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Applying Some Mathematical Models to Estimate Leaf Area of Christ's-thorn Jujube trees (*Ziziphus spina-christi* L.) Based on Leaf Morphometric Measurements in the Koya District

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ABSTRACT

The Christ's-thorn jujube (*Ziziphus spina-christi* L.) is an important agricultural, medicinal, and ecological plant. Understanding photosynthetic capability, biomass buildup, transpiration, and ecological modeling all depend on accurate estimates of leaf area. In this study, 610 mature leaves of *Z. spina-christi* were collected in Koya district, Iraqi Kurdistan Region, Erbil, and measured for leaf length (L), width (W), and area (LA) in October 2025. Leaf area was estimated using regression-based models, which were statistically validated using the Statistical Package for the Social Sciences software. Simple linear, multiple linear, and exponential regression models were developed to predict leaf area from their dimensions. Although simple linear regressions based on L or W individually were statistically significant ($P < 0.001$), they accounted for only 78–85% of the observed variation in leaf area ($R^2 = 0.783–0.849$); greater predictive performance was achieved by models using the product of leaf dimensions (LW). Among all models evaluated, the simple linear regression model LA = 0.082 + 0.69 (LW) emerged as the most effective, providing the highest precision for its type ($R^2 = 0.972$, mean square error = 0.1). The more complex multiple linear regression model, $LA = 0.15 + 8.28\ L^2 + 0.41\ W^2$ ($R^2 = 0.96$), and the exponential model, $LA = 0.89e^{0.31(L + W)}$ ($R^2 = 0.94$), also displayed high accuracy but with increased computational complexity. The model LA = a + b (LW) is suggested as the best method, taking into account both practical simplicity and predicted accuracy. It provides a dependable, effective, and non-destructive instrument for physiological and agronomic studies on *Z. spina-christi.*

Index Terms: Leaf Area Estimation, Mathematical Methods, Morphometric Variables, Regression Models, *Ziziphus spina-christi*

1. INTRODUCTION

Christ's-thorn jujube *Ziziphus spina-christi* L., (locally known as "Sidr," and their fruits called Nabag) is an evergreen, drought-tolerant tree belongings to the Rhamnaceae family, a species of extensive ecological and cultural importance in Iraq, where arid and semi-dry and warm environments overcome, it prefers well-drained sandy, or loamy soils, it tolerates moderate salinity, and can survive in both clay and rocky soils if water is occasionally available. In Iraq, it grows commonly at 0–500 m asl, and it plays an important role in maintaining ecological balance by stabilizing soils, reducing erosion, and providing food and shelter for local wildlife [1]-[3]. The species is also deeply embedded in Iraqi populations' ecology and economy, as its leaves, fruits, and bark are used in local medicine and nutrition [4], [5]. *Z. spina-*

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christi yields edible fruits that are high in dietary fiber, minerals such as calcium, potassium, and iron, vitamins, particularly Vitamin C, and carbohydrates. Furthermore, animals ate the tree's leaves as fodder [6].

In plant science, leaf area is a basic morphological parameter that represents many physiological processes in plants, such as light interception, photosynthetic capacity, transpiration rate, water-use efficiency, growth potential, biomass accumulation, and general physiological health [7], [8]. In addition, leaf area produces information about plant development, productivity, and stress tolerance, which is considerable for species like *Z. spina-christi* that have adapted to drought [9]. Understanding leaf area is essential to understanding adaptation strategies, productivity, and ecological performance for this species in Iraq and Kurdistan, where environmental conditions vary significantly between locations. However, direct measurement methods such as planimetry, digital scanning, laser area meter, taking leaf pictures and converting them to a binary system with an image application program, and leaf tracing are sometimes time-consuming, damaging, and labor-intensive, making them unsuitable for extensive fieldwork [4], [10], [11].

