefficient (r), coefficient of determination (R^2), Willmott’s agreement index (*d*), and root mean square error (RMSE), were used as criteria for selecting the best models. In the validation between observed and estimated values, the best estimates of individual LA of gherkin were obtained using the L×W product as an independent variable. The grouping of two gherkin cultivars (‘Caipira do Norte’ and ‘Liso Calcutá’) into a single model was possible. Based on higher accuracy and lower errors, the linear (LA = 0.7296×L×W; r = 0.9769, R^2 = 0.9543, d = 0.9882, and RMSE = 8.94) and power (LA = $1.0024\times(L\times W)^{0.9440}$; r = 0.9772, R^2 = 0.9549, d = 0.9883, and RMSE = 8.88) models, using grouped data, are indicated for individual LA estimation of the gherkin plants.

Keywords: *Cucumis anguria* L., non-destructive method, regression models, validation performance.

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Introduction

The leaf area (LA) is directly related to transpiration and photosynthetic rates (Nahas et al., 2019; Hernández-Fernandéz et al., 2021; Silva et al., 2023). Therefore, it is an important parameter in many studies to evaluate plant growth (Azevedo et al., 2017; Silva et al., 2021). The LA of plants plays a crucial role in their development and productivity, as it is directly related to photosynthetic capacity. Through their leaves, plants absorb sunlight and convert light energy into chemical energy, which is essential for growth and biomass production. Additionally, LA influences transpiration and gas exchange, vital processes for water regulation and carbon dioxide uptake (Domaratskyi, 2021; Croce et al., 2024). There are several methods for determining the LA of a plant, which are classified as destructive (direct) and non-destructive (indirect) (Al-Barzinji and Amin, 2016; Oliveira et al., 2019; Montelatto et al., 2020). Direct methods, despite being the most precise, are destructive (requires leaf excision) (Cirillo et al., 2017; Ribeiro et al., 2018), which prevents temporal measurements on the same leaf of the plant over time, and restricts its applicability in studies with limited number of leaves (Yeshitila and Taye, 2016; Salazar et al., 2018; Hernández-Fernandéz et al., 2021).

Due to the limitations of direct LA measurements, the development of models based on regression analysis using linear measurements of leaves (length – L and/or width – W) has been recurrent to estimate the individual LA of different plant species, such as *Brassica napus* L. (Cargnelutti Filho et al., 2015; Tartaglia et al., 2016; Dalmago et al., 2019), *Helianthus annuus* L. (Firouzabadi et al., 2015), *Solanum macrocarpon* (Ogoke et al., 2015), *Crotalaria juncea* (Carvalho et al., 2017), *Cichorium intybus* L. (Fernandes et al., 2017), *Coffea arabica* (Misgana et al., 2018), *Anacardium humile* (Gomes et al., 2020), *Nicotiana tabacum* L. (Schlösser et al., 2020), *Carica papaya* L. (Zhou et al., 2020), *Stevia rebaudiana* (Hernández-Fernandéz et al., 2021), *Brassica oleracea* var. *botrytis* (Silva et al., 2021), *Manilkara zapota* L. (Ribeiro et al., 2023), and *Dendranthema grandiflora* (Silva et al., 2023).

The use of different types of models in the test phase is important, as previously calibrated models may not have the same validation performance. For instance, in the study by Silva et al. (2021) the individual LA of three cauliflower cultivars (individually or jointly) was fitted based on the different regression model types. According to the results, the LA of the cv. 'Piracicaba de Verão' was better estimated with the linear or power models individually or jointly; while for LA of cv. 'SF1758', individual linear model or universal models (linear or power) were suggested. For LA estimation of the cv. 'Sabrina', it is preferable to use the universal models (linear or power) instead of individual models. Differently, in the study by Hernández-Fernandéz et al. (2021) it was not possible to use a generalized model to predict the LA of four stevia genotypes, because the genotype leaf architectures were very different.

Thus, the objective of this study was to propose regression models to estimate the leaf area of gherkin using linear dimensions of the leaves.

Materials and Methods

Study site and experimental conditions

The study was conducted with gherkin (*Cucumis anguria* L.) plants grown under hydroponic conditions in a greenhouse (east-west orientation and uncontrolled conditions with natural sunlight: protected on sides by 50 mesh anti-insect screens, and the roof was covered with 150-µm-thick polyethylene transparent film). The facilities are part of the experimental area of the Post Graduate Program in Agricultural Engineering of the Federal University of Recôncavo da Bahia (UFRB), Cruz das Almas, Bahia (12° 40’ 19” S, 39° 06’ 23”

W, at an elevation of 220 m above sea level), Brazil.

An experiment was carried out in a randomized blocks design with four replications, between January and April (summer-autumn) 2021 with two gherkin cultivars ('Caipira do Norte' and 'Liso Calcutá'). The gherkin plants were grown at different electrical conductivities (EC) of the nutrient solutions (ECsol) prepared in saline waters obtained by addition of NaCl to public-supply water (ECw of 0.5 dS m^{-1}). After adding the nutrients, the resulting ECsol values were 1.28, 2.43, 3.45, 4.27, 5.13, and 6.36 dS m^{-1}. In other experiment (autumn-winter) between May and August 2021, only the cv. 'Caipira do Norte' was used. The data were obtained only for validation of the models developed in the summer-autumn experiment. Thus, the cultivation was carried out only under control treatment (public-supply water; resulting ECsol value of 1.40 dS m^{-1} after adding the nutrients). In both experiments, the replacement of water consumed by plants was performed using the public-supply water (ECw of 0.5 dS m^{-1}).

