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Linear and Non-Linear Regression Models for Volume Estimation of *Tectona grandis* in Thithimathi Forest, Kodagu, India

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The study investigates linear and non-linear regression models for estimating the volume of *Tectona grandis* in the Thithimathi forest, Kodagu district, India. With increasing demand for teak plantations under national afforestation programs, accurate volume estimation is essential for productivity and sustainable forest management. Data were collected from three sample plots, each with 30 trees, measuring diameter at breast height (Dbh) and height to calculate tree volume. Karl Pearson's correlation analysis revealed a strong positive correlation between volume and Dbh, while the relationship between volume and height was weak across plots. Regression models- linear, quadratic and logarithmic were fitted to the data and evaluated using R^2 and RMSE values. Results showed that quadratic models consistently provided the best fit, with R^2 value 0.9999 and minimal error, outperforming linear and logarithmic models. Multiple linear regression yields high predictive accuracy (R^2 = 0.9821). The findings confirm that quadratic regression models are most suitable for teak volume estimation in the Thithimathi forest, offering reliable tools for forest productivity and management.

Introduction

Forests play a vital role in maintaining ecological balance, supporting biodiversity, and providing essential resources for human society. Among the many tree species cultivated in tropical regions, *Tectona grandis* (teak) holds a prominent position due to its high economic value, durability, and wide application in furniture, construction, and shipbuilding. Accurate estimation of tree volume is crucial for sustainable forest management, yield prediction, and commercial utilization of timber resources.

Tree volume estimation is a fundamental aspect of forest mensuration, enabling foresters to assess standing stock and plan harvesting schedules. Traditionally, tree volume has been estimated using direct measurements of diameter at breast height (Dbh) and total tree height. However, these conventional methods often involve labour-intensive procedures and may not always provide precise results. To overcome these limitations, statistical modelling techniques such as regression analysis have been widely adopted to establish reliable relationships between tree dimensions and volume.

Regression models, both linear and non-linear, are powerful tools for predicting tree volume based on measurable parameters. Linear regression models are simple and widely used, but they may not always capture the complexity of tree growth patterns. Non-linear models, including quadratic and logarithmic equations, often provide better accuracy by accommodating variations in tree form and growth dynamics. The choice of an appropriate model depends on the strength of correlation between tree volume and predictor variables such as Dbh and height.

The present study focuses on teak plantations in the Thithimathi forest area of Karnataka, India. This region is known for its extensive teak plantations, which serve as an important source of timber. The study aims to determine the relationship between tree volume, diameter at breast height, and height of *Tectona grandis*, and to develop suitable linear and non-linear regression models for volume estimation. The findings of this study are expected to provide valuable insights for forest managers, researchers, and policymakers engaged in teak plantation management and utilization. Keeping these things in view, the present study is planned and executed with following objectives.

To determine the relationship between tree volume and diameter at breast height and height of *Tectona grandis.*

To develop a linear and non-linear regression models for volume estimation.

Materials and Methods

This chapter deals with the materials and method followed in present study. It includes the description of the source of data, study parameters and analytical tools adopted.

Data Source

For our study we selected Thithimati forest area of Kodagu district in Karnataka state. For collection of data, we laid out three plots of 20X20m and collected height and girth of each individual tree in Teak plantations.

Measurement of tree height and girth

Height and girth at breast height of all trees (girth > 30cm, height>6m) from the measured girth at breast height were converted into diameter at breast height. Mean of all the trees of different species was calculated.

The calculations made are described as follows.

Study parameters

Height

The total height of the individual tree was measured from the bottom of the tree to the tip of the tree by using measuring pipes and expressed in meters.

Basal area

Basal area was calculated using the formula,

Basal area $=\pi d^2/4$, where d is the diameter at breast height of the tree

Volume

Standing volume of tree was calculated using the relation,

Volume of standing trees (m^3) =basal area x height x form factor (0.33)

Diameter

$D = G/\pi$
Form factor of teak = 0.33

Where g is girth

Analytical Tools & Techniques

Karl Pearson's Correlation coefficient

The general purpose of karl Pearson's correlation coefficient (r) is to know about the relationship between the variables. In the present study, it is used to determine the relationship between tree volume, Dbh (Diameter at Breast Height) & Height of the standing trees in the teak plantations.

