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Estimating leaf area in velvetleaf (*Limnocharis flava*) and kangkong (*Ipomea aquatica*): a precise and non-destructive approach for wetland vegetables

Abstract. Developing a leaf-area estimation model for vegetable cultivars in wetlands is essential to optimizing agricultural cultivation practices. This study aims to develop a non-destructive model for leaf area estimation in wetland vegetable cultivars (velvetleaf (*Limnocharis flava*) and kangkong (*Ipomoea aquatica*)) using regression-based models. The plants were cultivated in a wetland system. Measurements of leaf length and width were taken on all leaves of each plant, using the product of length and width (L×W) as predictor. The regression models for estimating leaf area were adjusted from linear, zero-intercept linear, quadratic, and power. The optimal model was evaluated using the determination coefficient (R^2) and the Root Mean Square Error (RMSE). The results showed that the most reliable regression model for estimating velvetleaf leaf area was linear regression with the equation $y = 0.881LW - 7.615$ ($R^2 = 0.954$; RSME = 7.916), and the power model for kangkong leaf area, with the equation $y = 0.9407LW^{0.9309}$ ($R^2 = 0.970$; RSME = 1.695). Differences in leaf shape among plant species result in different accuracies of leaf area estimation models. Thus, the model should be useful to guide future research and practical applications in monitoring leaf growth and determining harvest time.

Keywords: Leaf area estimation · Leaf shape · Regression models · Vegetable crops · Wetlands

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Introduction

The current rise in public awareness of the importance of vegetable consumption in promoting health has significantly increased the demand for vegetables in Indonesia. Vegetable and fruit consumption in Indonesia in 2024 reached around 89.3 kg per capita per year, equivalent to 244 grams per day (Ministry of Agriculture, 2024). This number is still far below the WHO recommendation of a minimum consumption of 400 g/day of fruits and vegetables (Ruiz-López & García-Villanova, 2023). The situation increases the opportunity for the development of domestic vegetable production.

The use of wetlands for vegetable cultivation can be a strategy for diversifying agricultural businesses while optimizing underutilized land. Indonesia has an estimated 20.6 to 40.5 million hectares of wetlands spread across various regions, mainly in Sumatra, Kalimantan, and Papua (Sulaiman et al., 2019). Approximately 9.53 million hectares of wetlands in Indonesia have potential for agricultural use, of which 6 million hectares are suitable for food crops (Aristin et al., 2024).

The use of wetlands for vegetable cultivation can be a strategy for diversifying agricultural businesses while optimizing underutilized land. Based on the inventory data from the Ministry of Environment and Forestry, Indonesia has an estimated 20.6 million hectares of wetlands spread across various regions in Sumatra, Kalimantan, and Papua (Bappenas, 2023). The largest portions of these wetlands consist of 13.43 million hectares of peatlands and 3.45 million hectares of mangroves. Approximately 9.53 million hectares of wetlands in Indonesia have potential for agricultural use, of which 6 million hectares are suitable for food crops (Aristin et al., 2024).

One important aspect of developing vegetables in wetlands is understanding plant growth characteristics, particularly leaf area. Leaf area is a very important physiological parameter due to its fundamental role in plant growth, photosynthates, and plant productivity (Rahimikhoob et al., 2023). Leaf area affects the efficiency of sunlight absorption and the production of photosynthates that will be translocated to plant organs (Pandey et al., 2021). In wetland conditions with specific environmental characteristics, information on the leaf area of vegetable plants is crucial for understanding plant growth responses to environmental stresses such as high humidity, low pH, and limited oxygen availability in the root zone.

Accurate leaf area measurement is necessary for various research and cultivation purposes, including plant growth analysis, leaf area index calculation, net assimilation rate, and evaluation of plant response to cultivation treatments (Dias et al., 2022). However, conventional leaf area measurement using destructive methods, such as gravimetry or millimeter paper, is time-consuming, costly, and damaging to the plants being observed (Ribeiro et al., 2019). Therefore, the current development of leaf area estimation methods is a leaf-dimension-based method (leaf length and width) that uses certain leaf shape constants or coefficients (Kumar et al., 2022). This method has advantages because it is non-destructive, easy to do, fast and accurate, does not require expensive equipment, and can be applied directly in the field. This non-destructive method is particularly important for long-term research that requires repeated observations on the same plants.

