Research Paper

A Novel Virtual Modeling Approach for Mango Tree Biomass Estimation Using Allometric Equations and Functional-Structural Plant Modeling (FSPM) with GroIMP

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Abstract: Biomass represents a critical ecological contribution of trees, including mango (*Mangifera indica* L.), necessitating rigorous academic approaches for quantification and modeling. This study develops a computational model to enhance understanding of mango tree morphology and physiology using Functional-Structural Plant Modeling (FSPM) implemented through GroIMP software. Comparative analysis reveals that the FSPM-based biomass model generates higher estimates than traditional allometric equations, though both approaches exhibit similar temporal trends. Longitudinal data demonstrate trunk diameter progression from 1.60 cm in year one to 20.35 cm in year twenty, corresponding to biomass increases from 0.35 kg to 263.33 kg. Quantitative validation using Euclidean Distance, Error, and Similarity metrics reveals significant discrepancies between model predictions and empirical data, particularly during early growth stages, with average Euclidean Distance of 54.73, average Error of 34.12%, and average Similarity of 65.88%. These findings highlight both the potential and limitations of FSPM approaches for mango biomass estimation, providing a foundation for improved cultivation management practices and predictive modeling refinement.

Keywords: Functional-Structural Plant Modeling, GroIMP, Plant Growth Simulation, Biomass Estimation, Allometric Equations, *Mangifera indica*, Computational Agriculture

Introduction

Agriculture plays a pivotal role in addressing escalating global food demand, driving the need for innovative research methodologies. Functional-Structural Plant Modeling (FSPM) represents a promising computational approach that integrates plant functional processes with structural development, enabling comprehensive analysis of plant growth dynamics under varying management practices. FSPM facilitates cultivation practice optimization by predicting economic outcomes related to planting system configurations, including plant spacing, average plant biomass, and potential economic returns from crop production (Wu et al., 2019; Jabar & Utama, 2020; Perdana, 2012).

Mango trees (*Mangifera indica* L.) constitute one of the most economically important agricultural commodities globally, particularly in tropical regions. Despite widespread cultivation, significant opportunities exist to enhance mango productivity and fruit quality through integrated, scientifically rigorous approaches. FSPM provides a powerful analytical tool for detailed investigation of mango tree growth and development patterns (Soualiou et al., 2021).

Carbon assimilated from atmospheric CO_2 through photosynthesis is stored as biomass distributed across various plant organs, including stems, branches, twigs, leaves, flowers, fruits, and roots. Biomass quantification serves as a critical reference for assessing growth potential in superior mango cultivars, with stand biomass estimation through allometric equations providing essential data for determining plant nutrient requirements (Sutaryo, 2009). Accurate biomass modeling enables evidence-based decision-making regarding fertilization strategies, resource allocation, and yield optimization.

This research aims to deepen understanding of mango tree morphology and physiology through computational modeling to determine plant biomass dynamics across developmental stages. The developed model serves as a scientific guide for farmers, agronomists, and agricultural stakeholders, facilitating informed, data-driven decisions in mango cultivation management. Specifically, this study employs the Growth Grammar-related Interactive Modelling Platform (GroIMP) as the modeling and simulation environment. GroIMP provides a three-dimensional modeling framework incorporating a specialized programming language (Growth Grammar or XL) that enables construction of dynamic, interactive plant models tailored to mango tree growth characteristics.

By integrating FSPM principles with GroIMP's computational capabilities, this study bridges theoretical plant physiology with practical agricultural applications, establishing a foundation for precision agriculture approaches in mango production systems. The integration of allometric equations with FSPM techniques provides comparative insights into biomass estimation methodologies, identifying strengths and limitations of each approach while advancing computational agriculture tools for tropical fruit tree management.

Materials and Methods

This research was carried out through a series of systematic stages to understand, design, and validate the computational model of the 'Mangifera indica L' Mango plant. Figure 1 shows the stages and methods used during the research process.

Data Collection

The data collection stage is a critical component in obtaining comprehensive insights into various aspects of mango trees, with a particular emphasis on trunk diameter as a key variable for biomass estimation. In addition to biometric measurements, we also gathered essential information on agricultural management practices and historical mango production to support a holistic analysis.

