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# Identification of Leaf Constant Values in Manalagi and Madu Mango Cultivars Based on Digital Image Processing

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***Abstract***

*Accurate leaf area measurement is crucial in plant physiology studies; however, conventional methods are often impractical and costly. This study aims to identify the leaf constant values of Manalagi and Madu mango cultivars using a digital image processing approach. A descriptive quantitative study was conducted at the Agrotechnology Laboratory of Pekalongan University using 40 healthy leaf samples from each cultivar. Leaf area was measured using ImageJ software, while leaf length and width were manually measured to calculate the leaf constant based on the Montgomery equation. The measurement data were analyzed using descriptive statistics, boxplots, linear regression analysis, and accuracy validation through RMSE, NRMSE, NSE, and Willmott's index of agreement (d). The results showed that the average leaf constant value was 0.706 for Manalagi and 0.779 for Madu, with homogeneous data distribution and no outliers. The correlation between the measured leaf area and the predicted leaf area was very strong, with $R^2$ values of 0.9947 for Manalagi and 0.9992 for Madu, along with very low prediction errors (NRMSE of 0.015 for Manalagi and 0.009 for Madu). Moreover, the NSE and Willmott's index values approached 1, indicating excellent model performance. These findings demonstrate that the derived leaf constants can be used as practical references for field leaf area estimation, contributing to more efficient agronomic research and horticultural crop management.*

**Keywords:** *Digital Image Processing, Leaf Area Estimation, Leaf Constant, Manalagi Mango, Madu Mango*

## 1. INTRODUCTION

Mango (*Mangifera indica* L.) is one of Indonesia's leading horticultural commodities, valued for its high economic potential and popularity among consumers (Kailaku et al., 2023; Rohman & Zulfikar, 2021). Among the various cultivars cultivated, Manalagi and Madu mangoes are well known for their sweet taste and distinctive aroma (Ardiani & Jannah, 2023; Ramadhan et al., 2024; Sembiring et al., 2020; Utami et al., 2019). In addition to serving as a significant source of income for farmers (Mardiah et al., 2024), mango plants are also frequently used as research subjects in agronomic studies, including investigations into leaf physiology and morphology as indicators of plant growth and productivity (Elhany et al., 2024). One of the most important physiological parameters in plant studies is leaf area, as it is closely correlated with photosynthetic capacity, nutrient uptake, and biomass accumulation (Akram-ghaderi & Soltani, 2007; Bhattacharya, 2019).

Accurate leaf area measurement is a fundamental requirement in plant physiology research (Gokkus & Gokkus, 2024; Kumar, 2009). However, conventional methods such as gravimetric techniques, graph paper, scanning, or the use of a Leaf Area Meter (LAM) present several limitations, including high costs, time-consuming processes, and complex measurement procedures (Al Ramadhani et al., 2024; Sala et al., 2015). Therefore, more practical, efficient, cost-effective, yet accurate approaches are needed. One widely used alternative is the Montgomery method, which estimates leaf area based on leaf length and width multiplied by a leaf constant value (k), expressed as $LA = L \times W \times k$. This leaf constant is a key parameter that is specific to each plant species or cultivar (Al Ramadhani, 2024; Sala et al., 2015), and thus must be determined before being applied in leaf area estimation.

Nevertheless, information regarding leaf constant values for Manalagi and Madu mango cultivars remains limited. These two cultivars exhibit distinct leaf shapes, which likely results in differences in

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their respective leaf constants (Putu et al., 2017). The absence of this data represents a gap in the development of Montgomery-based or dimension-based leaf area estimation methods specifically for mango plants. Hence, empirical studies are required to determine the leaf constant values of these cultivars using accurate and efficient approaches.

The objective of this study is to identify the leaf constant values of Manalagi and Madu mango cultivars using digital image processing techniques. The application of digital image processing is expected to provide rapid, accurate, and practical measurements of leaf dimensions and leaf area. By obtaining representative leaf constant values, leaf area estimation for mango plants in the field can be conducted more efficiently without the need for specialized measuring devices. This research is anticipated to make a significant contribution to the development of more adaptive and applicable methods for estimating the growth of horticultural crops across various levels of research and agricultural practice.