Estimating leaf area using non-destructive methods, particularly through linear regression, has emerged as an essential approach in agricultural and botanical research. Non-destructive techniques serve various applications, including assessing plant health, monitoring photosynthetic efficiency, and optimizing resource management under varying environmental conditions. The resulting model can be used to monitor leaf development by measuring leaf length and width without picking the leaves. By offering a low-cost, effective alternative to destructive methods, they enable researchers to repeatedly measure leaf area, allowing time-series data to be collected on the same leaves without disrupting their growth (Dias et al., 2022; Madhavi et al., 2022).

Several studies have demonstrated the efficacy of linear regression models in estimating leaf area from easily measurable parameters such as leaf length and width. Pacheco et al. (2020) illustrate how simple linear regression can yield high coefficients of determination (>0.90) when applied to leaf morphological dimensions, establishing a solid foundation for predicting leaf area. Similarly, Kumar et al. (2022) emphasize the advantages of non-destructive methods in approximating leaf area, specifically in the context of evaluating photosynthetic capacity and growth metrics. These findings are confirmed by Lakitan et al. (2023), who found that a linear relationship between leaf area and lamina dimensions is preferable for rapid measurements.

Despite these advancements, a notable gap remains in applying these techniques across diverse crop species and environmental conditions. While existing models may perform effectively for specific plants, their reliability across a broader range of species remains to be validated. Furthermore, Sabr (2020) points out that many existing models may not adequately account for variability introduced by different ecological contexts, indicating a need for the development of more universally applicable models. Enriching datasets to cover a broader range of species and environmental conditions is essential to enhance the applicability of non-destructive methods. The linear models of leaf area are specific to each plant species and can be influenced by growing conditions (Oliveira et al., 2019).

Current approaches have evolved beyond simple linear regression to incorporate more complex methods that improve accuracy, depending on leaf shape and plant species. The most common approaches use the product of length (L) and width (W), including methods with a zero intercept, power functions, and polynomials (Lakitan et al., 2023; Muda et al., 2024; Ribeiro et al., 2022). Muda et al. (2024) found that zero-intercept regression was suitable for estimating leaf area in butterhead lettuce grown under shallow water tables. The selection of a more accurate model is based not only on the R^2 value but also on the lowest RMSE, which indicates a smaller average prediction error.

At present, research on leaf area estimation in vegetable crops cultivated in wetlands remains very limited, resulting in a lack of accurate, reliable models for the specific wetland conditions in Indonesia. Information on leaf area is essential for understanding how vegetable crops grow in specific environmental conditions and for optimizing cultivation practices. This study observes two wetland-based vegetable crops, velvetleaf and kangkong, which are widely cultivated in Indonesia. Kangkong is ranked among the top five most consumed vegetables by the Indonesian population (Statistics Indonesia, 2025), while velvetleaf is a vegetable currently widely cultivated as a commercial commodity (Ramagita et al., 2025).

Unlike many dryland vegetables that possess relatively stable leaf geometries, velvetleaf and kangkong exhibit the physical capacity to adjust their morphology, such as stem length and leaf width, to survive in their respective environments. Kangkong frequently undergoes a transition from a narrow-lanceolate to a broad-cordate leaf shape, while velvetleaf adjusts its blade-to-petiole ratio in response to water depth. Consequently, general linear models often fail to capture these non-linear allometric shifts.

Therefore, this study aims to develop a regression model to estimate leaf area for velvetleaf and kangkong that can be used practically, accurately, and efficiently, accounting for morphological growth and leaf shape variation in vegetable crops. This study addresses the gap by comparing several regression models, including linear, zero-intercept, quadratic, and power regression approaches, ensuring a model that remains accurate across diverse growth stages under wetland environmental conditions. With a reliable model, leaf area measurements can be conducted more easily and quickly, supporting various research and applications in wetland agriculture, while helping farmers and field practitioners measure leaf area without compromising accuracy. A precise leaf-area estimation model is expected to fill the existing knowledge gap and provide practical contributions to vegetable crop management in wetland ecosystems.