To ensure robust and reliable data, we employed a multi-method approach. This included conducting detailed field surveys across diverse mango orchards, where we precisely measured environmental parameters such as soil conditions, microclimate, and tree characteristics. Furthermore, we carried out in-depth interviews with local farmers to capture their experiential knowledge and management strategies.

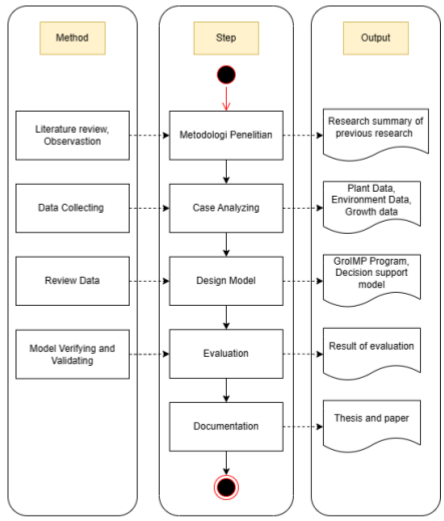

Fig. 1. Research Stages

A significant part of our investigation involved direct observations and data collection at the UPTD Balai Pembenihan dan Pembibitan Hortikultural in Indramayu, West Java, Indonesia. This hands-on approach allowed us to validate field measurements and gain deeper insights into nursery practices and tree development stages. The dataset obtained from this site is publicly available https://doi.org/10.6084/m9.figshare.28873859.v1 and can be accessed.

To complement our primary data, we also reviewed historical records, annual reports, and relevant scientific publications. This triangulation of data sources enhances the credibility of our findings and contributes significantly to our understanding of mango tree dynamics in varying agroecological contexts.

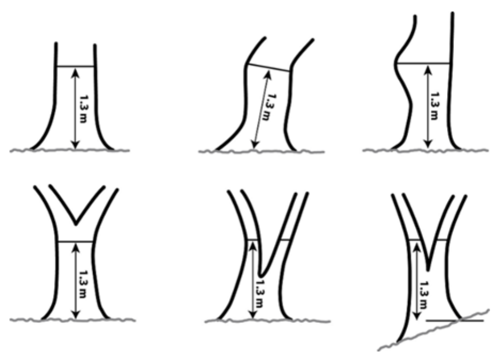

Fig. 2. Diameter at Breast Height (DBH)

The data set analyzed includes periodic measurements of trunk diameter taken from ages 1 to 20 years. This growth trend analysis of diameter allows for the estimation of the tree's biomass. The Allometric equation is employed to provide an accurate assessment of tree biomass, as it accounts for the relationship between physical dimensions, such as trunk diameter, and total tree mass. Please refer to Figure 4.1 for the Diameter at Breast Height (Heinrich, 2024).

Geographically, Indramayu Regency lies between 107° 52' - 108° 36' East Longitude and 6° 15' - 6° 40' South Latitude. Its topography mostly represents sloping areas or plains with an average ground inclination of 0 – 2%. The climate in Indramayu averages 18.26 rainy days with an average rainfall of 324.55 mm (Badan Pusat Statistik Indonesia, 2024)

The soil in Indramayu is formed from alluvial and marine deposits, generally having a clay texture, both in the topsoil and subsoil layers. Most of the soil has a heavy clay texture, with a clay fraction content of more than 60%; an average soil pH of 5.3-6.0; a cation exchange capacity value ranging from medium to high (19.8-27.99 cmolc kg-1); and an organic carbon content value ranging from very low to low (0.23-1.95%). Irrigation practices involve using groundwater, waiting for rainwater, or creating trenches around plants (irrigation channels) (Hikmat & Yatno, 2022).

Although this study focuses on mango trees in a specific area, the FSPM-GroIMP approach used has the potential to be applied to other plant species with similar growth characteristics, such as durian and citrus. Additionally, this model can be further developed by incorporating environmental variables such as temperature, humidity, and soil type to enhance its flexibility. Additional validation tests with data from various locations or simulations based on environmental variations will help ensure the model's generalization for application in various precision agriculture systems under different geographical conditions.