## 2. RESEARCH METHODS

### 2.1. Materials and Equipment

This study was conducted at the Agrotechnology Laboratory, Faculty of Agriculture, University of Pekalongan, from February to May 2025. The materials used were mango (*Mangifera indica* L.) leaves from Manalagi and Madu cultivars, with 40 leaf samples collected from each cultivar. Samples were taken from healthy, productive trees. The equipment included a smartphone with a 12 MP camera for leaf imaging, vertical and horizontal tripods, transparent acrylic sheets, white manila paper as the background, a black reference object measuring 5 × 5 cm for scale calibration, a ruler with 0,5 mm precision, a laptop, and ImageJ software version 1.51j8 for digital image processing.

### 2.2. Research Design and Conceptual Model

This study employed a descriptive quantitative research design with an approach focused on leaf constant identification. The conceptual model referred to Montgomery's (1911) equation for leaf area (LA) estimation, expressed as:

$$LA = L \times W \times k \tag{1}$$

where $LA$ is leaf area (cm$^2$), $L$ is leaf length (cm), $W$ is leaf width (cm), and $k$ is the leaf constant. The value of k was calculated using Equation 2.

$$k = \frac{LA}{L \times W} \tag{2}$$

In Equation 2, LA represents the measured leaf area obtained from digital image processing, whereas $L$ and $W$ were measured manually. The leaf constant value was thus calculated as the ratio between the measured leaf area and the product of leaf length and width.

### 2.3. Data Collection and Processing Procedures

The first step involved direct leaf imaging by placing each leaf on white paper containing the reference object for scale calibration (Al Ramadhani et al., 2024). Images were captured in a vertical position to minimize perspective distortion. The leaf images were then processed using ImageJ software to determine the measured leaf area in cm$^2$. Subsequently, the length and width of each leaf were measured manually using a ruler. These dimensional data were used to calculate the leaf constant value following Montgomery's formula (Equation 2).

All leaf constant values obtained from each sample were averaged to determine a representative constant value for each cultivar. A boxplot analysis was conducted to assess the distribution and stability of the constants. If the distribution showed good homogeneity without extreme outliers, the average constant value was used to re-estimate the leaf area (referred to as *Predicted Leaf Area*) based on leaf

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length and width (Equation 1). The Predicted Leaf Area was then compared with the *Measured Leaf Area* to evaluate the accuracy of the leaf constant in estimating leaf area.

### 2.4. Data Analysis Techniques

The data obtained were analyzed both descriptively and statistically. First, the distribution of the leaf constant values for each cultivar was analyzed using boxplot graphs to determine the spread, median, deviation, and presence of outliers (Williamson et al., 1989). Next, validation of the leaf constant values was conducted by calculating the *Predicted Leaf Area* using Montgomery's equation and comparing it with the *Measured Leaf Area*.

The agreement between the predicted and actual values was assessed using the coefficient of determination ($R^2$), Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMSE), Nash–Sutcliffe Efficiency (NSE), and Willmott's index of agreement (d) (Al Ramadhani, 2024; Al Ramadhani et al., 2023), as defined in Equations 3–7. These analyses were used to determine whether the leaf constant values obtained from each cultivar could be used as fixed parameters for estimating mango leaf area using the dimension-based method.

$$R^2 = \left[\frac{\sum(O_i-\bar{O})-(P_i-\bar{P})}{(O_i-\bar{O})\times\sum(P_i-\bar{P})}\right] \quad (3)$$

$$RMSE = \sqrt{\frac{\sum(P_i-O_i)}{n}} \quad (4)$$

$$NRMSE = \frac{1}{\bar{O}}\sqrt{\frac{\sum(P_i-O_i)^2}{n}} \times 100 \quad (5)$$

$$NSE = 1 - \frac{\sum(P_i-O_i)^2}{\sum(O_i-\bar{O})^2} \quad (6)$$

$$d = 1 - \frac{\sum(P_i-O_i)^2}{\sum(|P_i-\bar{O}|+|O_i-\bar{O}|)^2} \quad (7)$$

Keterangan:
$O_i$ : observed data
$\bar{O}$ : mean of observed data
$P_i$ : predicted data
$\bar{P}$ : mean of predicted data
$n$ : number of data
$d$ : *index of agreement*

