



RESEARCH ARTICLE

Growth dynamics, yield behaviour and economic returns of *Phyllanthus emblica* L. under agroforestry conditions across Tamil Nadu

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Abstract

Indian gooseberry (*Phyllanthus emblica* L.) has become increasingly important in India due to rising demand for Ayurvedic and natural health products. This study examines the growth and yield patterns of Indian gooseberry over its lifespan. Trees aged 6 to 35 years were studied in different conditions. The research was carried out in two regions of Tamil Nadu—the North Western Zone (NWZ) and North Eastern Zone (NEZ). These regions differ in climate and soil, providing a comprehensive assessment of how the species performs in varied environments. Biometric parameters including total tree height and diameter at 2 m vertical intervals were recorded using a tree telescope. Multiple linear regression (MLR) analysis was employed to develop zone-specific yield prediction equations and yield tables, bypassing conventional form-factor assumptions. The yield prediction model common to both zones takes the form $Y = -0.059 + 0.001X_1 + 1.67X_2 + 0.004X_3 - 0.038X_4$, while monetary yield is expressed as $Y = 0.093 + 0.001X_1 + 0.302X_2 + 3.545X_3 - 0.039X_4$. Pronounced inter-zonal differences in growth and productivity emerged from the results, underscoring the significant influence of site-specific soil conditions and local climate in shaping tree performance. The yield tables derived from this analysis offer a statistically grounded and field-applicable framework for estimating productivity, guiding management decisions and supporting the sustainable use of Indian gooseberry across the varied regional environments of Tamil Nadu.

Keywords: climatic gradients; farm tree systems; Indian gooseberry; monetary yield prediction; volume estimation

Introduction

Phyllanthus emblica L., commonly known as Indian gooseberry or amla, is a native tree of considerable economic worth that farmers across India have integrated into their farming systems for generations, drawn equally by its tolerance of harsh site conditions, its range of productive uses and the reliable income its harvest commands in both local and export markets (1, 2). Its remarkable adaptability to diverse soil and climatic conditions, particularly in dry and semi-arid environments, makes it equally suitable for marginal and productive farmlands, though considerable genotypic variation in stress response has been documented (2). In Tamil Nadu, amla-based tree farming has become increasingly prevalent in the North Western Zone (NWZ) and the North Eastern Zone (NEZ), where tree-based farming systems are increasingly adopted to secure sustained income, diversify livelihoods and generate favourable long-term economic returns (2, 3).

Quantifying age-specific productivity is fundamental to understanding tree crop performance and yield tables remain the primary predictive tool for capturing growth dynamics from

measurable biometric parameters (4). When integrated with prevailing market prices and cultivation costs, these tables form the basis for constructing monetary yield tables, enabling estimation of key economic indicators such as gross income, net returns, benefit : cost (B : C) ratio and net present value (NPV) across the rotation period (5, 6). Collectively, these indicators are widely recognised as reliable benchmarks for evaluating the long-term financial sustainability of agroforestry and tree-based land-use investments (7, 8).

Materials and Methods

Study area

The study was conducted across selected agricultural landscapes in two contrasting agro-climatic zones of Tamil Nadu, India, namely the NWZ and the NEZ (Fig. 1). These zones were purposively selected to capture variations in climatic conditions, rainfall patterns and soil characteristics that influence the growth and productivity of Indian gooseberry (*P. emblica*) plantations. Plantations representing age