Materials and Methods

The research was carried out during the rainy season from February to March 2025 with a tropical climate. The experimental site was a lowlands urban area, located in Pematang Sulur Village, Telanaipura, Jambi City. Temperature and humidity measurements during the study are shown in Fig. 1. The plants used in this study were vegetables commonly sold in markets and consumed by the community, namely velvetleaf and kangkong. Both plants can survive in waterlogged soil and have different leaf shapes. Velvetleaf leaves are oval-shaped, smooth, and have curved veins. Meanwhile, kangkong has arrowhead or heart-shaped leaves with pointed tips and a smooth surface.

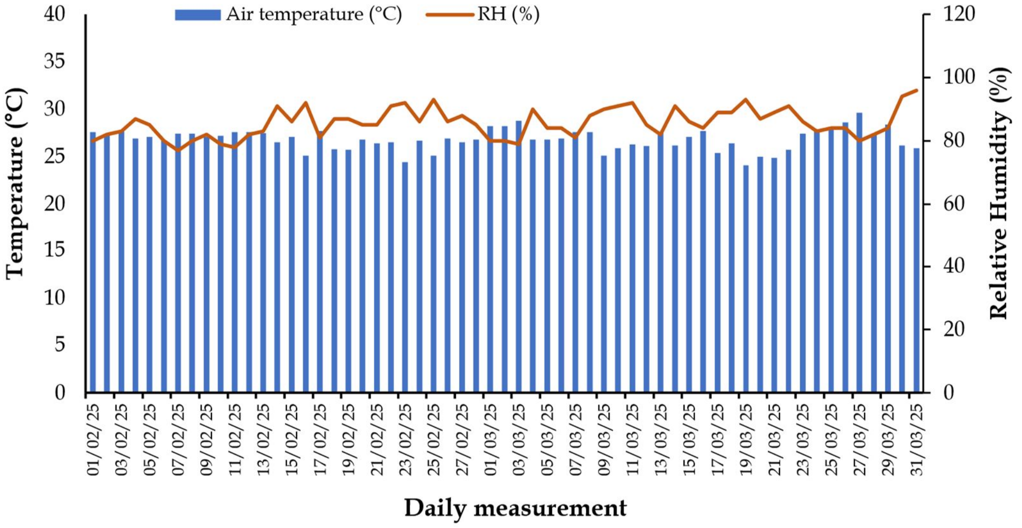

Figure 1. Daily air temperature and relative humidity during the research

The velvetleaf used in this study was derived from certified seeds. Velvetleaf seeds were germinated by sowing them in a container filled with a mixture of soil and water until sprouts appeared (approximately 30 days), then transferred to the nursery. Meanwhile, kangkong was propagated vegetatively using 10 cm-long stem shoots, then planted in a nursery containing a 1:1 mixture of soil and manure and watered until the soil was moist. After 2 weeks, each plant was transferred to a plastic pot containing 2 kg of soil. Then every pot was filled with 400 ml of water until the soil was flooded up to the lower stem, approximately 5 cm above the soil surface. The plants were placed in an area covered with a transparent plastic roof to prevent rainwater from entering, but still exposed to sunlight. To maintain waterlogged conditions, water was added daily until the water level reached 5 cm above the soil surface. Plants were fertilized by spraying Bayfolan D leaf fertilizer at 2 mL L^{-1} every 4 days.

Data collection. The study was conducted with three replicates. Each group consisted of 32 plants, with 16 plants of each type, yielding a total of 48 plants of each type. The total number of plants (population) was 96, and 50% were randomly selected as samples. Leaf length (L) and leaf width (W) were measured on all leaves of an individual plant, starting when the leaves began to open (Fig 2). Observations were conducted every two days over an 18-day period, starting from 28 days after planting at the onset of the vegetative phase until 46 days after planting at the end of the vegetative stage, marked by the emergence of flowers. Leaf length was measured along the midrib, starting from the base of the leaf (the point where the leaf blade meets the petiole) to the tip of the leaf. Leaf width was measured at the widest part of the leaf blade, from the left edge to the right edge. Immature leaves were measured when they had fully unfolded.