## 3. RESULTS AND DISCUSSION

Digital image processing serves as the initial stage in obtaining accurate and efficient leaf area measurements (Fu et al., 2025; Ngo et al., 2022). This process begins with capturing leaf images vertically using a white background and a reference object for scale calibration. The leaf images are then converted into black-and-white binary images using ImageJ software so that the leaf portion can be visually identified and its area calculated based on the number of pixels calibrated against the reference object (Al Ramadhani et al., 2024). Figure 1 presents the stages of digital image processing for Manalagi and Madu mango leaves. Figures 1a and 1c show the original leaf images for each cultivar, while Figures 1b and 1d display the binary image conversions used for leaf area calculations. This stage is critical to ensure that the obtained leaf area data are highly accurate before being used in calculating the leaf constant (Sudianto & Husna, 2025).

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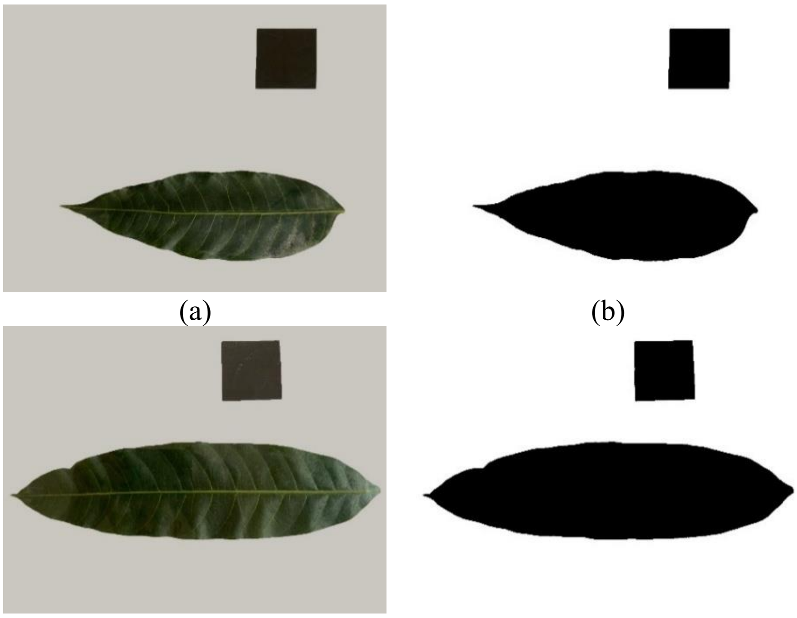


Figure 1. Digital image processing and leaf area measurement: (a) Manalagi mango leaf image, (b) Manalagi mango binary image, (c) Madu mango leaf image, and (d) Madu mango binary image

Table 1 shows that the measured leaf area and leaf dimensions of the two mango cultivars exhibit considerable variation. Based on leaf area measurements obtained through digital image processing and manual leaf dimension measurements, Manalagi mango leaves had leaf constant values ranging from 0,686 to 0,724, with an average of 0,706, whereas Madu mango leaves had a range of 0,766 to 0,793, with an average of 0,779. These results indicate that the leaf shape and proportions of the two cultivars differ, influencing the resulting leaf constant values (Daningsih et al., 2024; Nguyen & Do, 2025).

Table 1. Measured leaf area (digital image processing) and leaf dimension measurements for Manalagi and Madu mango cultivars