To overcome these limitations, researchers have developed non-destructive mathematical models [12], especially regression-based equations, which predict leaf area from simpler, easily measured parameters such as leaf length and width. These models enable rapid, cost-effective, and repeatable estimations of leaf area without damaging the plants [13], [14].

Despite the widespread presence of *Z. spina-christi* across Iraq, including in semi-arid regions of Kurdistan, there remains a shortage of locally validated regression models tailored to this species in the Iraqi context, where only one study was conducted in the Anbar governorate, including simple linear regression only [3]. Therefore, generating a specific to the species and the region is critical for increasing the accuracy of estimating leaf area with supports the ecological and physiological studies. So, this study aims to develop and compare some regression equation models constructed on leaf length, width, and available combination to predict leaf area of *Z. spina-christi* by evaluating and validating different equation forms (simple linear, multiple linear, and exponential models), to identify the most accurate and practical models for non-destructive leaf area estimation for use in future physiological, ecological, and botanical studies.

2. MATERIALS AND METHODS

The study conducted on *Z. spina-christi* L. aged 5 years, cultivated in Koya district located 70 km east of the capital of the Erbil province, Iraq and is 620 m above sea level, situated 36.042° N, 44.632°W at a distance of 6 km from the Koya City Centre (Fig. 1), in a silty loam soil with pH of 7.7, Ec

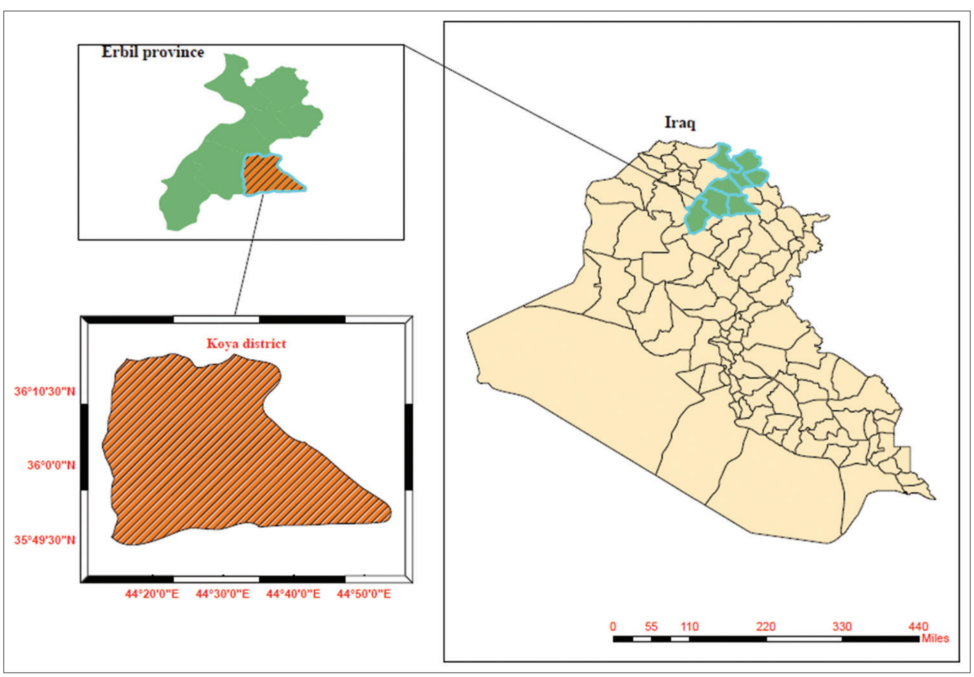

Fig. 1. Study area of Koya district

of 0.17 mS/cm, TDS of 109 ppm, OM of 1.45%, total N of 0.21%, and total phosphate of 320 ppm.

Leaf sampling was done in the fall season, the 15th of October 2025, by collecting mature leaves of different sizes from different positions of branches from different directions (north, south, east, and west). Meteorological data during the leaves' growth in the previous fall, winter, spring, and summer (before sampling) are detailed in Table 1.