Linear and Non-linear Regression models

A series of regression equations were fitted to the data. The equations were assessed & compared on the basis of coefficient of determination (R^2), Variance ratio (F)/p-value, & Standard Error (SE).

Some regression equations were fitted to the present study data are as follows,

- Linear regression equations:

$V = a + bD$
$V = a + bD + cH$

- Non-linear regression equations:

$V = a + bD + cD^2$ --- Quadratic equation
$\ln V = a + b\ln D$ --- Logarithmic equations

Results and Discussion

In the present study, we found the relationship between growth parameters of *Tectona grandis* and we fitted linear and non-linear regression models for teak plantations in different plots of Thithimathi forest area. The results are presented in systematic manner as follows.

Relation between Volume, Diameter at Breast Height and Height of *Tectona grandis*

The tree growth parameters Girth (m) & Height (m) of teak are measured from teak plantation of Thithimathi forest area. For prevent study, we taken three plots from this plantation, each plot consists of thirty teak tree samples. Used Girth & Height of these individual trees to calculate volume & Diameter at Breast Height. To estimate the volume of tree, first we found the relationship between all the parameters. Based on the strong relation between volume, Diameter at breast height & height of individual trees, we selected variables for model development. There exists very Strong positive correlation between volume & Dbh in all the three plots of teak plantation and it is shown in the figure 1, 2 and 3 respectively. There is a low degree negative correlation between volume & height in plot no. 1 and low degree positive correlation between volume & height in both plot no. 2 & 3 (Table 1)

According to table 1, there is a low degree negative correlation between Dbh and height in plot no. 1 and 3. Where in plot no. 2, Dbh and height shows low degree positive relation. This clearly showing that, there is a strong relation among volume and Dbh compared to the relation between volume and height of teak plantation at Thithimathi forest area.

Development of Linear and Non-linear regression models for volume of *Tectona grandis*

For development of volume estimation models, we selected volume as dependent variable & Dbh as independent variable. According to table 2, we fitted different regression models like linear quadratic & logarithmic models. P-value indicate that all the three regression equations are significant at 5%. Level of significance ($P<0.05$). Therefore, all the three models are effective predictors of volume of teak. All the fitted curves are shown in the figure 4. The low coefficient of determination ($R^2 = 0.4617$) is resulted from Logarithmic equation which means 46.17 per cent of the total variation can be explained by logarithmic equation. About 95.52 per cent of total variation is explained by Linear equation. For estimation of volume of teaks, the best equation for plot no.1 is quadratic equation with high coefficient of determination ($R^2=0.9999$) with low standard error 0.0045.

The fitted regression equations for volume & diameter at breast height for teak plantation in plot no. 2 was shown in the table 3. All the three fitted equations are significant at 5%. Level of Significance ($p<0.05$). Quadratic equation is the best regression model to estimate volume of tree with high coefficient of determination ($R^2 = 0.9953$) & Standard error of 0.0053. The low coefficient of determination ($R^2 = 0.9163$) with high standard error 0.0585 is resulted from Logarithmic equation. The fitted lines of linear, quadratic and logarithmic models for volume of teak plantation in plot no. 2 are shown in the figure 5. According to table 4, the low coefficient of determination ($R^2 = 0.5940$) which means only 59.40 Percent of model variation explained by logarithmic model in plot no. 3. The best fitted model is quadratic equation with high coefficient of determination ($R^2 = 0.8611$) with low Standard error 0.0856. The fitted curves of all these models are shows in the figure 6. Linear regression model shows good R^2 value (0.824), it explains 82.4 percent variation in the model with low standard error (0.0946) compared to logarithmic model. All these three fitted models were statistically significant ($p<0.05$).