Computational Model Development

This process includes designing algorithms and implementing software to predict the growth and yield of 'Mangifera indica L' mangoes based on predetermined parameters. The model undergoes iterations and refinements based on initial feedback and interim simulation results.

Based on the data collected, the computational model was developed into a 3D visual form using GroIMP software with the FSPM method and the object-oriented XL programming language. (Zhang, et al., 2020). Computational model development involves several key steps, including data preprocessing, model initialization, and iterative growth simulation. The model is developed into a 3D visual form using GroIMP software with the FSPM method and the object-oriented XL programming language. The model considers growth rate, size, and tree age factors and is rendered in 3D using the GroIMP's Relational Growth Grammar (RGG) (Kniemeyer, Buck-Soruin, & Kurt, 2007). The growth grammar rules are derived from the natural growth patterns of mango trees and implemented using the Lindenmayer system (L-system) to iteratively build the tree structure.

The model development involves initializing parameters such as initial trunk diameter "(D_0 = 5)", annual growth rate (G, represented by "i[diameter] += random(0.1, 0.1))", and tree maturity threshold (D_max, interpreted from the condition "if(year!= 20))". The growth grammar rules are derived from the natural growth patterns of mango trees and implemented using the object-oriented XL programming language in GroIMP software.

Model Validation

This research involves the verification and validation of the model. The results of the developed computational model are validated by comparing the model with field data. This is done to ensure that the model accurately represents the growth of mango trees. Additionally, verification is conducted to assess the model's accuracy and to validate the model based on the data used. This verification process involves checking the calculations and formulas used in constructing the model and comparing them against established theoretical frameworks. One key component is the use of a linear equation to evaluate how well the model fits the actual data. The linear model is defined by Equation (1)

$$y = mx + b \quad (1)$$

Where y is the dependent variable, x is the input variable (typically representing time, such as year), m is the slope or gradient of the line, and b is the intercept. This equation helps in identifying the trend and direction of the relationship between variables. To assess the accuracy and reliability of the model, three additional metrics are calculated: Euclidean Distance, Mean Absolute Error, and a Similarity Score. These are expressed respectively in Equations (2), (3), and (4)

$$D = \sqrt{\sum(x_i - y_i)^2} \quad (2)$$

$$E = \frac{\sum|x_i - y_i|}{n} \quad (3)$$

$$S = 1 - \frac{\sum|x_i - y_i|}{\sum|x_i + y_i|} \quad (4)$$

In these formulas, x_i and y_i denote the model-predicted and actual values for each observation i, while n is the total number of observations. Equation (2) measures the overall deviation between predicted and actual values, Equation (3) gives the average prediction error, and Equation (4) quantifies similarity between the two data sets, approaching 1 as similarity increases.

However, the study does not define the acceptable threshold values for these validation metrics or compare the results with existing validation benchmarks. Establishing reference values from previous studies would enhance the robustness of the validation process. Future research should incorporate standardized validation criteria to ensure the model's performance aligns with widely accepted accuracy standards in plant growth modeling.

A comprehensive conclusion about the developed model can be drawn by integrating linear equations for model fitting, allometric equations for biomass estimation, and Euclidean-based error metrics. These results also serve as feedback for refining the simulation process in future studies.

Additionally, the values of Euclidean Distance, Error, and Similarity are calculated to assess how closely the model matches the actual data, ensuring that the model has a high level of accuracy using the Euclidean Distance, Error, and Similarity formulas.

By using the linear equation for the Equation formula, the allometric equation for biomass, and the calculations of Euclidean Distance, Error, and Similarity, conclusions about the developed model can be drawn. These results will also provide feedback for further research simulation results.

Results

Virtual Model Plant

To provide a more comprehensive understanding of the variations in the shape of tree trunks at a height of 1.3 meters that may influence DBH measurement results, Figure 3 illustrates the different trunk configurations observed at that height in the 1st, 5th, and 10th years. These configurations include straight trunks without irregularities, slightly inclined trunks, basal flares, branches near the measurement point, forked trunks, and trees growing on sloped ground. Each of these variations has the potential to affect the accuracy of diameter measurements taken at a height of 1.3 meters.