2.1. Samples Collection

A total of 610 leaves of *Z. spina-christi* L. were carefully harvested, ensuring that only healthy, fully developed leaves were included in the study. Immediately after collection, the leaves were placed individually on flat sheets of paper to prevent moisture accumulation or physical deformation.

The leaves of *Z. spina-christi* L. are alternate, 3-nerved from the base, ovate-oblong to elliptic, rounded or subcordate at the base, 2.5–6 cm long, obtuse or retuse at the apex, margins entire or obsoletely crenate [15]. By maintaining each leaf's natural size, shape, and structural integrity, this technique allowed for precise morphological measurements for further examination. To prevent misunderstandings or measurement errors throughout the recording process, extra care was taken to maintain uniform handling and labeling.

2.2. Leaf Area Estimation, Measurements, and Parameters

In this research, three main leaf characteristics were assessed for each leaf sampled from *Z. spina-christi*: leaf length, leaf width, and leaf area (the average lengths, widths, and areas of the 610 leaves were found to be 3.26 cm, 2.61 cm, and 6.10 cm^2, respectively). Leaf length was characterized as the measurement from the base of the leaf to its tip, while leaf width was taken at the broadest section perpendicular to the midrib (Fig. 2a). Both measurements were taken using a standard ruler with an accuracy of 0.1 cm, and all values were recorded in centimeters (cm).

To enable precise leaf area measurement, all gathered leaves were photocopied with a high-resolution printer, generating flat and uniform images appropriate for further analysis (Fig. 3). The leaf area was subsequently calculated from these printed images utilizing a planimeter, a commonly used instrument for accurately determining the two-dimensional surface area of leaves, with results reported in square centimeters (cm^2) (Fig. 2b) [16], [17].

The use of manual measurements for both length and width, with planimetric assessments of leaf area (Fig. 3), assures dependable data that offer independent variables for introducing regression equations, which reduces biases from leaf curving and enables correction across samples [18]. Every measurement was exactly recorded in an organized dataset for statistical analysis.

TABLE 1: Meteorological data during the last year of taking the samples (October 2024–September 2025)

Months	Air temperature °C	Soil temperature °C	Rain mm	Sun hours
October	24.6	25.7	0	9.2
November	14.5	17.4	32	6.8
December	8.2	11.2	26.3	7.0
January	9.8	9.9	21.9	7.5
February	8.3	8.9	39.3	7.7
March	16.7	14.1	50.8	8.9
April	21.9	19.0	25.4	9.3
May	29.1	27.8	4.8	10.5
Jun	38.3	36.1	0	12.3
July	37.2	38.2	0	11.2
August	37.0	38.4	0	10.8
September	30.8	32.4	0	10.1

2.3. Statistical Analysis and Regression Modeling

To assess the correlations between leaf dimensions and measured leaf area and to create predictive models for non-destructive leaf area estimation for *Z. spina-christi*, statistical analyses of the data were done using the Statistical Package for the Social Sciences version 20 program. An analysis of variance was carried out to detect the significance of the different regression models, at a 5% probability level [19].

The relationship between measured leaf area as the dependent variable and each of leaf length, leaf width, the sum of leaf length and width, and the product of leaf length and width was used as independent variables using basic linear regression analyses, where equation 1 was applied. A preliminary evaluation of predictive potential was provided by this method, which made it possible to ascertain the degree of correlation between individual predictors and leaf area.

The combined effect of leaf length and width and their combinations on leaf area was then investigated using multiple linear regressions, which allowed for the integration of two independent variables as they appear in equation 2, and produced a more reliable and accurate estimation model. To account for possible non-linear regression, exponential regression was also tested using leaf length and width and all possible combinations as independent variables.