The plants grew under a nutrient film technique (NFT) hydroponic system consisting of 3-m-long channels and 100 mm in diameter. One hydroponic channel was arranged per bench with a 3.0% slope, maintaining a 0.6 × 1.0 m distance between plants and channels, respectively. In addition, each experimental unit consisted of a 50-L capacity plastic tank to store the nutrient solution and a 34-W washing-machine electric drain pump to inject the mixture into the hydroponic channel.

Gherkin sowing and nutrient solutions preparation and management

The gherkin seeds (Feltrin® Sementes, Farroupilha, RS, Brazil) of 'Caipira do Norte' and 'Liso Calcutá' in summer-autumn experiment and 'Caipira do Norte' in autumn-winter experiment were sown in 80-mL plastic cups containing coconut fiber substrate (Amafibra Ltda., Artur Nogueira, SP, Brazil), on January 25 and May 17, 2021, respectively. During 13 days, the irrigations occurred with public-supply water (ECw of 0.5 dS m^{-1}). Then, plants received a nutrient solution (Furlani et al., 1999) at 50% strength for 12 and 16 days for the summer-autumn and autumn-winter experiments, respectively.

Later, the seedlings were transplanted (25 and 29 days after sowing for the summer-autumn and autumn-winter experiments, respectively) into the final cultivation system. In both experiments, six seedlings in each hydroponic channel were distributed. In case of summer-autumn experiment, three seedlings of each cultivar were used.

Data collection

Measurements of leaf length (L), leaf width (W), and leaf area (LA) in leaves of gherkin were performed. From the measurements of L and W, the L×W product was calculated. At 50 days after transplanting (DAT) for the summer-autumn experiment, in each hydroponic channel were evaluated two plants (one of each cultivar). At 54 DAT in the autumn-winter experiment, five plants were evaluated (one per hydroponic channel). In each plant, 10 leaves were detached (sought to collect leaves from the smallest to the largest size). In both experiments, L was measured parallel to the midrib direction from the lamina apex to the petiole base. W was determined at the widest point perpendicular to the primary leaf axis (Figure 1). L and W were determined using a ruler. LA was measured using a portable leaf area meter model CI202 (CID Bio-Science, Inc., Washington, USA).

L, W, and LA measurements of the summer-autumn experiment were randomized, 80% were used in the test of the models and the remaining 20% for their validation. Before developing the models, the L/W ratio was calculated. There was no significant difference in the L/W ratio, so salinity did not influence the shape of the leaves, and the different models could be fitted to estimate the LA of gherkin. The models were fitted based on the measurements of individual cultivar (192 measurements of each cultivar) and also for the grouped data (two cultivars, a total of 384 measurements).

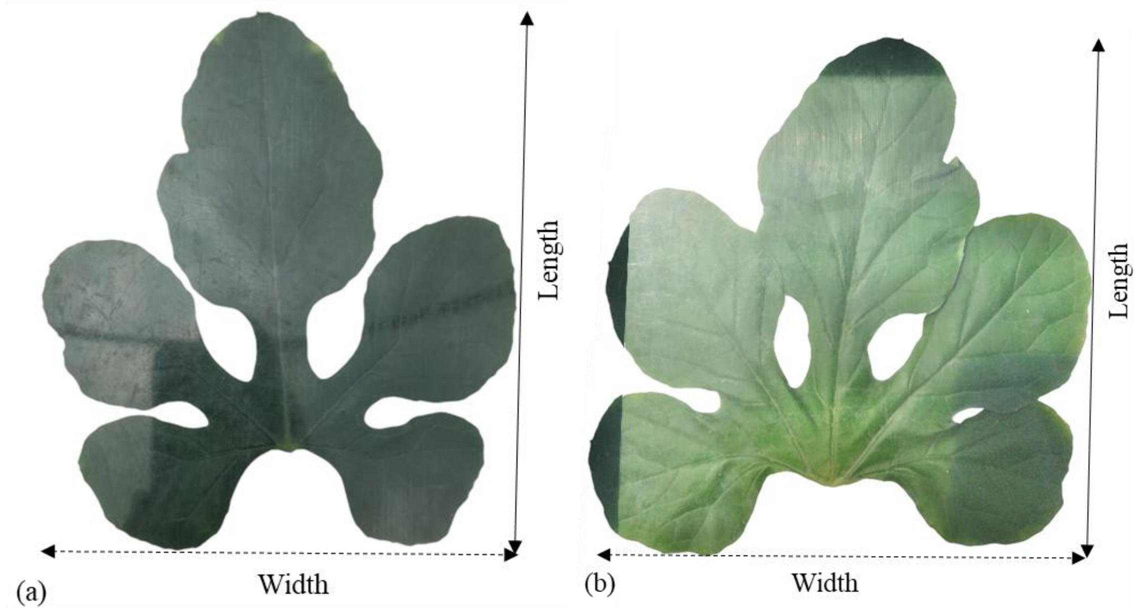


Figure 1: Leaves of gherkin ‘Caipira do Norte’ (a) and ‘Liso Calcutá’ (b) in the summer-autumn experiment.