| Sample | Manalagi mango | | | | Madu mango | | | |
|---|---|---|---|---|---|---|---|---|
| | **Measured Leaf Area ($cm^2$)** | **Length (cm)** | **Width (cm)** | ***k*** | **Measured Leaf Area ($cm^2$)** | **Length (cm)** | **Width (cm)** | ***k*** |
| 1 | 169,350 | 29 | 8,2 | 0,712 | 201,04 | 27,5 | 9,5 | 0,770 |
| 2 | 80,009 | 20 | 5,8 | 0,690 | 190,89 | 27 | 9 | 0,786 |
| 3 | 94,891 | 21 | 6,5 | 0,695 | 118,56 | 21,2 | 7,2 | 0,777 |
| 4 | 120,561 | 27,5 | 6,2 | 0,707 | 130,12 | 24,5 | 6,9 | 0,770 |
| 5 | 113,569 | 26,4 | 6,2 | 0,694 | 116,76 | 21,9 | 6,8 | 0,784 |
| 6 | 100,381 | 23,1 | 6,3 | 0,690 | 102,31 | 20,8 | 6,3 | 0,781 |
| 7 | 143,076 | 25,6 | 7,9 | 0,707 | 98,78 | 20,1 | 6,2 | 0,793 |
| 8 | 132,539 | 28 | 6,9 | 0,686 | 135,71 | 24,9 | 7 | 0,779 |
| 9 | 155,719 | 26,5 | 8,4 | 0,700 | 215,88 | 26,2 | 10,5 | 0,785 |
| 10 | 131,751 | 26 | 7,1 | 0,714 | 147,98 | 26,1 | 7,2 | 0,787 |
| 11 | 144,749 | 24,5 | 8,3 | 0,712 | 107,22 | 21,4 | 6,4 | 0,783 |
| 12 | 105,539 | 27 | 5,6 | 0,698 | 85,94 | 22,3 | 5 | 0,771 |
| 13 | 110,751 | 25,6 | 6 | 0,721 | 89,84 | 21 | 5,4 | 0,792 |
| 14 | 127,456 | 28 | 6,5 | 0,700 | 71,54 | 19,2 | 4,8 | 0,776 |
| 15 | 113,397 | 20 | 7,9 | 0,718 | 82,93 | 23,1 | 4,6 | 0,780 |
| 16 | 118,980 | 23,6 | 7,1 | 0,710 | 132,56 | 24,9 | 6,9 | 0,772 |
| 17 | 127,085 | 27 | 6,5 | 0,724 | 142,80 | 25,1 | 7,3 | 0,779 |
| 18 | 139,543 | 25 | 8 | 0,698 | 65,52 | 17,2 | 4,9 | 0,777 |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 19 | 156,140 | 26,3 | 8,2 | 0,724 | 82,71 | 15,2 | 7 | 0,777 |
| 20 | 98,780 | 20,1 | 7 | 0,702 | 145,82 | 28 | 6,8 | 0,766 |
| 21 | 89,124 | 19,2 | 6,5 | 0,714 | 187,52 | 26,7 | 8,9 | 0,789 |
| 22 | 76,645 | 17,2 | 6,2 | 0,719 | 192,86 | 29,2 | 8,6 | 0,768 |
| 23 | 79,765 | 18 | 6,2 | 0,715 | 157,32 | 26,3 | 7,7 | 0,777 |
| 24 | 96,675 | 19,8 | 6,8 | 0,718 | 103,62 | 24,8 | 5,4 | 0,774 |
| 25 | 113,873 | 23 | 7 | 0,707 | 162,89 | 28 | 7,4 | 0,786 |
| 26 | 125,463 | 25,7 | 7 | 0,697 | 78,90 | 20,1 | 5 | 0,785 |
| 27 | 100,989 | 20,1 | 7,1 | 0,708 | 142,93 | 26,4 | 6,9 | 0,785 |
| 28 | 89,887 | 18,9 | 6,8 | 0,699 | 67,68 | 15,8 | 5,5 | 0,779 |
| 29 | 103,679 | 20,5 | 7,1 | 0,712 | 89,61 | 22,8 | 5,1 | 0,771 |
| 30 | 100,895 | 19,9 | 7,2 | 0,704 | 92,87 | 23,6 | 5,1 | 0,772 |
| 31 | 98,849 | 19,7 | 7,1 | 0,707 | 109,67 | 25,4 | 5,6 | 0,771 |
| 32 | 95,557 | 20,5 | 6,5 | 0,717 | 168,62 | 26,7 | 8,1 | 0,780 |
| 33 | 98,091 | 21 | 6,7 | 0,697 | 142,12 | 25,3 | 7,2 | 0,780 |
| 34 | 91,261 | 19,4 | 6,6 | 0,713 | 84,91 | 17,5 | 6,2 | 0,783 |
| 35 | 98,876 | 21,4 | 6,4 | 0,722 | 113,41 | 24,6 | 5,9 | 0,781 |
| 36 | 101,732 | 22,5 | 6,5 | 0,696 | 176,89 | 27,8 | 8,1 | 0,786 |
| 37 | 88,976 | 20,8 | 6,1 | 0,701 | 93,82 | 18,9 | 6,3 | 0,788 |
| 38 | 88,436 | 18,7 | 6,8 | 0,695 | 114,87 | 24,7 | 6 | 0,775 |
| 39 | 110,672 | 24,3 | 6,5 | 0,701 | 211,57 | 29,1 | 9,4 | 0,773 |
| 40 | 114,768 | 24 | 6,7 | 0,714 | 153,21 | 27,4 | 7,2 | 0,777 |