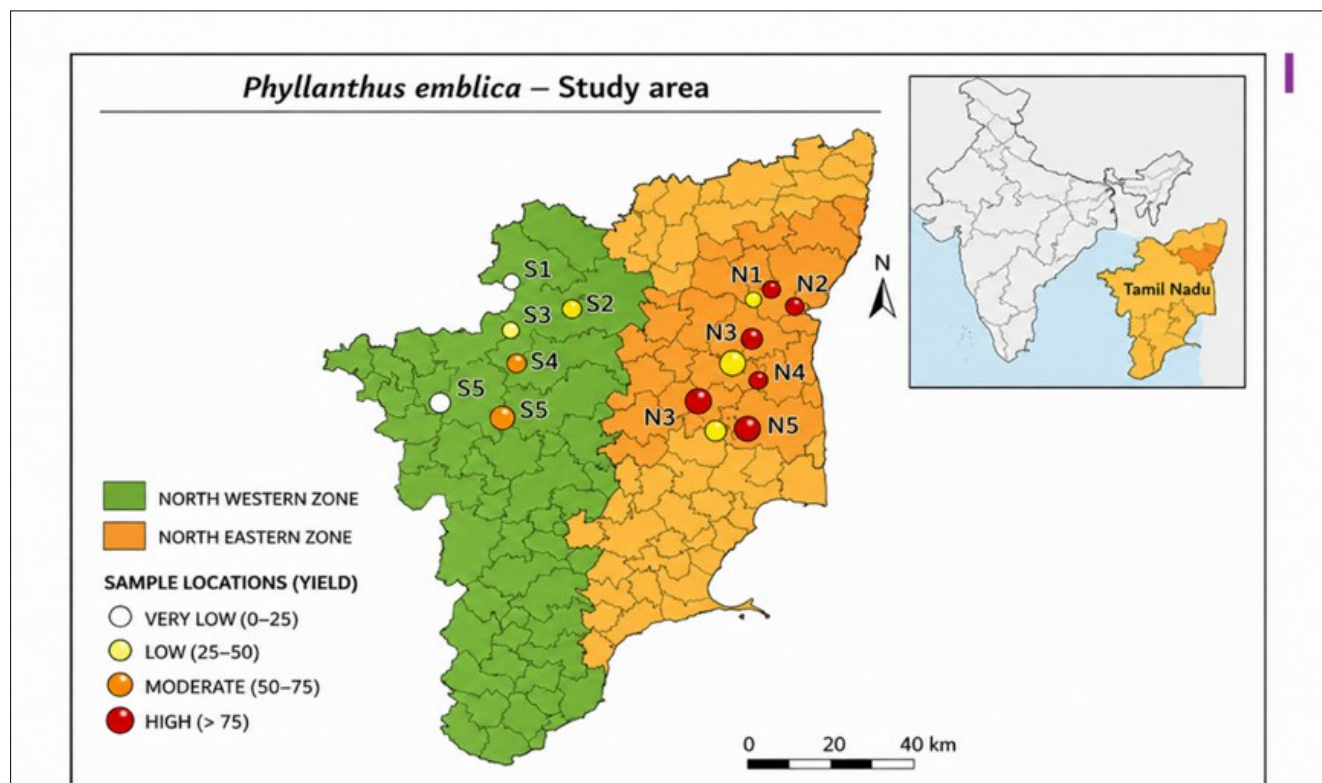


Fig. 1. Location of study area.

classes ranging from 6–35 years were identified within each agro-climatic zone based on plantation age, management history, accessibility and suitability for field measurements (Table 1).

A simple random sampling (SRS) technique was employed for tree selection and data collection. Within six age classes (6–10, 11–15, 16–20, 21–25, 26–30 and 31–35), ten sample trees were randomly selected for detailed biometric assessment. Consequently, a total of 60 sample trees were measured in each agro-climatic zone. To adequately represent plantation variability, five sample plots were established in each plantation, with a sampling intensity of 10 % of the total plantation area. The geographical coordinates of each sample plot were recorded using a handheld global positioning system (GPS) device to facilitate spatial referencing and mapping of the study sites.

Volume estimation

Stem volume of Indian gooseberry (*P. emblica*) was estimated using sectional measurements of the main bole, following standard forest mensuration procedures (9, 10). For every sampled tree, total height, clear bole height (CBH) and stem diameter at successive 2 m intervals from ground level were measured in the field. Tree heights were recorded using a Leica DISTO D810 laser distance meter and mid-section diameters were taken at the midpoint of each 2 m segment to keep volumetric calculations as accurate as the stem taper would permit. Trees were then grouped into six age classes:

6–10, 11–15, 16–20, 21–25, 26–30 and 31–35 years, so that changes in stem form across successive growth stages could be captured systematically. The volume of each 2 m section was calculated using the standard cylindrical formula (11):

$$V = \pi r^2 h \quad \text{Eq. 1}$$

Where, V = stem volume (m^3), r = mid-section radius (m) and h = section height (m). Individual section volumes were summed to derive the total stem volume for each tree.