Fig. 3. Simulation using GroIMP

To gain a deeper understanding of the variations in mango tree trunk shapes at a height of 1.3 meters, which can affect the measurement results of Diameter at Breast Height (DBH), this study conducted simulations using GroIMP. Figure 3 shows various trunk configurations observed in the 1st, 5th, and 10th years. These variations include straight trunks without abnormalities, slightly tilted trunks, trunk base widening, branches near the measurement point, double-branched trunks, and trees growing on sloping land. Each of these variations can affect the accuracy of tree diameter measurements. Thus, more precise modeling is needed to correct possible measurement errors due to tree structural factors.

The tree growth modeling in this study uses the Functional Structural Plant Model (FSPM) approach based on Growth Grammar implemented in GroIMP software. Growth grammar is a growth rule developed based on the natural growth patterns of mango trees, involving parameters such as trunk diameter growth rate, branching angle, and biomass distribution. In its implementation, the Lindenmayer system (L-system) is used to iteratively build the tree structure. Initial parameters such as initial trunk diameter (D_0), annual growth rate (G), and tree maturity threshold (D_max) are included as the basis for the simulation.

Each iteration in the simulation model adapts changes in trunk diameter and branch distribution based on environmental parameters, including light factors, nutrient availability, and growing space competition. These growth rules are calibrated using field data to ensure that the resulting simulations accurately represent the dynamics of mango tree growth.

Data Trunk of Tree

The biomass from mango trees is considered a carbon-neutral energy resource, as the carbon released during burning matches the amount absorbed by mango trees during photosynthesis. Using mango tree biomass enables us to diversify our energy sources, improve energy security, and reduce the risks linked to dependence on a single energy source

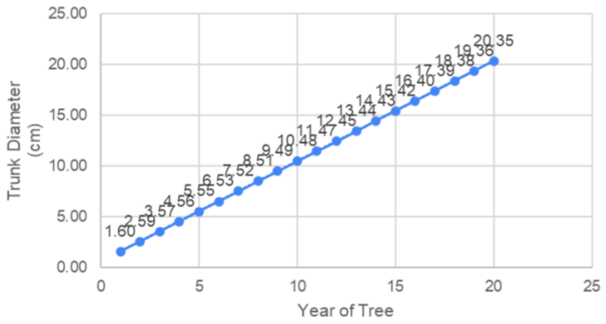

Fig. 4. Trunk Diameter

The graph of the linear equation depicted in Figure 1 shows a strong correlation between the diameter of the mango tree and its age. This relationship is represented by the equation (y = 0.9868x + 0.6132), with a coefficient of determination (R^2 = 1.0). This analysis confirms a significant relationship between tree diameter and age, indicating that the regression model explains 100% of the variation in the data (Marga, 2024).

Additionally, research supports this finding, revealing an (R^2) value of 0.9417 for the relationship between plant diameter and age. Studies by Serli further demonstrate that as trees age, their diameter increases, underscoring the influence of age on tree growth (Serli & Agustina, 2021).

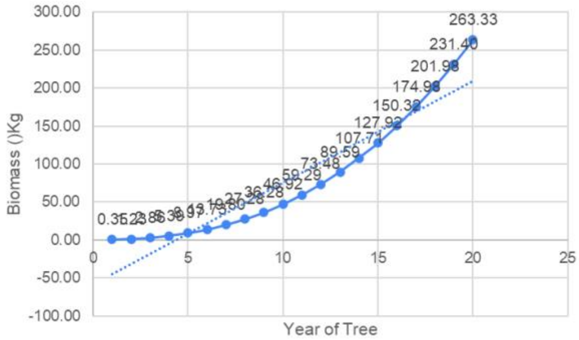

Fig. 5. Biomass

The findings shown in Figure 2 depict the linear regression equation for biomass growth, formulated as (y=13,334x - 57,867). The coefficient of determination (R^2 = 0.8969) reveals that 89.69% of the variation in the biomass data is accounted for by the linear regression model used. This evaluation demonstrates a noteworthy relationship between biomass growth and the regression model, which successfully explains 89.69% of the variation in the data. Furthermore, research by Dao showed that the diameter at breast height (DBH) for mango plants, calculated using an allometric equation, achieved a coefficient of determination of (R^2 = 95.45) (Dao, Bationo, Traoré, Bognounou, & Thiombiano, 2021).