The relationships between LA (dependent variable) and L, W or L×W (independent variables) were fitted using linear without intercept (y = ax) and power ($y = ax^b$) models; where: ‘y’ is the measured LA, ‘x’ are the independent variables (L, W or L×W) and ‘a’ and ‘b’ are the parameters of the models. Before fitting the models, the degree of collinearity between the L and W measurements was analyzed. The variance inflation factor ($VIF = 1/1\text{-}r^2$) was calculated as described by Marquaridt (1970); r is the correlation coefficient. If the VIF values are less than 10, then problems of collinearity between L and W are considered insignificant and, therefore, these parameters can be included in empirical models. In the present study, there were no problems of collinearity between L and W, with VIF values ranging between 0.09 and 0.10; thus, the L×W product could be used in the development of the models.

The best models were selected based on Pearson’s linear correlation coefficient (r), coefficient of determination (R^2), Willmott’s agreement index (*d*), and root mean square error (RMSE) as presented in Table 1.

Validation of the models

In the model validation phase, 20% of the measurements (L, W, and LA) were employed which were not used in the development phase of the summer-autumn experiment (dependent data). In the autumn-winter experiment only with the gherkin ‘Caipira do Norte’ (independent data), a total of 150 measurements were used in the validation. In the summer-autumn experiment, the grouped data models were validated with the individual data of each cultivar or for two cultivars jointly. In addition to the validation using the models developed for each cultivar individually and jointly, the models for a respective cultivar were also validated with the data of another cultivar. For instance, the models developed for cv. ‘Caipira do Norte’ were validated with the data of the cv. ‘Liso Calcutá’, and vice versa.

Table 1: Pearson's linear correlation coefficient (r), coefficient of determination (R^2), Willmott's agreement index (*d*), and root mean square error (RMSE) used as criteria for selecting the best models for individual LA estimation of the gherkin plants

Statistical indicators	Description
$r = \frac{\sum_{i=1}^{n}(OLA_i - \overline{OLA})(ELA_i - \overline{ELA})}{\sqrt{\sum_{i=1}^{n}(OLA_i - \overline{OLA})^2 \sum_{i=1}^{n}(ELA_i - \overline{ELA})^2}}$	OLA_i – observed leaf area; ELA_i – estimated leaf area; $\overline{OLA}$ – mean of observed leaf area; $\overline{ELA}$ – mean of estimated leaf area; n – observation numbers.
$R^2 = 1 - \frac{\sum_{i=1}^{n}(OLA_i - ELA_i)^2}{\sum_{i=1}^{n}(OLA_i - \overline{OLA})^2}$	
$d = 1 - \left[\frac{\sum_{i=1}^{n}(OLA_i - ELA_i)^2}{\sum_{i=1}^{n}(\lvert OLA_i - \overline{OLA}\rvert + \lvert ELA_i - \overline{OLA}\rvert)^2}\right]$	
$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(OLA_i - ELA_i)^2}{n}}$	

Statistical analysis

Descriptive statistics of the data were calculated for each leaf parameter. Statistical analysis was performed using Microsoft Office Excel® application.

Results and Discussion

As shown in Table 2, a descriptive analysis (minimum, maximum, amplitude, mean ± standard deviation, and coefficient of variation) of the measurements of L, W, L×W, and LA of gherkin was performed. In both experiments, the patterns of measurements of L, W, L×W, and LA of the leaves of gherkin 'Caipira do Norte' were similar. From the high amplitude of the data (13.40 and 12.00 cm for L, 15.60 and 13.10 cm for W, 257.50 and 231.30 cm^2 for L×W product, and 194.87 and 168.08 cm^2 for LA in the 'Caipira do Norte' and 'Liso Calcutá' cultivars, respectively) in the summer-autumn experiment, it was possible to model the LA of gherkin for a wide range of leaf sizes and shapes. The amplitude of the CV values further supports this, with the highest data variability observed for the L×W product and the measured LA.

Table 2: Results of descriptive statistics of the leaf length (L, in cm), leaf width (W, in cm), L×W product (in cm^2), and observed leaf area (LA, in cm^2) of gherkin plants

Cultivars	Parameters	Min	Max	Amp	Mean ± SD	CV (%)
	Summer-autumn experiment					
'Caipira do Norte' (*n* = 240)	L	2.50	15.90	13.40	9.70 ± 2.97	30.62
	W	2.40	18.00	15.60	10.54 ± 3.26	30.93
	L×W	6.00	263.50	257.50	111.49 ± 60.90	54.62
	LA	4.90	199.77	194.87	85.38 ± 45.58	53.38
'Liso Calcutá' (*n* = 240)	L	3.00	15.00	12.00	9.74 ± 2.59	26.59
	W	2.90	16.00	13.10	10.44 ± 2.77	26.53
	L×W	8.70	240.00	231.30	108.56 ± 50.91	46.90
	LA	7.40	175.48	168.08	83.22 ± 38.26	45.97
	Autumn-winter experiment					
'Caipira do Norte' (*n* = 250)	L	4.20	15.70	11.50	10.51 ± 2.24	21.31
	W	4.10	17.90	13.80	11.04 ± 2.45	22.19
	L×W	17.22	279.24	262.02	121.11 ± 50.81	41.95
	LA	16.25	214.18	197.93	91.19 ± 34.54	37.88

n – number of measurements; Min – minimum; Max – maximum; Amp – amplitude; SD – standard deviation; CV – coefficient of variation.