The distribution of leaf constant values for both cultivars was further analyzed using boxplots to examine distribution patterns, variability, and the presence of outliers. As shown in Figure 2, Manalagi mango leaves had a median constant value of 0,707 with a relatively narrow spread, indicating homogeneous data and the absence of outliers. Conversely, Madu mango leaves had a median constant of 0,779, also with a narrow spread, but slightly higher than that of Manalagi. Both boxplots revealed that the leaf constant values fell within a narrow interquartile range, indicating stability in the constant values for each cultivar (Walker et al., 2018). The absence of outliers for both cultivars suggests that all sample data were consistent, and the average constant value (*k*) is suitable for use in leaf area calculations using the Montgomery method.

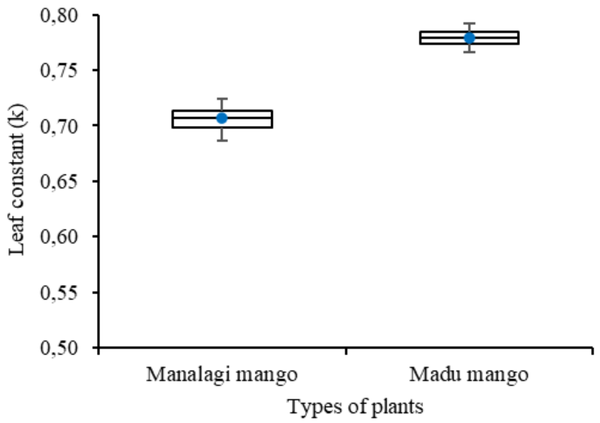


Figure 2. Boxplot of leaf constants for Manalagi and Madu mango cultivars.

The next stage involved analyzing the correlation between the measured leaf area obtained from digital image processing and the predicted leaf area calculated using the average leaf constant value determined in this study through the Montgomery method. This correlation analysis aimed to evaluate how well the obtained leaf constant values could produce leaf area estimates close to direct measurements (Sala et al., 2015). Accordingly, the relationship between these two datasets provides

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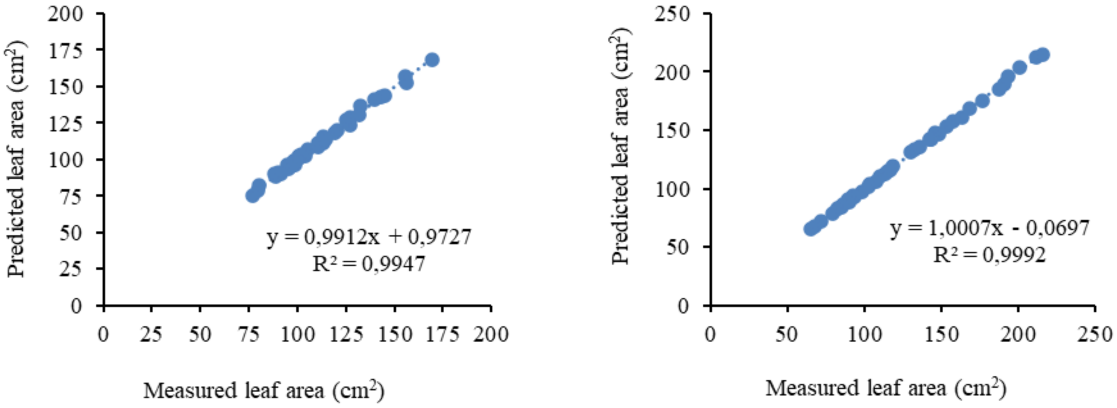
insight into the accuracy and reliability of the leaf constant-based prediction method. The correlation analysis results are presented in scatter plots (Figure 3), including the linear regression equations and coefficients of determination ($R^2$) as indicators of relationship strength.




(a) (b)

Figure 3. Correlation plots between measured leaf area (digital image processing) and predicted leaf area using the leaf constant method: (a) Manalagi mango, and (b) Madu mango.