Leaf area (LA) was predicted using the product of length and width (L×W) as the predictor in a simple regression model. The predicted leaf area was verified by comparing the regression values and actual leaf area measurements. Actual leaf area was measured at harvest by collecting all leaves from each sample plant and measuring them individually using a Digital Image Scanner with Easy Leaf Area software. This software is used for quick and non-destructive leaf area measurements by placing leaf samples on a white background and taking digital photos (Easlon & Bloom, 2014). The number of leaf samples in this study was 200–400, which represents a strong sample size (n > 200) to ensure the model has statistical power and represents population variability while remaining accurate across various growth stages (Pérez-Harguindeguy et al., 2013).

Data analysis. Various regression models have been used in previous studies to predict leaf area. This study used several of the most accurate regression models to predict leaf area, namely: (a) linear model, (b) zero-intercept linear, (c) quadratic, and (d) power (Lakitan et al., 2023;

Muda et al., 2024). The predictor used to predict leaf area in this study was L×W. The L×W predictor is the most optimal variable for predicting leaf area in plant species with different leaf shapes (Lakitan et al., 2017; Liu et al., 2017) and provides smaller RMSE results compared to regression models with predictors L and W (Ribeiro et al., 2024). The most accurate regression model was evaluated based on the coefficient of determination (R^2) dan the lowest RMSE. All statistical analyses were performed using IBM SPSS Statistics Version 25 for Windows (IBM Corporation, Armonk, USA) with a significance level of $p < 0.05$.

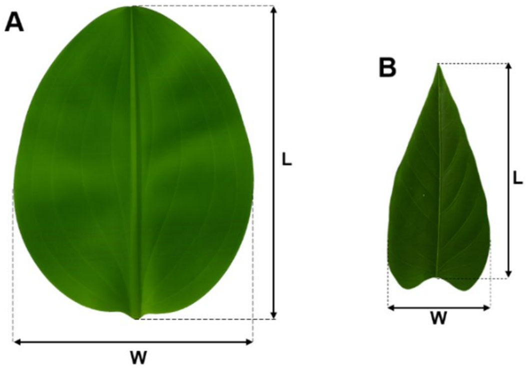

Figure 2. Illustrative of leaf midrib length (L) and width (W) in velvetleaf (A) and kangkong (B)

Results and Discussion

The area of the main leaf was determined by the length and width of the leaf, so the leaf growth observed in this study focused on the increase in leaf blade length and leaf width. Differences in plant species affect the rate of growth and development of leaves between plants. Table 1 displays the descriptive statistics for length, width, and aspect ratio (L/W) data along with the maximum, minimum, mean, and standard deviation. Leaf length was measured after the leaves had fully opened. The length of velvetleaf leaf blades ranged from 16.8 to 5.9 cm with an average of 11.21 cm and an average leaf elongation of 18 mm. Meanwhile, leaf width ranged from 15.5 to 4.7 cm with an average of 9.6 cm and an average leaf expansion of 13 mm. The increase in length and width of velvetleaf leaves occurred more rapidly in the early observation period until day 4, then increased slowly with the addition of new leaves until day 18 (Fig. 3).

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The increase in length and width of velvetleaf leaves is shown in Figure 3 (A and B). Velvetleaf leaves showed more consistent growth at each observation, with an average increase in length of 1.5 cm over the observation period. Meanwhile, the average increase in leaf width was greater than the increase in leaf length, which was 2.5 cm during the observation period.

Table 1. Descriptive analysis of leaf length (L) and width (W) in velvetleaf and kangkong

Plant	Parameter	Maximum	Minimum	Mean ± standard deviation
Velvetleaf	Length (cm)	16.80	5.90	11.21 ± 0.36
	Width (cm)	15.50	4.70	9.60 ± 0.49
	L/W ratio	1.33	1.17	1.23 ± 0.05
Kangkong	Length (cm)	12.6	1.9	6.95 ± 0.44
	Width (cm)	6.4	1.1	3.22 ± 0.23
	L/W ratio	2.24	2.00	2.09 ± 0.09