This high data amplitude enhances the representativeness of the regression models and ensures high precision in their development. These models can be reliably used to estimate the leaf area of gherkin leaves during different stages of crop development. Other authors reinforce the use of a database with wide variability to ensure the development of models that may have a wide utility (Cargnelutti Filho et al., 2015; Ribeiro et al., 2019ab; Toebe et al., 2019; Ribeiro et al., 2020; Silva et al., 2023; Ribeiro et al., 2025).

Regression models developed to estimate the leaf area of different plant species can provide researchers with many advantages in experiments, as it is possible to obtain LA without causing damage to plants, that is, multiple measurements can be made over time on the same leaf (Brito-Rocha et al., 2016; Lavanhole et al., 2018; Toebe et al., 2021). In the present study, the behavior of the 'Caipira do Norte' (Figure 2) and 'Liso Calcutá' (Figure 3) cultivars were similar in relation to data dispersion. Linear patterns between L and W and L×W and LA and nonlinear between L and L×W, L and LA, W and L×W, and W and LA were observed. Therefore, indicating the need to test different types of regression models from the linear measurements of the leaves for leaf area estimation. Linear without intercept (y = ax) and power ($y = ax^b$) models were tested in the present study, as shown in Table 3.

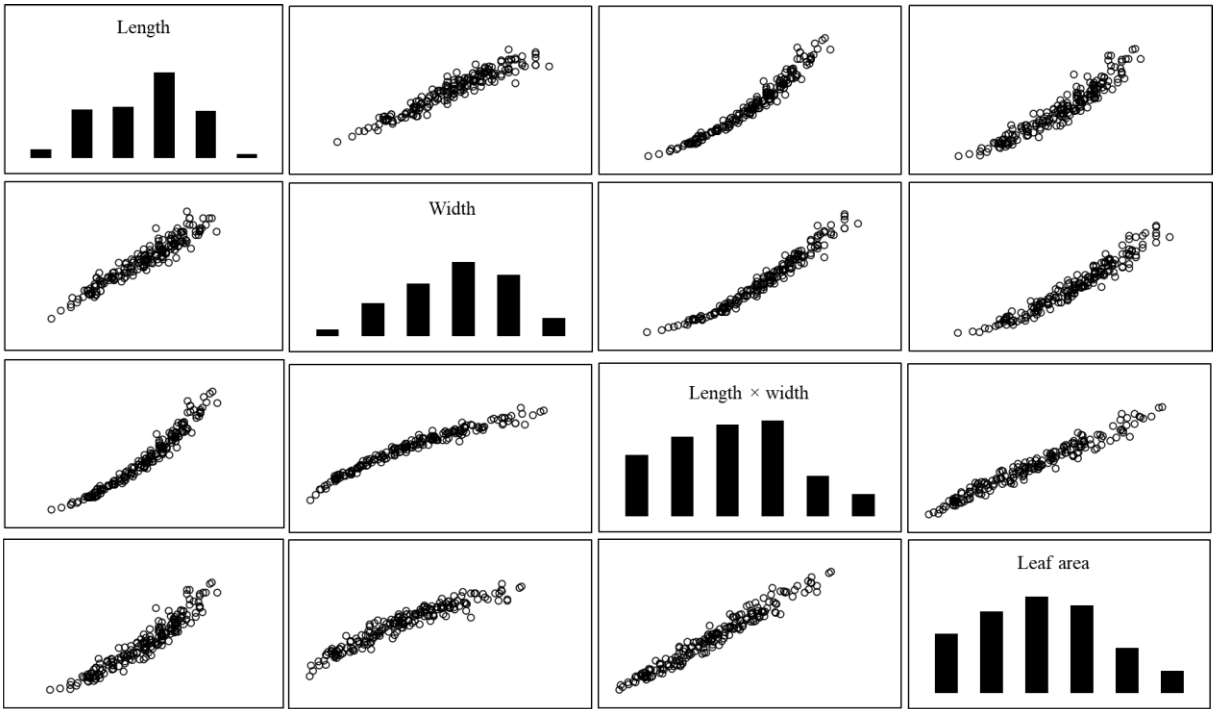


Figure 2: Frequency histograms (diagonal) and data dispersion between the length, width, length × width product, and leaf area of 192 leaves of gherkin 'Caipira do Norte' used in the test of models to estimate the leaf area.