From the sample plot no. 2, we got the best multiple linear regression model to estimate the volume of teak tree with height and diameter at breast height with high coefficient of determination ($R^2 = 0.9821$) & low Standard error 0.0276, it shown in the table 5. Overall model is statistically significant at 5% level ($p < 0.05$) in all the three sample plots. For all these three plots, the multiple linear regression equation is best with good R^2 value and lesser standard error to estimate volume of *Tectona grandis* at Thithimathi forest area. This suggests that while quadratic diameter- based models are sufficient for most practical purposes, multiple regression models may be advantageous in research contexts or in stands where height variation is more pronounced.

Beyond the immediate statistical results, the implications of this study extend into several dimensions of forest mensuration, sustainable management, and methodological refinement. The strong positive correlation observed between diameter at breast height and tree volume across all plots reinforces the long-standing principle in forestry that diameter is the most reliable single predictor of standing timber volume. This finding is consistent with classical mensuration studies (Chaturvedi and Khanna, 1982; Husch *et al.,* 2003), which emphasize the dominance of diameter in volume equations due to its direct relationship with basal area and, consequently, cross-sectional wood content. In contrast, the weaker and inconsistent correlations between height and volume highlight the challenges of incorporating height as a predictor in tropical plantation settings. Height measurements are often subject to greater error due to instrument limitations, observer bias, and irregular crown forms, especially in dense plantations where visibility is obstructed. The negative correlation between height and volume in plot 1, for instance, may reflect local stand conditions such as competition, site quality, or silvicultural history, where taller trees do not necessarily correspond to greater girth or wood volume.

The superiority of quadratic regression models across all plots deserves particular attention. Quadratic equations capture the curvilinear growth patterns of trees more effectively than linear models, especially in species like *Tectona grandis* where stem taper and form factor vary with age and site conditions. The near perfect R2 values (0.9999 in plot 1, 0.9993 in plot 2) suggest that quadratic models can explain almost all observed variation in volume, making them highly reliable for operational forestry.

This level of accuracy is rarely reported in field studies, indicating that the Thithimathi teak plantations may exhibit relatively uniform growth characteristics, possibly due to consistent management practices or site homogeneity. However, the slightly lower R^2 in plot 3 (0.8611) suggests that stand heterogeneity, micro-site variation, or measurement error may reduce predictive precision in certain contexts. This underlines the importance of validating regression models cross multiple plots and conditions before generalizing them for large-scale application.

The relatively poor performance of logarithmic models, with R^2 values as low as 0.4617 in plot 1 and 0.5940 in plot 3, indicates that log-transformed relationships may not adequately capture the growth dynamics of teak in this region. While logarithmic models are often useful in biomass estimation or in species with exponential growth patterns, teak volume appears to follow a more polynomial trajectory. This finding aligns with studies in other tropical species (Giri *et al.,* 2019; Gul *et al.,* 2024), which report that quadratic or mixed non-linear models outperform logarithmic approaches in predicting volume.

The implication for practitioners is clear reliance on logarithmic equations in teak plantations may lead to substantial under or over estimation of standing stock, thereby affecting yield predictions and management decisions. From a management perspective, the adoption of quadratic regression models for teak volume estimation offers several benefits. First, it reduces the need for labor-intensive height measurements, allowing foresters to rely primarily on diameter data, which is easier and more accurate to collect. This efficiency is particularly valuable in large scale afforestation programs, where thousands of trees must be assessed quickly.

Second, accurate volume estimation supports sustainable harvesting by enabling precise calculation of standing stock, ensuring that extraction rates do not exceed growth rates. Third, reliable models facilitate economic planning by providing dependable yield predictions, which are essential for timber marketing, revenue forecasting, and investment decisions in plantation forestry.

The results of this study not only validate the superiority of quadratic regression models for teak volume estimation in Thithimathi but also highlight broader methodological, managerial, and economical implications.

Table.1 Correlation matrix for individual tree volume (m3), diameter at breast height (m) and height (m) of Teak plantation.