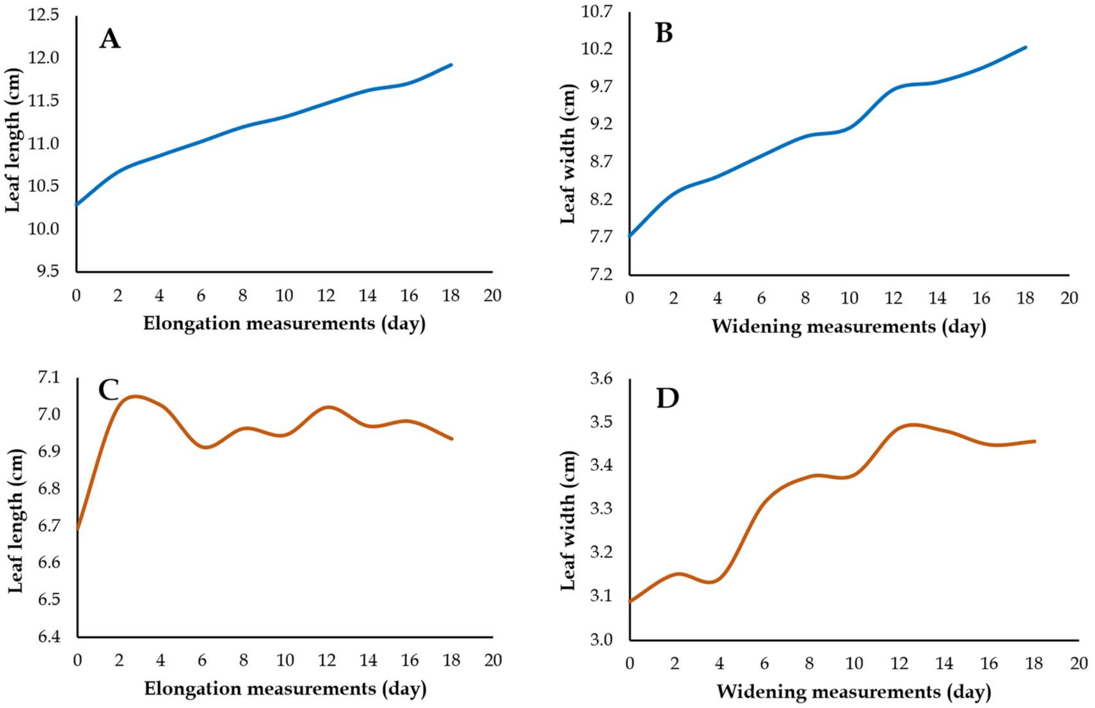

Figure 3. Daily leaf elongation and widening of velvetleaf (A and B) and kangkong (C and D)

Meanwhile, the growth of kangkong leaves is shown in Figure 3 (C and D). The growth graph shows that the average increase in the length and width of kangkong leaves is highly variable and inconsistent across observations. The increase in the length of kangkong leaves is faster in the first 4 days, but tends to be stable (no increase in leaf length) until the end of the observation. The average increase in kangkong leaf length was 0.2 cm. Meanwhile, the increase in kangkong leaf width was greater during the observation period, averaging 0.4 cm. This value indicates that leaf growth in both plants experienced a greater increase in leaf width than in leaf length.

Meanwhile, the ratio of leaf length to width is used to predict leaf shape. A higher L/W ratio indicates a more slender/elongated leaf shape, while a ratio of less than 1 indicates a more symmetrical leaf shape (Lakitan et al., 2023). Figure 4 shows that leaf shape development during the observation period was relatively consistent. The average L/W ratio for velvetleaf leaves was 1.23, while the L/W ratio for kangkong leaves was 2.09, twice that of velvetleaf leaves. This value is consistent with the slender shape of kangkong leaves with elongated tips. Meanwhile, the L/W ratio value for velvetleaf leaves was close to 1, indicating oval-shaped leaves.

Leaf shape is commonly used as the main characteristic in identifying plant species and is often considered a constant trait. Leaf growth has a self-regulatory pathway but is also influenced by increases in cell number, growth conditions, environmental factors, and plant genetics (Vercruysse et al., 2020). Leaf growth has a specific time limit, marked by the cessation of cell division earlier at the leaf tip and later at the leaf base. Once cell division stops, the rate of leaf growth will cease (Lakitan et al., 2018). There are differences in leaf size when they begin to open; velvetleaf leaves reach their full size in about 2 days, while kangkong leaves take about 8 days. In some plant species, leaf shape can change during the development stage (Li et al., 2020). However, in this study, the length and width ratio of velvetleaf and kangkong leaves during growth did not undergo significant changes, indicating that the shape of velvetleaf and kangkong leaves remained static/constant during the leaf enlargement process.