Construction of yield models

Yield models were developed through multiple linear regression (MLR) analysis, establishing quantitative relationships between merchantable stem volume and key tree growth variables (4, 12). Tree age (years), mean stem diameter and total height served as explanatory variables, while merchantable volume ($\text{m}^3 \text{ tree}^{-1}$) comprising standard stem timber and small wood was treated as the response variable (13). Stem diameters were recorded at 2 m bole intervals using a tree telescope, enabling direct volume estimation without form-factor assumptions (10). Regression analyses were carried out in IBM SPSS within a general linear modelling framework (14), yielding the prediction equation:

$$Y = a + b_1 X_1 + b_2 X_2 + b_3 X_3 \quad \text{Eq. 2}$$

Where, Y = yield (m^3), a = intercept, X_1 = tree age (years), X_2 = mid-diameter (m), X_3 = tree height (m) and b_1 , b_2 , b_3 = their

Table 1. Study areas selected for yield and monetary yield modelling of wild amla

Parameter	(NWZ)	North Eastern Zone (NEZ)
Agroclimatic zone	North Western Zone of Tamil Nadu	North Eastern Zone of Tamil Nadu
Geographic extent	11°30'–12°30' N latitude; 77°00'–78°30' E longitude	12°00'–13°30' N latitude; 79°00'–80°30' E longitude
Mean annual temperature (°C)	24–34 °C	22–32 °C
Yield influencing variables	Tree age, mid-diameter, height and moisture availability	Tree age, mid-diameter, height and site quality

corresponding regression coefficients.

Validation of yield models

Model validity was assessed using a combination of goodness-of-fit statistics and standard diagnostic tests (4, 14). The coefficient of determination (R^2) and adjusted R^2 were used to evaluate explanatory power and model parsimony respectively (12), while t -tests confirmed the statistical significance of individual regression coefficients. Model robustness was further verified through split-sample validation, where predicted yields were compared against observed values withheld from calibration. The close agreement between observed and predicted values, coupled with the absence of systematic residual trends, confirmed the statistical reliability of the models for yield prediction and yield table construction in tree-based production systems (4, 12).

Development and validation of economic yield tables

Monetary yield tables were constructed by integrating predicted physical yields with prevailing market prices, a widely adopted approach in forest economic valuation (4, 6, 7). Money yield (₹ tree⁻¹) was estimated as the product of merchantable yield and the average market price of ₹10 per kg of fruits and served as the dependent variable. Tree age, mean diameter and predicted physical yield were used as independent variables (12, 15). The resulting model was structured as:

$$MY = a + b_1X_1 + b_2X_2 + b_3X_3 \quad \text{Eq. 3}$$

Where, MY = money yield (₹ tree⁻¹), X_1 = tree age, X_2 = average diameter, X_3 = predicted physical yield and b_1 , b_2 , b_3 = the fitted regression coefficients.

Validation of monetary yield tables followed established forest growth and economic modelling conventions (12, 15–17). Model fit was assessed through R^2 , standard error of estimate (SEE), mean absolute error (MAE) and root mean square error (RMSE) (18, 19). Residual plots confirmed that the assumptions of linearity, homoscedasticity and normality were reasonably satisfied (20) and chi-square (χ^2) tests showed no meaningful departure between observed and expected economic yields (12, 15). The resulting tables offer a statistically robust and practically applicable tool for economic appraisal and management planning in tree-based production systems (5, 7, 21).

Results and Discussion

Growth attributes of *P. emblica* showed a consistent increasing trend with age. In the 31–35-year age class, mean diameter at breast height (DBH), total height, CBH and stem volume reached 23.27 cm, 14.18 m, 4.14 m and 0.2737 m³ tree⁻¹ respectively. Stem volume increased more markedly than height during the later age classes, reflecting continued radial growth and volume accumulation. The periodic annual volume increment during 26–35 years was 0.0173 m³ tree⁻¹ year⁻¹, indicating that appreciable volume growth continued up to 35 years. These results suggest that the 31–35-year observations provide useful information for extending the yield trajectory and improving age-dependent yield modelling of *P. emblica* (Supplementary Fig. 1).