As shown in Figure 3, the relationship between measured and predicted leaf area exhibited a very strong correlation for both cultivars. For Manalagi mango (Figure 3a), the regression equation was y = 0,9912x + 0,9727 with an $R^2$ value of 0,9947. For Madu mango (Figure 3b), the regression equation was y = 1,0007x – 0,0697 with an $R^2$ of 0,9992. The $R^2$ values close to 1 indicate an extremely strong linear relationship between the measured leaf area (digital image processing) and the predicted leaf area calculated using the leaf constant (*k*) obtained from this study. These findings suggest that the Montgomery method, when applied with the leaf constants determined in this research, provides highly accurate predictions of mango leaf area for both Manalagi and Madu cultivars. The tight clustering of data points around the regression line further supports the reliability of the obtained constants as parameters for mango leaf area estimation (Breure & Siregar, 2021; Qin et al., 2024).

Table 2. Statistical analysis results for measured and predicted leaf areas using the leaf constant method.

| Types of plants | RMSE | NRMSE | NSE | d |
|---|---|---|---|---|
| Manalagi mango | 1,614 | 0,015 | 0,995 | 0,999 |
| Madu mango | 1,209 | 0,009 | 0,999 | 1 |

The next step was a statistical evaluation to measure the accuracy and performance of the leaf constant (*k*) model in estimating leaf area for the two mango cultivars. Based on the statistical analysis results in Table 2, the measured and predicted leaf areas for Manalagi mango showed excellent agreement. The RMSE value of 1,614 and NRMSE of 0,015 indicate that the prediction errors from the leaf constant method are minimal relative to the mean measured leaf area. Furthermore, the NSE value of 0,995, close to the maximum of 1, demonstrates that the prediction model is highly efficient in modeling the relationship between measured and predicted leaf areas. The Willmott's index of agreement (*d*) value of 0.999 further confirms that the predictions closely matched the actual values (Al Ramadhani et al., 2024; Koyama, 2023). These findings indicate that the Manalagi mango leaf constant (*k*) of 0,706 is highly accurate and can be practically applied for leaf area estimation.

The analysis results for Madu mango also demonstrated excellent performance, even outperforming Manalagi in prediction accuracy. The RMSE value of 1,209 and NRMSE of 0,009 indicate lower prediction errors, reflecting higher precision. The NSE value of 0,999, nearly perfect, implies that almost

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all variability in measured leaf area can be explained by the predicted values. The Willmott's index of agreement (*d*) value of 1 indicates a perfect match between predictions and actual data (Al Ramadhani, 2024; Kumar et al., 2017). Therefore, the Madu mango leaf constant of 0,779 is not only valid but also demonstrates extremely high predictive accuracy, making it highly reliable for practical field applications.

Overall, the results of this study show that leaf area measurement using leaf constants derived from digital image processing is highly effective for both Manalagi and Madu mango cultivars. These findings are consistent with previous studies applying similar methods to other crops such as apple, avocado, water apple, mangosteen, and rambutan, which also reported cultivar-specific leaf constants that improved leaf area measurement efficiency (Al Ramadhani, 2024; Sala et al., 2015; Wu et al., 2018). However, this study offers a distinct advantage by specifically identifying leaf constants for two Indonesian mango cultivars that have been scarcely investigated scientifically. The availability of these leaf constants enables rapid, cost-effective leaf area measurements without specialized equipment, providing substantial benefits for research, agricultural management, and the development of crop monitoring technologies.

## 4. CONCLUSION

This study successfully identified the leaf constant values in Manalagi and Madu mango cultivars using a digital image processing method, which proved to be effective and accurate in estimating leaf area. The analysis yielded leaf constant values of 0,706 for the Manalagi cultivar and 0,779 for the Madu cultivar. These constants were able to predict leaf area with a very low error rate and a very high level of agreement with actual measurements, as evidenced by statistical analyses including $R^2$, RMSE, NRMSE, NSE, and Willmott's index of agreement (d). The findings provide an important contribution to the development of rapid, practical, and equipment-free methods for estimating plant growth. Furthermore, the results can be applied in field-based plant growth monitoring, particularly in supporting precision cultivation decision-making. It is therefore recommended that future research include testing on a wider range of mango cultivars and other plant species, as well as the development of digital-based applications to enhance the ease and accuracy of implementation under various agroecological conditions.

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