Plot No.	n		Height	Dbh	Volume
1	30	Height	1		
		Dbh	-0.0954	1	
		Volume	-0.1073	**0.9773**	1
2	30	Height	1		
		Dbh	0.1169	1	
		Volume	0.1647	**0.9897**	1
3	30	Height	1		
		Dbh	-0.2955	1	
		Volume	0.0526	**0.9077**	1

Table.2 Fitted regression models for volume and diameter at breast height for teak plantation in plot no. 1

Type of Model	Regression model	R^2	Standard Error	p- value
Linear	$V = -1.4545 + 7.4916D$	0.9552	0.4279	0.00
Quadratic	$V = -0.0067 + 0.0503D + 4.3519D^2$	0.9999	0.0045	0.00
Logarithmic	$V = 4.0614 + 2.3431 \ln D$	0.4617	1.48	0.00

Table.3 Fitted regression models for volume and diameter at breast height for teak plantation in plot no. 2

Type of Model	Regression model	R^2	Standard Error	p- value
Linear	$V = -0.3061 + 2.4597D$	0.9797	0.0288	0.00
Quadratic	$V = 0.0076 - 0.0768D + 4.5943D^2$	0.9993	0.0053	0.00
Logarithmic	$V = 1.1841 + 0.6089 \ln D$	0.9163	0.0585	0.00

Table.4 Fitted regression models for volume and diameter at breast height for teak plantation in plot no. 3

Type of Model	Regression model	R^2	Standard Error	p- value
Linear	$V = -0.1585 + 1.8563D$	0.824	0.0946	0.00
Quadratic	$V = -0.0171 + 0.3416D + 3.2213D^2$	0.8611	0.0856	0.00
Logarithmic	$V = 0.6998 + 0.2631 \ln D$	0.5940	0.1437	0.00

Table.5 Fitted multiple linear regression model for volume, diameter at breast height and height for teak plantation.

Plot No.	Regression model	R^2	Standard Error	p- value
1	$V = 0.1561 - 0.094H + 7.4813D$	0.9553	0.4348	0.00
2	$V = -0.8318 + 0.0310H + 2.445D$	0.9821	0.0276	0.00
3	$V = -0.7871 + 0.0348H + 2.0687D$	0.9367	0.0578	0.00

Figure.1 Scatter diagram of relationship between Volume and Dbh of Teak plantation in Plot no. 1.