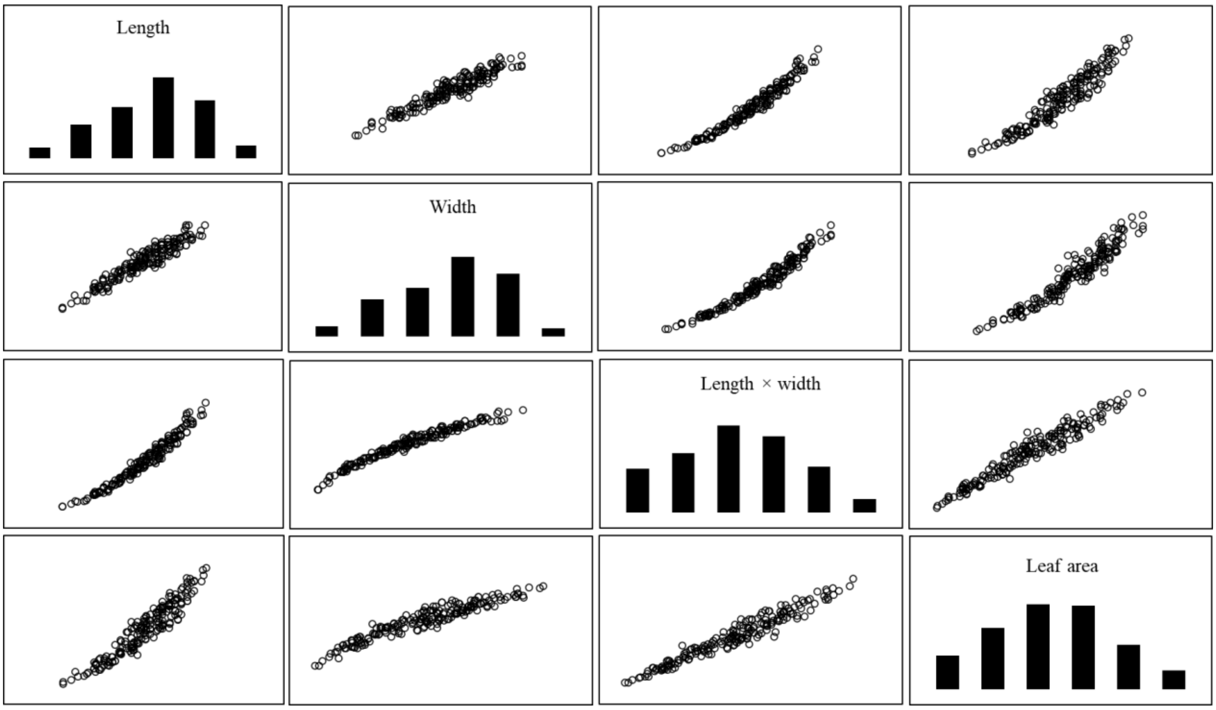


Figure 3: Frequency histograms (diagonal) and data dispersion between the length, width, length × width product, and leaf area of 192 leaves of gherkin 'Liso Calcutá' used in the test of models to estimate the leaf area.

Table 3: Models for individual leaf area estimation of gherkin 'Caipira do Norte' and 'Liso Calcutá' in summer-autumn experiment

Models No.	Parameters	Fitted models	r	R^2	*d*	RMSE
		'Caipira do Norte'				
1	L	LA = 9.4606×L	0.9520	0.9063	0.9126	21.38
2	W	LA = 8.7069×W	0.9679	0.9368	0.9214	20.36
3	L×W	LA = 0.7541×L×W	0.9804	0.9611	0.9899	9.12
4	L	$LA = 1.2664 \times L^{1.8233}$	0.9599	0.9215	0.9791	12.70
5	W	$LA = 1.1836 \times W^{1.7892}$	0.9732	0.9471	0.9860	10.44
6	L×W	$LA = 1.2388 \times (L \times W)^{0.9025}$	0.9804	0.9613	0.9895	9.03
		'Liso Calcutá'				
7	L	LA = 9.0642×L	0.9508	0.9041	0.9049	18.86
8	W	LA = 8.4760×W	0.9585	0.9188	0.9083	18.32
9	L×W	LA = 0.7585×L×W	0.9718	0.9444	0.9855	9.06
10	L	$LA = 1.3201 \times L^{1.7988}$	0.9539	0.9099	0.9758	11.52
11	W	$LA = 1.0768 \times W^{1.8322}$	0.9623	0.9260	0.9791	10.46
12	L×W	$LA = 1.0018 \times (L \times W)^{0.9442}$	0.9725	0.9458	0.9849	8.98
		Grouped data				
13	L	LA = 9.2636×L	0.9508	0.9040	0.9083	20.05
14	W	LA = 8.5941×W	0.9640	0.9293	0.9154	19.33
15	L×W	LA = 0.7296×L×W	0.9769	0.9543	0.9882	8.94
16	L	$LA = 1.2714 \times L^{1.8181}$	0.9572	0.9163	0.9776	11.42
17	W	$LA = 1.1598 \times W^{1.7997}$	0.9685	0.9380	0.9835	10.43
18	L×W	$LA = 1.0024 \times (L \times W)^{0.9440}$	0.9772	0.9549	0.9883	8.88