Regression model for leaf area prediction. Regression models and equations were obtained from the relationship between actual leaf area measurements and leaf length and width. In this study, the predictor used was L×W because it achieved the highest accuracy and the lowest

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RMSE compared to using L and W separately (Irwan & Wicaksono, 2017; Ribeiro et al., 2024). Leaf area testing used four regression models, namely linear, zero-intercept linear, quadratic, and power. Model accuracy was based on the higher coefficient of determination (R^2) and the lowest RMSE. However, in the context of model prediction accuracy, selecting an accurate model prioritizes absolute error metrics, such as RMSE (Ribeiro et al., 2022) . A lower R^2 value does not necessarily mean that the model is less accurate.

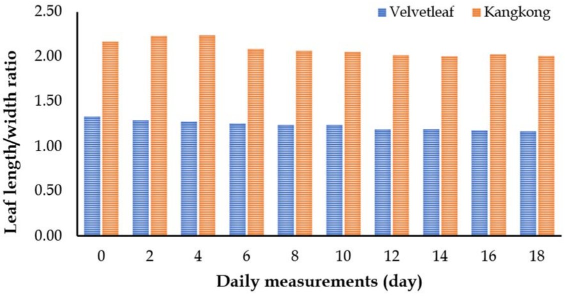

Figure 4. Ratio of leaf length and width (L/W) in velvetleaf and kangkong

Based on the results in Table 2, the most accurate model for estimating leaf area was the linear model for velvetleaf, and the power model for kangkong resulted in R^2 of 0.954 and 0.970, and RMSE of 7.916 and 1.695 for velvetleaf and kangkong, respectively. This model was selected based on the lowest RMSE, indicating a smaller average prediction error. Thus, the reliable equations to estimate leaf area for velvetleaf and kangkong are $y = 0.881LW - 7.615$ and $y = 0.9407LW^{0.9309}$, respectively. These results are similar to previous studies, which showed that the linear regression model using the LW predictor is effective and accurate for estimating leaf area with simple shapes across multiple species (Muda et al., 2024; Ribeiro et al., 2022). Meanwhile, the power model is occasionally more accurate for species with complex leaf shapes (Ribeiro et al., 2019). The differences in the selected models between velvetleaf and kangkong are due to differences in leaf shape, for which the linear model is more appropriate for predicting the area of oval-shaped and symmetrical leaves. In contrast, the power regression is more appropriate for slender leaves with tapered tips. A significant relationship between predicted and actual leaf area was confirmed using the selected model, as shown in Figure 5.

The total leaf area development in each subsequent observation was predicted using the selected regression equation model. The development of velvetleaf leaf area increased until day 12, then began to decline until day 18 (Fig. 6A). This occurred because some older leaves began to yellow and die, and the addition of new leaves slowed and then stopped. Meanwhile, in kangkong, the total leaf area continued to increase until day 18. It indicates that in kangkong, new leaves grow in greater numbers and more rapidly than in velvetleaf (Fig. 6B).

Based on the above discussion, accurate determination of leaf length and width is necessary to estimate leaf area for velvetleaf and kangkong to support vegetable production. The data reported in this study are consistent with previous research on other species, which found that model validation using a combination of measured leaf length and width yielded a high correlation between observed and predicted leaf area (Muda et al., 2024; Ribeiro et al., 2024). Under the same environmental conditions, namely in a wetland environment, research by Lakitan et al., (2023) on three varieties of Swiss chard showed that multiplying the length and width of the leaves provided an accurate estimate of leaf area. Thus, the results of this study indicate that the most reliable regression models for estimating leaf area in velvetleaf and kangkong were linear and power, respectively, using the LxW predictor.