Regression-based yield modelling in *Phyllanthus emblica*

The MLR model accounted for 92.9 % of the observed yield variation ($R^2 = 0.929$), establishing the selected biometric variables as dependable predictors of merchantable yield. Stem diameter stood

out as the strongest individual predictor, which is consistent with the well-recognised role of radial growth in driving biomass accumulation (12, 13). Tree age and height both contributed positively to yield, though their influence was comparatively modest, suggesting that productivity gains taper off once trees approach physiological maturity. Clear bole height returned a negative coefficient, a pattern most plausibly attributed to the structural compromise between stem elongation and crown area as the bole extends upward. The photosynthetically active crown is effectively compressed, limiting productive capacity. The fitted equation confirms the model's suitability for yield estimation and yield table

Table 2. Regression-based yield modelling in *Phyllanthus emblica*

Variables	Regression coefficient (Y)
Intercept (a)	-0.059
Age (years) (X_1)	0.001
Diameter at breast height (DBH) (X_2)	1.677
Height (cm) (X_3)	0.004
CBH (X_4)	-0.038
R^2	0.929

construction (Table 2).

$$Y = -0.059 + 0.001X_1 + 1.677X_2 + 0.004X_3 - 0.038X_4 \quad \text{Eq. 4}$$

Where, Y: estimated merchantable stem yield (m³ tree⁻¹); X_1 : tree age (years), X_2 : diameter at breast height (cm), X_3 : total tree height (m), X_4 : clear bole height (m).

Monetary yield modelling and revenue analysis

The monetary yield model showed excellent predictive performance, explaining 98.9 % of the variation in economic returns ($R^2 = 0.989$). Fruit width had the strongest positive effect on monetary yield, followed by fruit length, while fruit weight contributed positively but to a lesser extent. The fitted equation indicated that fruit size traits were the major determinants of economic value in *P. emblica* plantations. The strong influence of fruit length and width suggests that larger fruits contribute substantially to market returns (7, 15). The high R^2 value confirms the reliability of the model for monetary yield estimation and economic assessment. However, the negative coefficient for fruit yield should be interpreted as a statistical association within the dataset rather than a direct causal relationship. Overall, the model provides a useful tool for economic yield prediction and plantation management (Table 3). The equation is as follows:

$$MY = 0.093 + 0.001X_1 + 0.302X_2 + 3.545X_3 - 0.039X_4 \quad \text{Eq. 5}$$

Where, MY: monetary yield/economic return (₹ tree⁻¹),

Table 3. Monetary yield modelling and revenue analysis

Variables	Regression coefficient
Intercept (a)	0.093
Weight (X_1)	0.001
Fruit length (cm) (X_2)	0.302
Fruit width (cm) (X_3)	3.545
Fruit yield (X_4)	-0.039
R^2	0.989

X_1 : fruit weight (kg tree^{-1}), X_2 : fruit length (cm), X_3 : fruit width (cm), X_4 : fruit yield (kg tree^{-1}).

Residual diagnostic tests confirmed that all core assumptions of linear regression were satisfactorily met (Fig. 2). Residuals were uniformly scattered around zero with no systematic curvature, supporting model linearity despite natural biological variation among trees (22). The Q-Q plot indicated near-normal error distribution, while the scale-location plot confirmed reasonable homoscedasticity, minor variance inflation in larger trees was expected rather than concerning. Cook's distance and leverage statistics revealed no influential outliers, ensuring model stability

(23). Overall, the diagnostics affirm that the model is statistically sound and well-suited for yield estimation and yield table development.