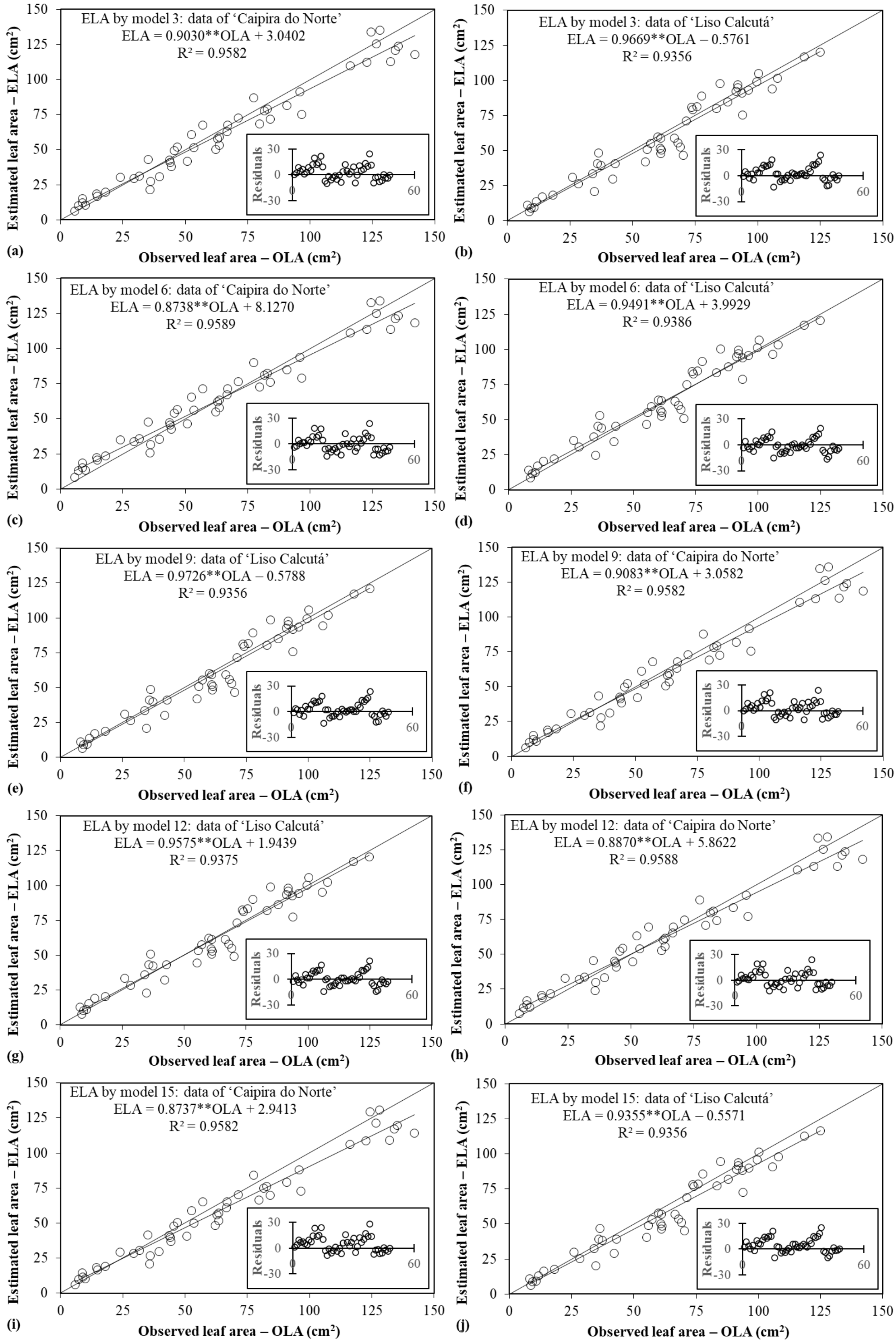
L – leaf length; W – leaf width; LA – leaf area; r – Pearson's linear correlation coefficient; R^2 – coefficient of determination; *d* – Willmott's agreement index; RMSE – root mean square error.

A total of 18 models for individual leaf area estimation of gherkin cultivars (individually or jointly) were fitted based on the input variables L, W or L×W. In general, for the gherkin cultivars analyzed individually or jointly, the L×W product was the independent variable that best explained most variations in LA in comparison to individual measurements (L or W). Using the power-type model with individual measurements of L or W provides good accuracy; however, with slightly higher RMSE values compared to those obtained using the L×W product. Therefore, we chose to select the models involving the use of the L×W product. Six models (3 and 6 for cv. 'Caipira do Norte', 9 and 12 for cv. 'Liso Calcutá', and 15 and 18 for grouped data) were used in the validation (Table 3).