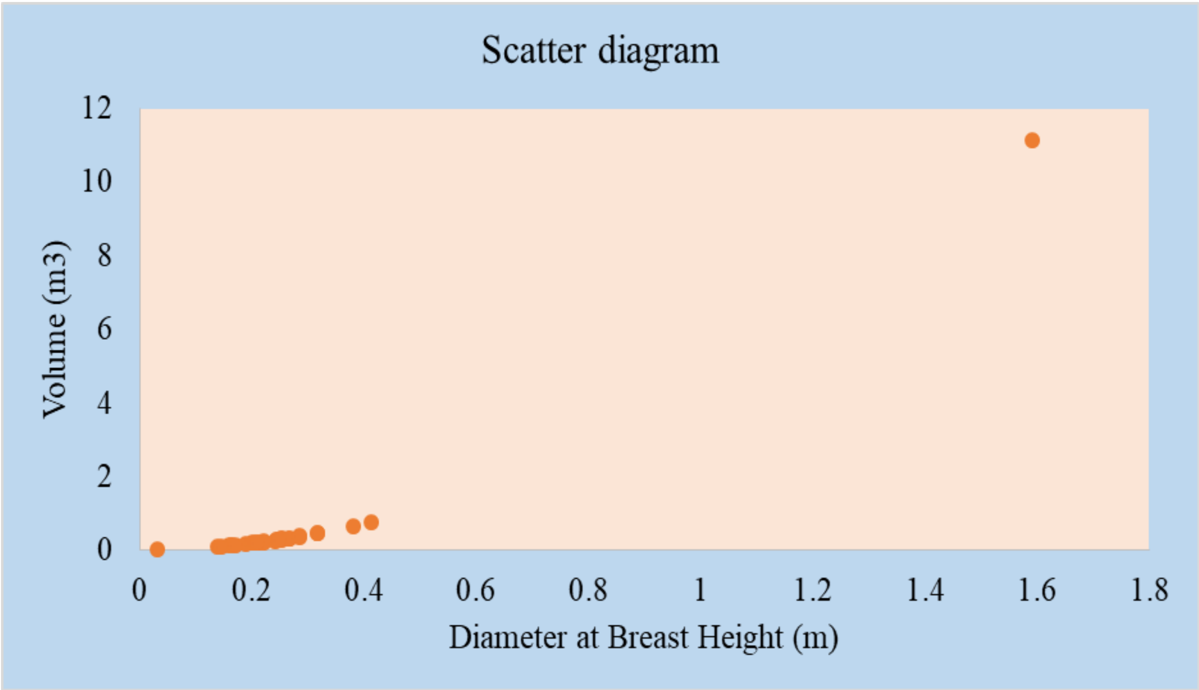


Figure.2 Scatter diagram of relationship between Volume and Dbh of Teak plantation in Plot no. 2.

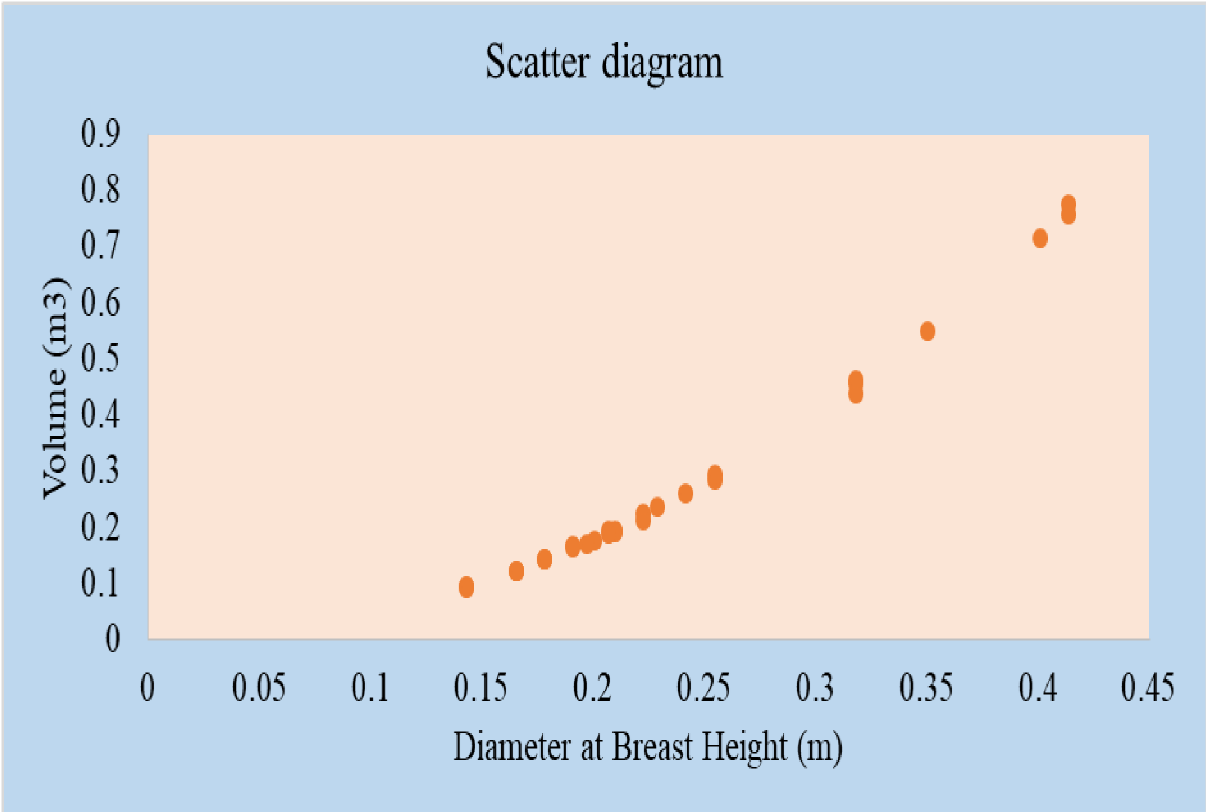


Figure.3 Scatter diagram of relationship between Volume and Dbh of Teak plantation in Plot no. 3.