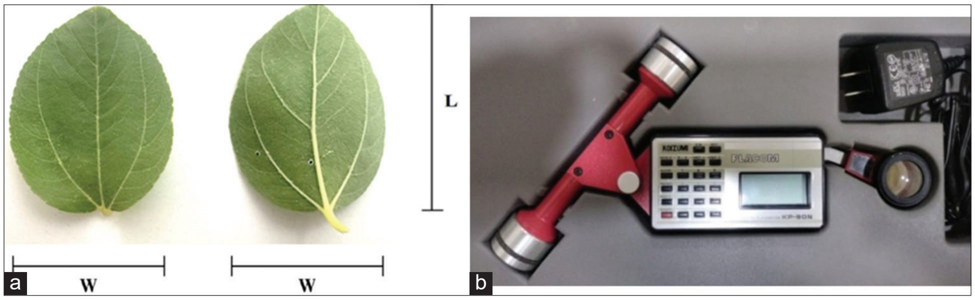

Fig. 2. (a) Adaxial and abaxial leaf surfaces of *Ziziphus spina-christi* L. appearing the leaf width and length, (b) the planimeter used to measure the leaves area.

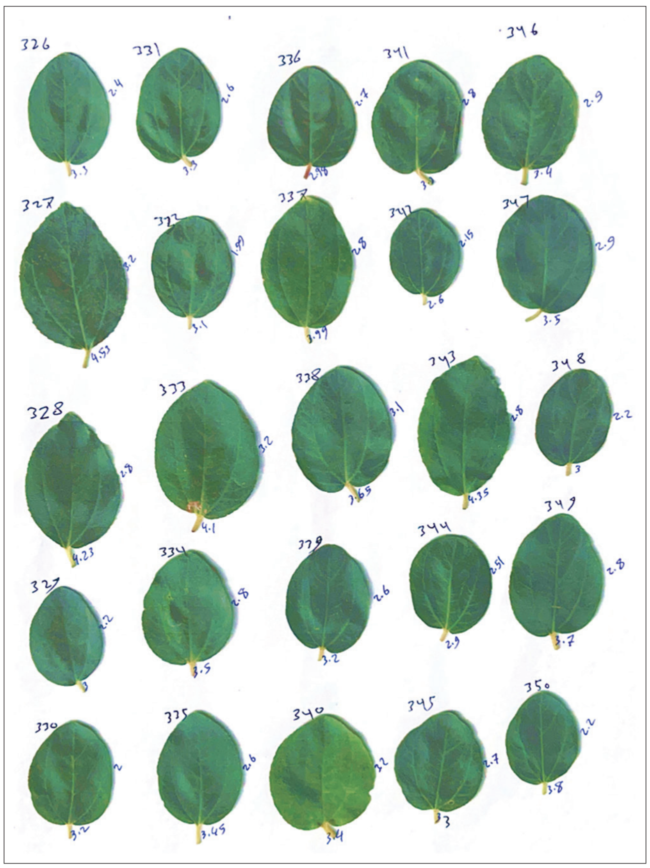

Fig. 3. A sample of the manual measurements for leaf length and width, arranged on a flat sheet of paper with planimetric assessments of leaf area.

The coefficient of determination (R^2), which indicates the percentage of leaf area variability explained by the independent variables, and the mean square error (MSE), which provides a measure of the average squared deviation between predicted and actual leaf area values, were used to evaluate the accuracy and performance of each regression model [20]. Together, these metrics ensure a comprehensive assessment of the models' predictive power and reliability for non-destructive leaf area estimation under field conditions.

The simple linear regression models that used the products of leaf length and width are appearing in equation 1.

$$LA = a + b\left(L, W, L+W, or\ LW\right) \tag{1}$$

Whereas, for the multiple linear regression, the models appear in equation 2 were used.

$$LA = a + b1\left(L\ or\ L^2\right) + b2\left(W\ or\ W^2\right) \tag{2}$$

And for the exponential models, the models shown in equation 3 were used.

$$LA = ae^{b(L, L^2, W, W^2,\ L+W\ or\ LW)} \tag{3}$$

3. RESULTS AND DISCUSSION

The results in Table 2 represent simple linear regression models showing highly significant relationships between the dependent variable LA and each of L, W, and their combinations as independent variables. It is shown that r^2 values of between 0.78 for the model based on W as an independent variable and 0.99 for the model that depends (LW), and MSE values of 0.10–0.83 for the (LW and W) independent variables, respectively.