Reinforcing these results, for other plant species, such as *Capsicum annuum* (Padrón et al., 2016), *Durio zibethinus* (Kumar et al., 2017), *Litchi chinensis* Sonn. (Oliveira et al., 2017), *Olea europaea* (Koubouris et al., 2018), *Erythroxylum simonis* (Ribeiro et al., 2018), *Pennisetum glaucum* (Leite et al., 2019), *Moringa oleifera* (Macário et al., 2020), *Stevia rebaudiana* (Hernández-Fernandéz et al., 2021), *Manilkara zapota* L. (Ribeiro et al., 2023), *Dendranthema grandiflora* (Silva et al., 2023), *Ricinus communis* L. (Ribeiro et al., 2025), the best estimates of LA were obtained from the L×W product.

In the literature there are different types of mathematical models developed to estimate the LA of various plant species and leaf types. However, they point out that usually the models are restricted to specific species and leaf shapes (Dutra et al., 2017; Hernández-Fernandéz et al., 2021; Silva et al., 2021). In this context, as done in the present study, designing robust models involving more than one cultivar of the same species and with different leaf shapes is paramount, thus avoiding biased models for a given cultivar. Using dependent data (summer-autumn experiment), a smaller data dispersion around of the 1:1 line was verified with the models 3 (Figure 4a), 6 (Figure 4c), 9 (Figure 4f), 12 (Figure 4h), 15 (Figure 4i), and 18 (Figure 4k) in the validation with data of the gherkin 'Caipira do Norte'. For gherkin 'Liso Calcutá', there was a greater data dispersion, regardless of the model (Figures 4b, 4d, 4e, 4g, 4j, and 4l). In the validation with independent data (autumn-winter experiment) only of the gherkin 'Caipira do Norte', data dispersion around of the 1:1 line was similar for all constructed models (Figure 5).

In summary, the models called universal can be used to estimate the LA of other gherkin cultivars, unless the leaf morphology of these cultivars differs considerably from that of the cultivars used in this study. This is reinforced by other studies with different crops, such as *Gladiolus* x *grandiflorus* Hort. (Schwab et al., 2014), *Vitis vinifera* L. (Buttaro et al., 2015), *Juglans regia* L. (Keramatlou et al., 2015), *Coffea canephora* (Schmildt et al., 2015), *Solanum aethiopicum* (Nakanwagi et al., 2018), *Acca sellowiana* (Sánchez-Mora et al., 2019), *Solanum tuberosum* L. (Oliveira et al., 2020), *Manihot esculenta* Crantz (Trachta et al., 2020), and *Chrysanthemum morifolium* (Fanourakis et al., 2021), which developed universal models to estimate LA of these species.


ELA by model 3: data of ‘Caipira do Norte’
ELA = 0.9030**OLA + 3.0402
R² = 0.9582
ELA by model 3: data of ‘Liso Calcutá’
ELA = 0.9669**OLA – 0.5761
R² = 0.9356
ELA by model 6: data of ‘Caipira do Norte’
ELA = 0.8738**OLA + 8.1270
R² = 0.9589
ELA by model 6: data of ‘Liso Calcutá’
ELA = 0.9491**OLA + 3.9929
R² = 0.9386
ELA by model 9: data of ‘Liso Calcutá’
ELA = 0.9726**OLA – 0.5788
R² = 0.9356
ELA by model 9: data of ‘Caipira do Norte’
ELA = 0.9083**OLA + 3.0582
R² = 0.9582
ELA by model 12: data of ‘Liso Calcutá’
ELA = 0.9575**OLA + 1.9439
R² = 0.9375
ELA by model 12: data of ‘Caipira do Norte’
ELA = 0.8870**OLA + 5.8622
R² = 0.9588
ELA by model 15: data of ‘Caipira do Norte’
ELA = 0.8737**OLA + 2.9413
R² = 0.9582
ELA by model 15: data of ‘Liso Calcutá’
ELA = 0.9355**OLA – 0.5571
R² = 0.9356
Estimated leaf area – ELA (cm²)
Observed leaf area – OLA (cm²)
Residuals
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)

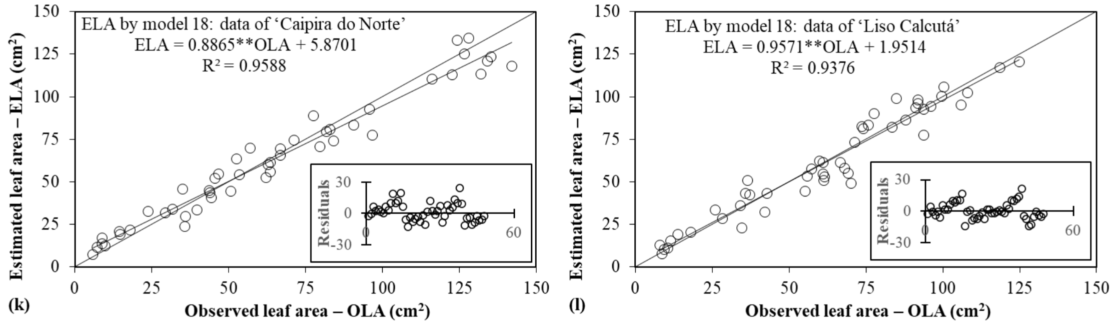


Figure 4: Analysis of dispersion pattern of differences between observed leaf area (OLA) and estimated leaf area (ELA) using different individual and grouped data models for two gherkin cultivars ('Caipira do Norte' and 'Liso Calcutá') in summer-autumn experiment (dependent data). An analysis of the residual dispersion pattern is also presented in the graphs.