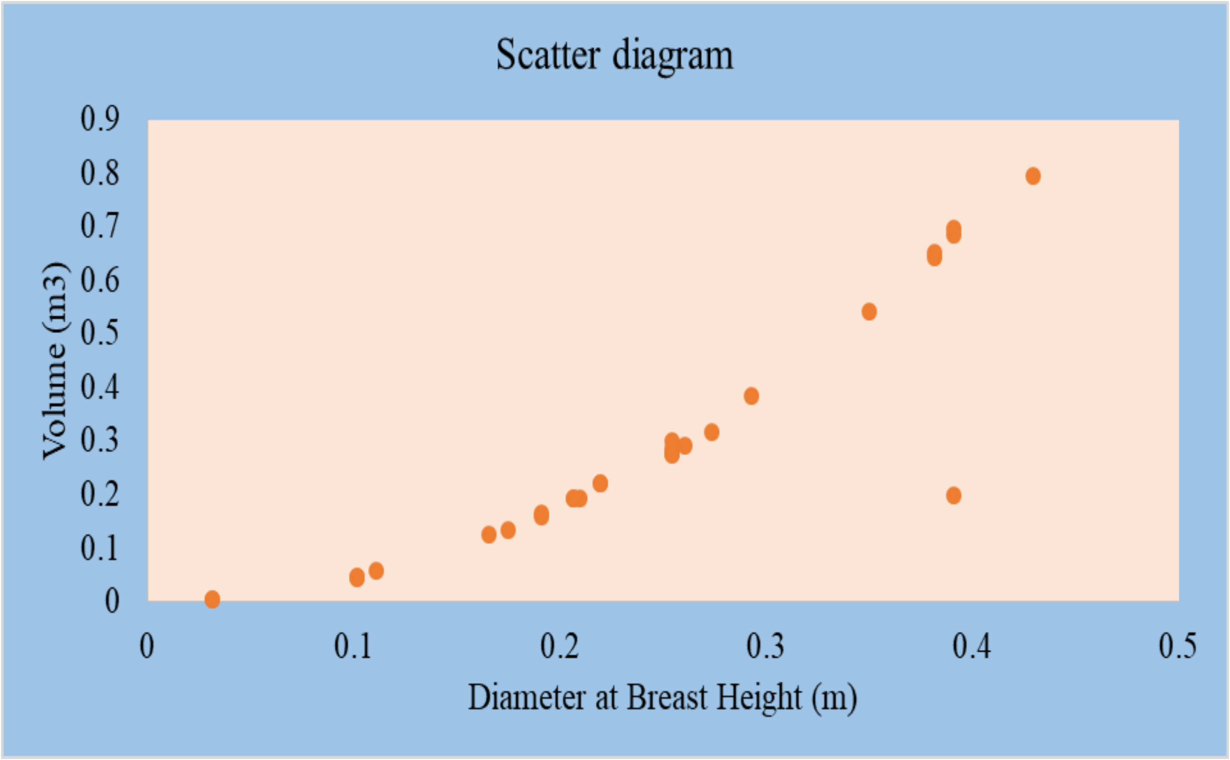


Figure.4 Fitted models for Volume (m^3) of Teak plantation in plot no. 1

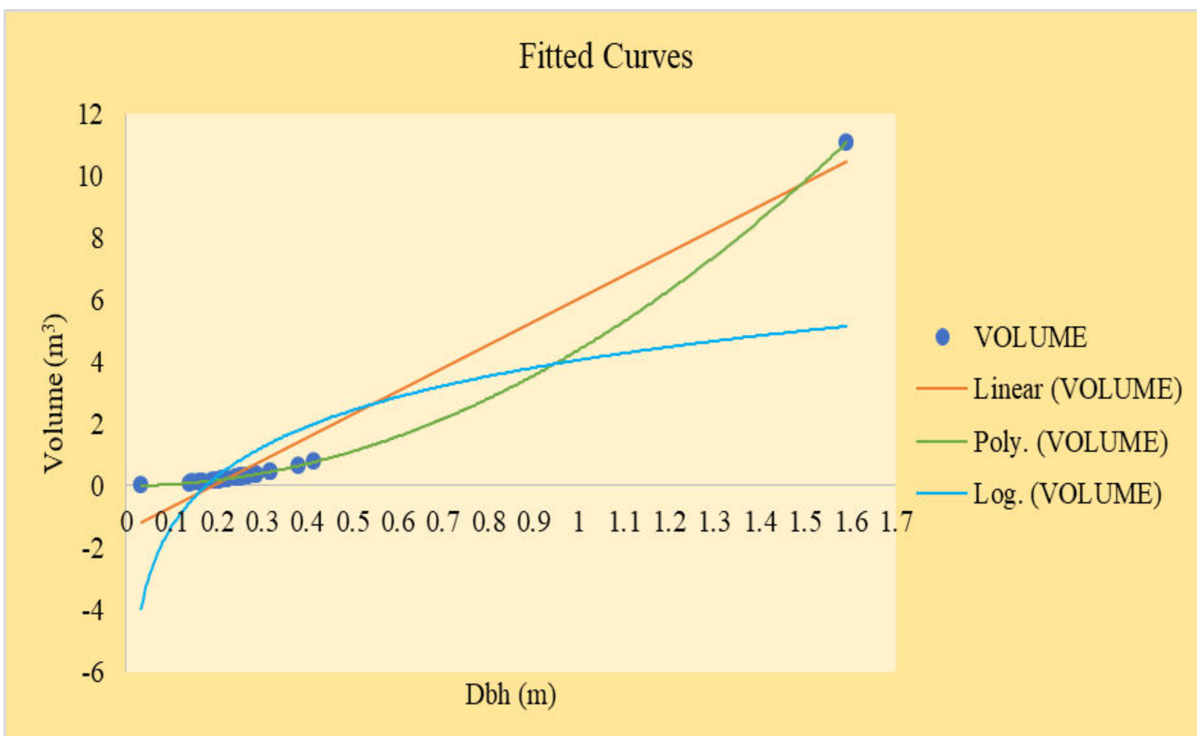


Figure.5 Fitted models for Volume (m^3) of Teak plantation in plot no. 2

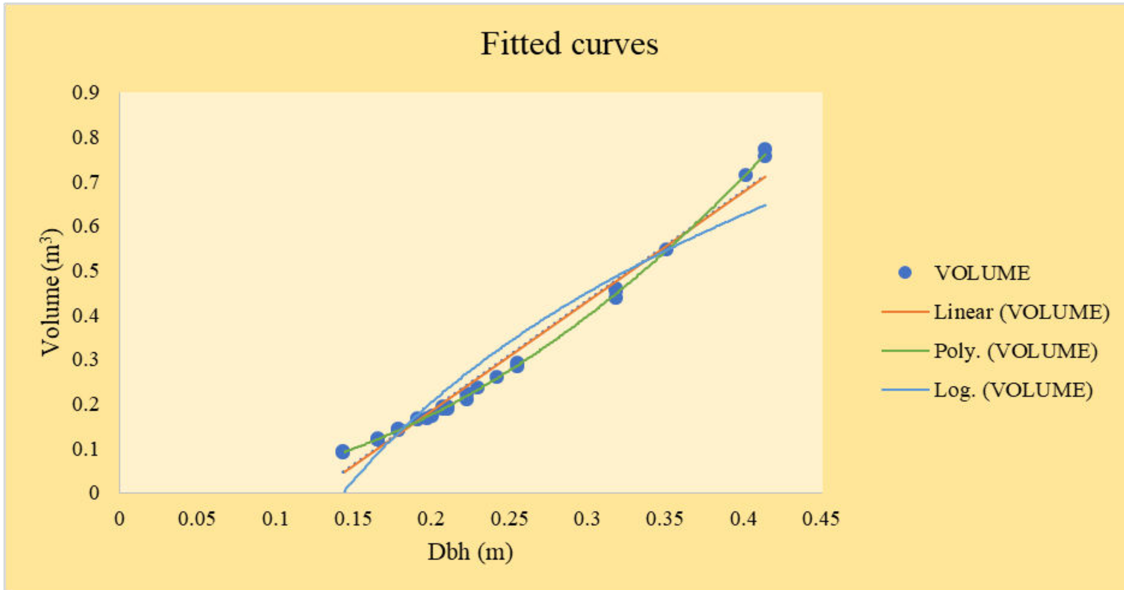
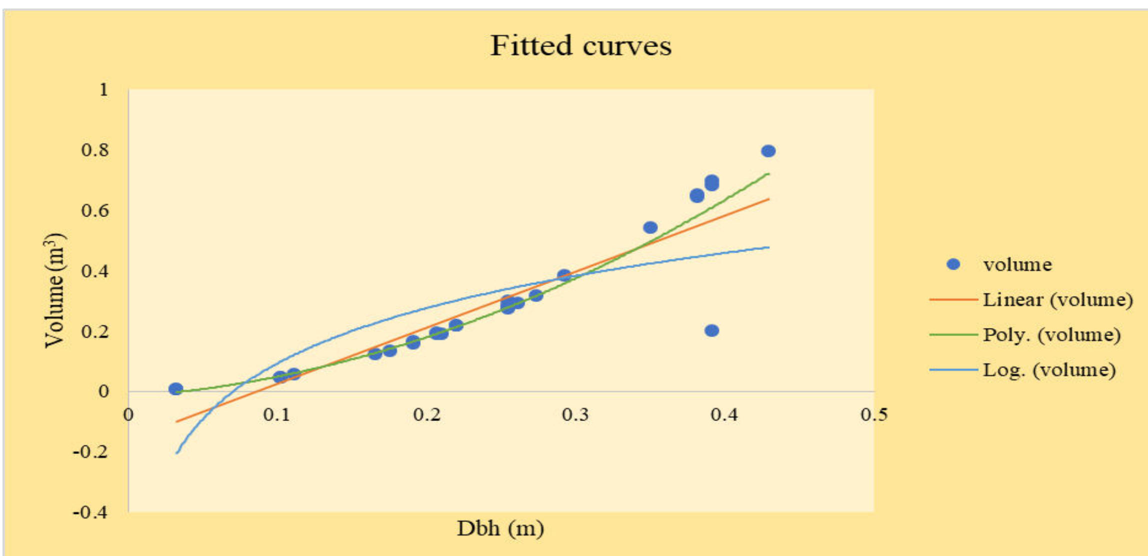


Figure.6 Fitted models for volume (m^3) of Teak plantation in plot no. 3



By demonstrating the limitations of logarithmic models, the potential of multiple regression, and the efficiency of diameter-based approaches, the study provides a comprehensive framework for improving volume estimation in tropical plantations. The findings reinforce the centrality of accurate mensuration in sustainable forestry and open avenues for future research into advanced modelling techniques, regional calibration, and practical integration of statistical tools into everyday forest management.

In conclusion, the analysis of teak plantations in the Thithimathi forest demonstrated that diameter at breast height (Dbh) is the most reliable predictor of tree volume, showing a consistently strong positive correlation across all plots. In contrast, tree height exhibited weaker and less consistent relationships with volume. Among the regression models tested, quadratic equations provided the highest accuracy, with superior R^2 values and minimal error compared to linear and logarithmic models. This confirms that non-linear approaches, particularly quadratic regression, are best suited for capturing the growth dynamics of *Tectona grandis*.

Multiple linear regression models also performed well, especially when both Dbh and height were included as predictors, achieving high explanatory power and low error rates. These findings highlight the practical value of quadratic equation for precise volume estimation, while also recognizing the usefulness of multiple regression in certain contexts. Together, these models offer forest managers and researchers robust tools for sustainable resource assessment, productivity planning, and effective management of teak plantations in the region.

Author Contributions

Sharanappa: Investigation, formal analysis, writing—original draft. G. T. Thippesha: Validation, methodology, writing—reviewing. R. Manjula:—Formal analysis, writing—review and editing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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