Residual diagnostics confirmed that the monetary yield model satisfied all core regression assumptions (Fig. 3). Residuals were randomly distributed around zero with no systematic bias, supporting model linearity (24, 25). The Q-Q plot indicated near-normal error distribution, with minor tail deviations attributable to natural tree variability and market price fluctuations (26). Homoscedasticity was broadly maintained across fitted values and Cook's distance with leverage statistics identified no influential

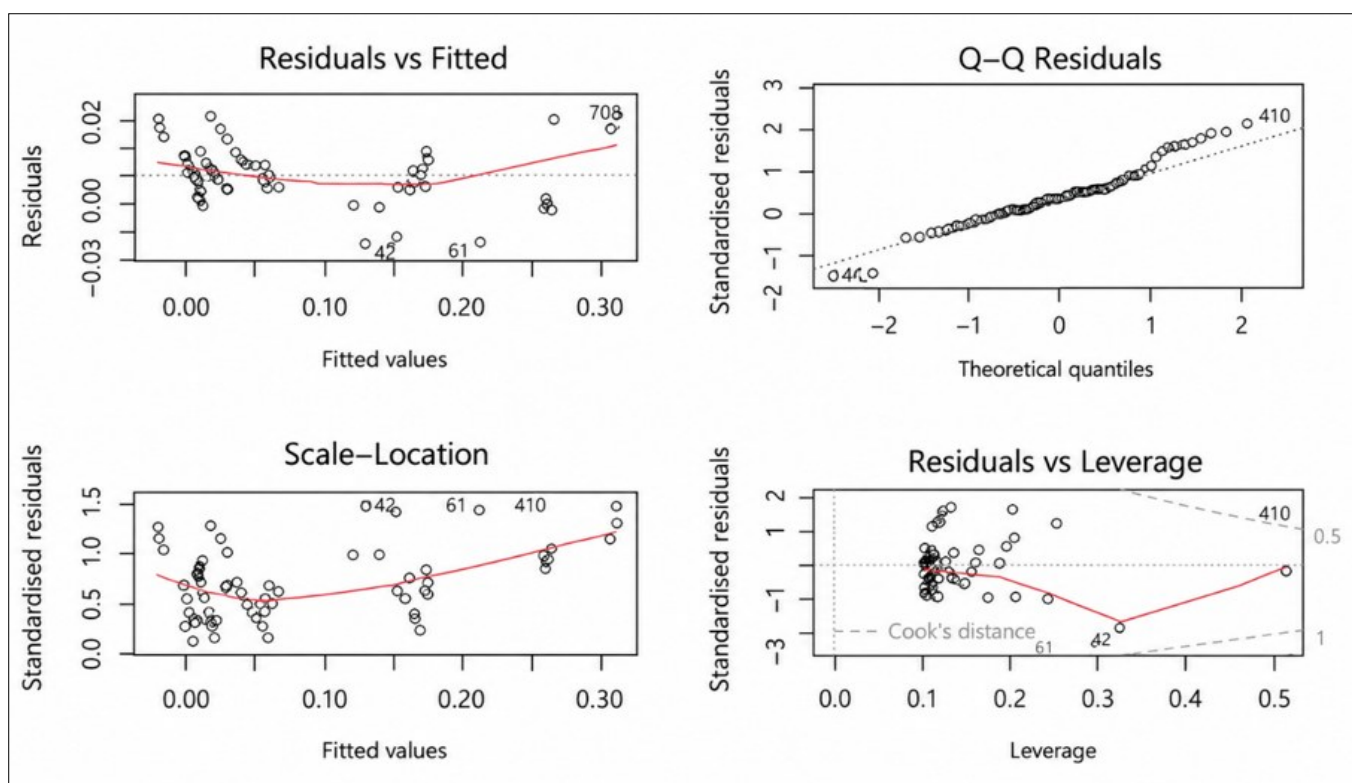


Fig. 2. Residual diagnostic assessment of the yield regression model.