Table 2. Regression model for predicting leaf area using LxW as predictor

Vegetable	Regression type	Equation	R^2	RSME
Velvetleaf	Linear	LA = 0.881LW - 7.615	0.954	7.916
	Zero-intercept linear	LA = 0.828LW	0.995	8.231
	Quadratic	LA = 0.0005(LW)^2 + 0.763LW - 0.651	0.955	7.938
	Power	LA = 0.599LW$^{1.064}$	0.964	21.234
Kangkong	Linear	LA = 0.697LW + 1.304	0.969	1.722
	Zero-intercept linear	LA = 0.74LW	0.993	1.805
	Quadratic	LA = -0.002(LW)^2 + 0.798LW + 0.231	0.970	1.710
	Power	LA = 0.9407LW$^{0.9309}$	0.970	1.695

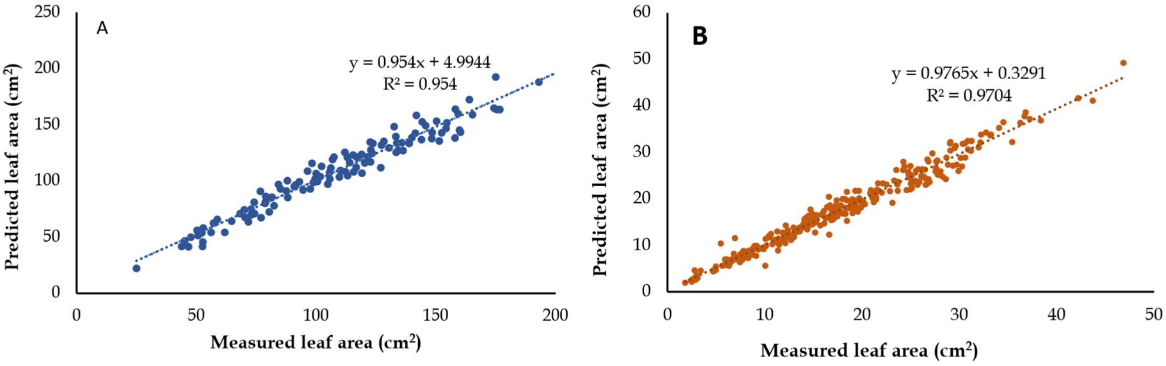

Figure 5. The relationship between predicted and measured leaf area (LA) regression model for velvetleaf (A) and kangkong (B)

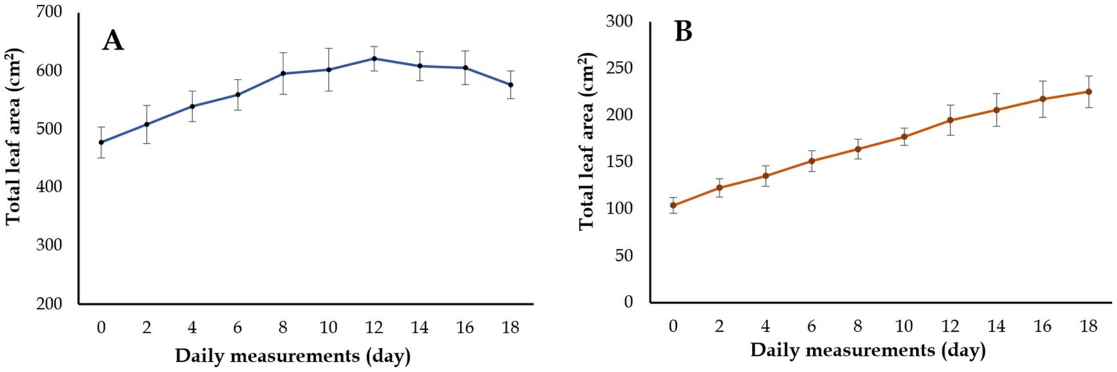

Figure 6. Total leaf area of velvetleaf (A) and kangkong (B) using zero-intercept linear models

Conclusion

The linear regression model developed in this study provides a practical, non-destructive solution for estimating leaf area. However, it remains limited to specific plant species and environmental conditions. Since leaf shape can vary depending on growth conditions, this formula may require further adjustment when applied under different conditions. For future research, it is essential to test these models across various land types and leverage technologies such as machine learning (artificial intelligence). By integrating manual methods with machine learning, more adaptive models can be developed to account for structural changes in plants across varying environments, thereby achieving higher accuracy without damaging field samples.

Acknowledgments

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