Among the models tested, the simple linear regression model using the product of leaf length and width, expressed as: LA = 0.08 + 0.69 (LW), demonstrated the highest predictive accuracy ($r^2 = 0.99$, MSE = 0.10) while maintaining computational simplicity. While all simple linear models were statistically high significant ($P < 0.001$), the models depends either the leaf length or width alone explained only 78–85% of the variation in leaf area ($r^2 = 0.78$–0.85), whereas the models depend each of leaves' length and width explained 95–99% of the variation in leaf area ($r^2 = 0.95$–0.99).

As seen for the multiple linear regression, the results in Table 3 show highly significant relationships between the dependent variable LA and each of L, W and their combinations regarding the multiple linear regression models that show very close values of R^2 between 0.95 and 0.96 for all models that depends L with W, L^2 with W^2, L^2 with W and L with W^2 as independent variables, whereas MSE values were between 0.11 when L^2+W^2 were determined as independent variables and 0.19 when L with W were the independent variables. The more complex multiple linear regression model, $LA = 0.15 + 0.28\ L^2 + 0.41\ W^2$, was the best-regarded and provided high accuracy, having a higher R^2 of 0.96 and the lowest MSE of 0.11.

The exponential regression models used to predict *Z. spina-christi* sp. leaf area were highly significant, where leaf length and width and their combination were dependent as independent variables, as shown in Table 4. The model depends sum of leaf length and width $LA = 0.89\ e^{0.31(L+W)}$, was the best model, having the highest r^2 of 0.94 and a low MSE of 0.01.

As mentioned in the Materials and Methods section, the mean total leaf area was 6.10 cm^2, with an average length of 3.26 cm and an average width of 2.61 cm. When these mean length and width values were applied to the best simple linear regression model, the predicted leaf area was 5.95 cm^2, followed by the multiple linear regression model (5.92 cm^2) and finally the exponential regression model (5.49 cm^2).

The result of this study agrees with that of previous studies [18] on *Nerium oleander* L., which used different regression models (simple linear, multiple linear, and exponential models), and [20] on *Buxus empervirens, Duranta repens L., Lantana cammara, Morus alba*, and *Pittosporum tobira* plant species, who used simple and multiple linear regression and found that the simple linear regression relying on the product of multiplying L by W is the best independent variable for estimating the most accurate leaf area compared to L, W, or L+W as independent variables. Al-Hadethi and Al-Marsoumi [21], who used only the simple linear regression in their study for predicting jujube leaf area, found that the mathematical model (LA = 0.7528(LW) + 0.0241) was the best and most accurate model, whereas in the current study, more accurate predictive performance was achieved by adopting models dependent on both leaf dimensions (LW).

Regarding the multiple linear regression equations, the current study results are like the results obtained by Al-Barzinji and Amin [18] on *N. oleander* L., where the model dependent on L^2 with W^2 was more accurate than other models. Furthermore, only the multiple linear regression model ($LA = a+b_1L + b_2W$) was more accurate than simple linear regression models used for predicting leaf area of *Acer negundo, B. empervirens, Carissa macrocarpa, Dombeya wallichii, D. repens* L., *Ficus nitida, L. cammara, Ligustrum* sp., *M. alba*, and *P. tobira* [20]. Furthermore, Cho *et al*. [22] concluded that the model (LA) = −210.61 + 13.358W + 0.5356LW ($R^2 = 0.980$) may be useful for the estimation of the individual leaf area of cucumber (*Cucumis sativus* L.).