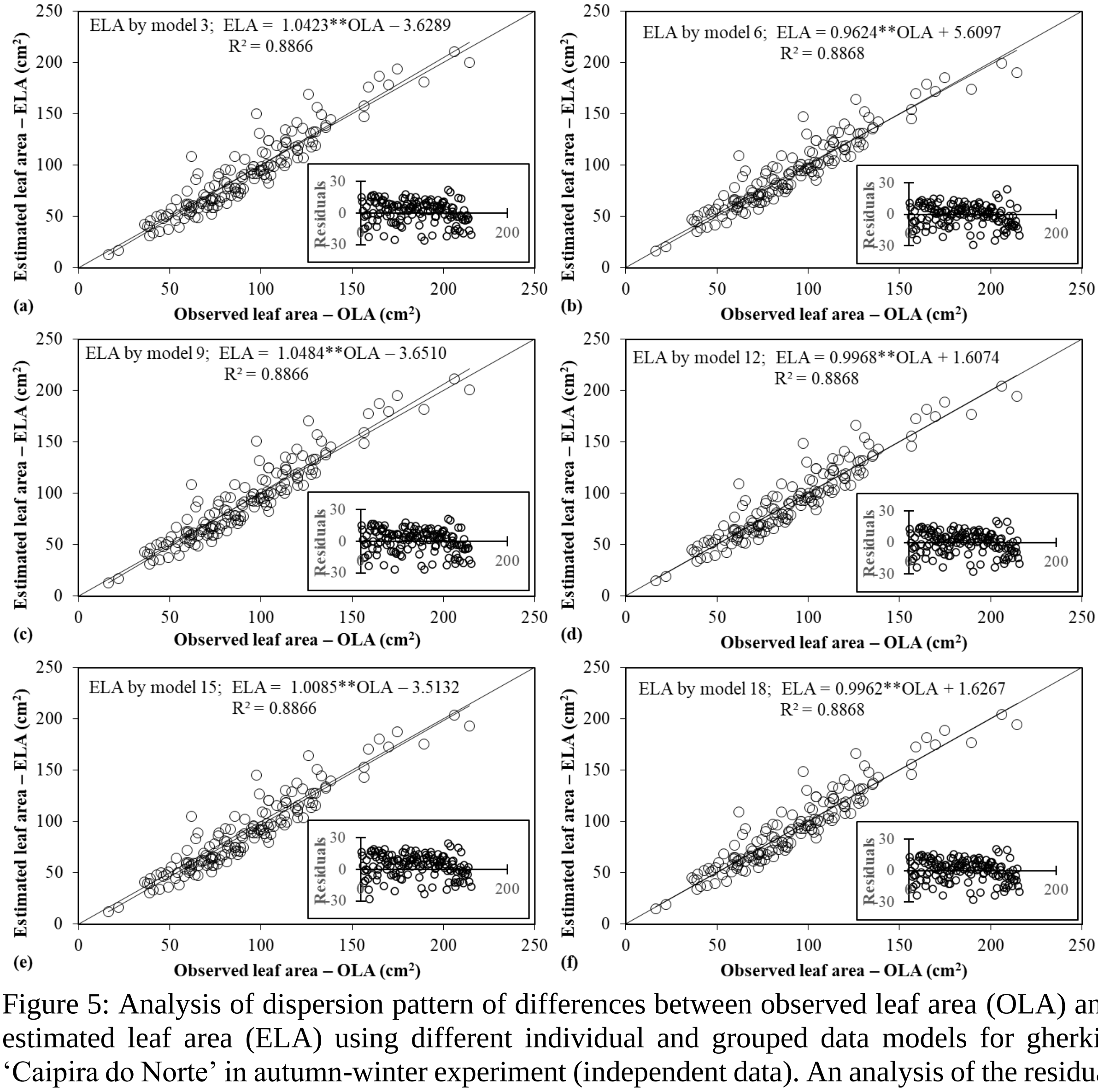


Figure 5: Analysis of dispersion pattern of differences between observed leaf area (OLA) and estimated leaf area (ELA) using different individual and grouped data models for gherkin 'Caipira do Norte' in autumn-winter experiment (independent data). An analysis of the residual dispersion pattern is also presented in the graphs.

Conclusions

From linear measurements (length – L, width – W, or L×W), we developed linear and power models to estimate the individual leaf area (LA) of the gherkin (*Cucumis anguria* L.). The best estimates of individual LA of gherkin were obtained using the L×W product as an independent variable.

The grouping of two gherkin cultivars (‘Caipira do Norte’ and ‘Liso Calcutá’) into a single model was possible. Therefore, based on higher accuracy and lower errors, the linear (LA = 0.7296×L×W; r = 0.9769, R^2 = 0.9543, d = 0.9882, and RMSE = 8.94) and power (LA = $1.0024\times(L\times W)^{0.9440}$; r = 0.9772, R^2 = 0.9549, d = 0.9883, and RMSE = 8.88) models, using grouped data, are indicated for individual LA estimation of the gherkin.

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