Model Verification and Validation

Analyzing biomass can aid in forecasting the growth, yield, and carbon storage capacity of mango trees. Table 1 outlines the Euclidean Distance method, which assesses how closely observation results align with actual data as a means to evaluate error and similarity.

Table 1: Analysis of Biomass

Year	Trunk Diameter	Euclidean Distance	Error	Similarity
1	1.60	44.53	27.76%	72.24%
2	2.59	31.17	19.43%	80.57%
3	3.57	17.63	10.99%	89.01%
4	4.56	2.92	1.82%	98.18%
5	5.55	1.73	1.08%	98.92%
6	6.53	17.36	10.82%	89.18%
7	7.52	29.43	18.35%	81.65%
8	8.51	40.47	25.23%	74.77%
9	9.49	50.45	31.44%	68.56%
10	10.48	59.12	36.85%	63.15%
11	11.47	66.12	41.21%	58.79%
12	12.45	70.95	44.22%	55.78%
13	13.44	72.86	45.41%	54.59%
14	14.43	70.65	44.03%	55.97%
15	15.42	61.97	38.63%	61.37%
16	16.40	39.72	24.76%	75.24%
17	17.39	46.04	28.69%	71.31%
18	18.38	87.28	54.40%	45.60%
19	19.36	123.84	77.19%	22.81%
20	20.35	160.44	100.00%	0.00%
AVG.		**54.734**	**34.12%**	**65.88%**

According to Table 1, the average Euclidean Distance stands at 54.734. This suggests that, on average, the model's predictions deviate by approximately 54.73 units from the actual values. Additionally, the average error rate is 34.12%, indicating a notable discrepancy between predicted and actual outcomes. Conversely, the model shows an average similarity of 65.88% with the actual observations, reflecting a moderate level of accuracy in predicting biomass growth. These findings imply that while the linear regression model offers valuable insights into the biomass growth of mango trees, its performance is moderate, characterized by a relatively high error rate and potential for improvement in predictive accuracy. Enhancing the model or exploring more complex algorithms could help mitigate prediction errors and bolster overall reliability.

Conclusion

The biomass model generally yields higher values than the allometric equation; however, both models show a moderate level of similarity, suggesting their potential reliability for estimating biomass. Data indicates a consistent increase in both trunk diameter and biomass of mango trees over the years. Specifically, the average trunk diameter grows from 1.60 cm in the first year to 20.35 cm by the 20th year, while biomass significantly rises from 0.35 kg to 263.33 kg. The analysis reveals an average Euclidean Distance of 54.73 between the outputs of the two models, illustrating notable differences. Furthermore, an average error rate of 34.12% underscores the biomass model's tendency to produce higher values compared to the allometric equation.

Despite these discrepancies, the average similarity value of 65.88% reflects a moderate agreement between the two approaches. These findings highlight the utility of the biomass model in tree growth studies, while also identifying areas for improvement to enhance its predictive accuracy and reliability.

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Author's Contributions

Oki Marzuqi: Collect and analyze data, construct, simulate and finalize the model. Also drafted and finalized the manuscript.

Azhar Indra Rusmana: Collect and analyze data, construct, simulate and finalize the model. Also drafted and finalized the manuscript.

Ditdit Nugeraha Utama: Wrote and finalized the manuscript.

Ethics

This manuscript represents the original work of the author and has not been published elsewhere. The authors have thoroughly reviewed and approved the content, ensuring its accuracy and compliance with academic standards. The research and publication processes have been conducted with a strong commitment to research integrity and ethical practices. No potential ethical issues or conflicts of interest have been identified during this study. We have adhered strictly to the ethical guidelines established by BINUS University to ensure the responsible conduct of this research. We are committed to maintaining the highest standards of research ethics, and any concerns or inquiries regarding the ethical aspects of this manuscript may be directed to the corresponding author.

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