With respect to the exponential results, the same results were obtained by Al-Barzinji and Amin [18], where the exponential

TABLE 2: Simple linear regression models that used for estimating leaf area for *Ziziphus spina-christi* sp. with respect to the morphometric variables of the leaf length, width, and some of their compatibles

Model No.	Regression equation	Intercept (a)	Coefficient (b)	Coefficient of determination (r^2)	Coefficient of correlation (r)	Mean square error	Standard error	P-value
1	LA=a+bL	−4.48	3.25	0.85	0.92	0.58	0.76	0.001
2	LA=a+bW	−5.03	4.26	0.78	0.89	0.83	0.91	0.001
3	LA=a+bL+W	−6.40	2.10	0.95	0.97	0.19	0.11	0.001
4	LA=a+bLW	0.08	0.69	0.99	0.99	0.10	0.32	0.001

TABLE 3: Multiple linear regression models that used for estimating leaf area for Ziziphus spina-christi with respect to the morphometric variables of the leaf length, width, and some of their compatibles

Model No.	Regression equation	Intercept (a)	Coefficient (b_1)	Coefficient (b_2)	Coefficient of Determination (R^2)	Coefficient of Correlation (R)	Mean square error	Standard error	P-value
5	$LA=a+b_1L+b_2W$	−6.45	2.09	2.21	0.95	0.98	0.19	0.44	0.001
6	$LA=a+b_1L^2+b_2W^2$	0.15	0.28	0.41	0.96	0.98	0.11	0.34	0.001
7	$LA=a+b_1L^2+b_2W$	−2.80	0.28	2.23	0.96	0.98	0.13	0.36	0.001
8	$LA=a+b_1L+b_2W^2$	−3.40	2.02	0.41	0.96	0.98	0.14	0.38	0.001

TABLE 4: Exponential linear regression models that used for estimating leaf area for *Ziziphus spina-christi* sp. with respect to the morphometric variables of the leaf length, width, and some of their compatibles

Model No.	Regression equation	Intercept (a)	Coefficient (b)	Coefficient of Determination (r^2)	Coefficient of Correlation (r)	Mean square error	Standard error	P-value
9	$LA=ae^{bL}$	1.23	0.48	0.82	0.91	0.02	0.12	0.001
10	$LA=ae^{bL2}$	2.95	0.06	0.76	0.87	0.02	0.14	0.001
11	$LA=ae^{bW}$	1.06	0.65	0.81	0.90	0.02	0.12	0.001
12	$LA=ae^{bW2}$	2.63	0.11	0.77	0.88	0.01	0.13	0.001
13	$LA=ae^{b(L+W)}$	0.89	0.31	0.94	0.97	0.01	0.68	0.001
14	$LA=ae^{b(LW)}$	2.45	0.10	0.89	0.94	0.09	0.95	0.001

model L+W was more accurate than other models for *N. oleander* L. leaves. The results also agree with Yang *et al*. [23], who found that the TMEAD-BiLSTM model achieved the highest prediction accuracy ($R^2 > 0.99$), while the non-linear models exhibited lower accuracy ($R^2 > 0.78$).

4. CONCLUSION

The present study successfully developed and confirmed regression models for estimating the leaf area of *Z. spina-christi*, demonstrating that leaf length and width are highly correlated and can serve as consistent predictors of leaf area. Among the models tested, the simple linear regression using the product of leaf length and width (LA = 0.08 + 0.69 [LW]) achieved the highest accuracy ($R^2 = 0.972$) while maintaining computational simplicity, making it a practical and efficient tool for non-destructive leaf area estimation in both field and laboratory conditions. These findings suggest that physiologically relevant traits can be accurately predicted by readily measurable morphological parameters, providing an affordable substitute for direct planimetric measurements.

By incorporating mature leaves of various sizes, our results capture a wide spectrum of intraspecific variability. Therefore, the conclusions and the developed regression models are robust and can be generalized across different environments. Predictive accuracy may be improved by including extra morphological characteristics or digital imaging methods, especially when evaluating young or unusually shaped leaves or when stress is present.

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