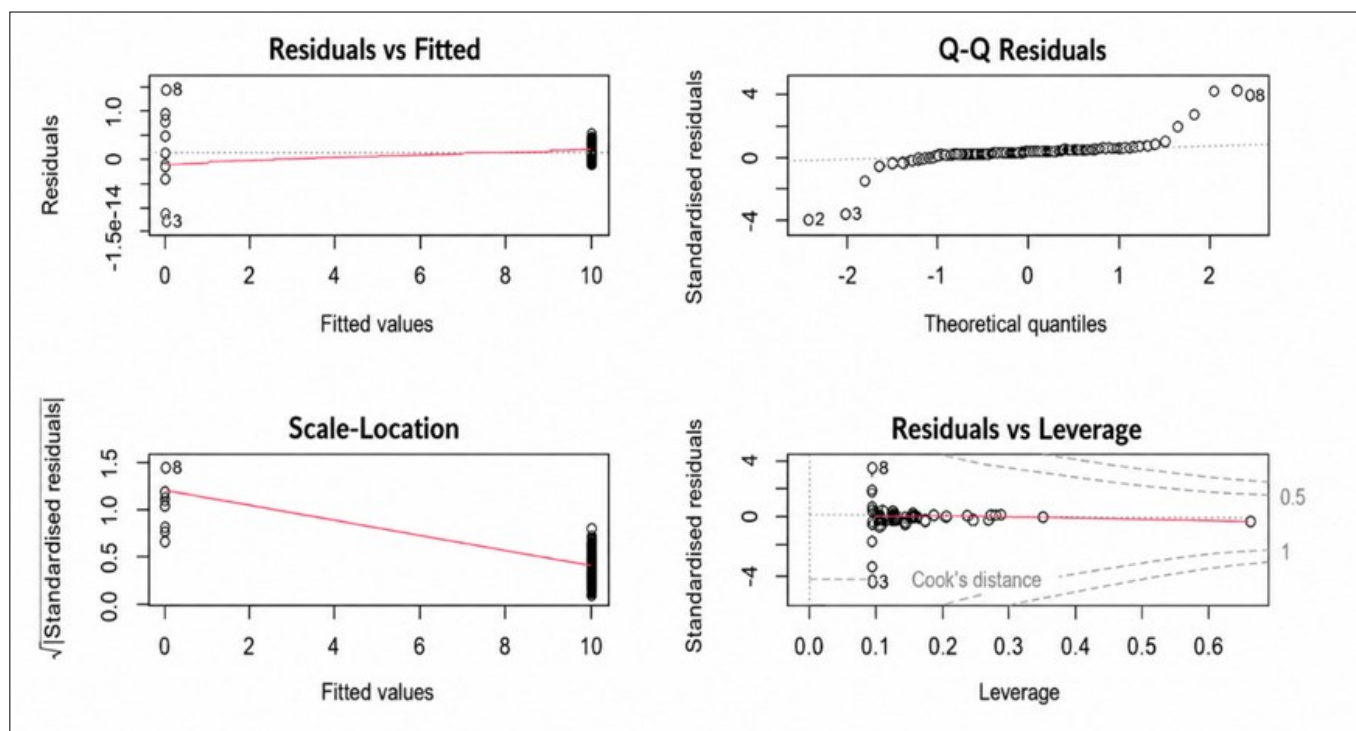


Fig. 3. Residual diagnostics of the monetary yield prediction model.

outliers (27). These diagnostics collectively confirm the model's statistical integrity for monetary yield estimation and economic yield table construction in *P. emblica* plantations.

The 3D cone plot provided an integrated visualisation of physical and monetary yield trends across agro-climatic zones (Fig. 4). Progressive cone elongation with increasing age, diameter and height confirmed that yield and economic returns rise consistently with tree growth. The colour gradient from blue to red illustrated increasing productivity, while stronger vectors in the upper size range suggested nonlinear economic gains in larger trees. This pattern reinforces the predictive reliability of both yield and money yield models for *P. emblica* under NWZ and NEZ conditions (4, 28).

The correlation matrix (Fig. 5) brought out strong and ecologically interpretable relationships among tree growth, yield and climatic variables. Age class tracked closely with stem volume and biomass ($r = 0.864, p < 0.001$), confirming that stand productivity builds progressively as trees advance through successive ontogenetic stages. Stem weight and stem volume were virtually interchangeable as productivity indicators, returning a near-perfect correlation of $r = 1.000$ ($p < 0.001$) (12, 13). Within the climatic variables, maximum temperature exerted a clear negative influence on both stem volume ($r = -0.714, p < 0.05$) and yield ($r = -0.659, p < 0.05$), whereas rainfall and humidity maintained moderate positive associations with growth, a pattern that points to moisture availability as the principal climatic lever governing productivity

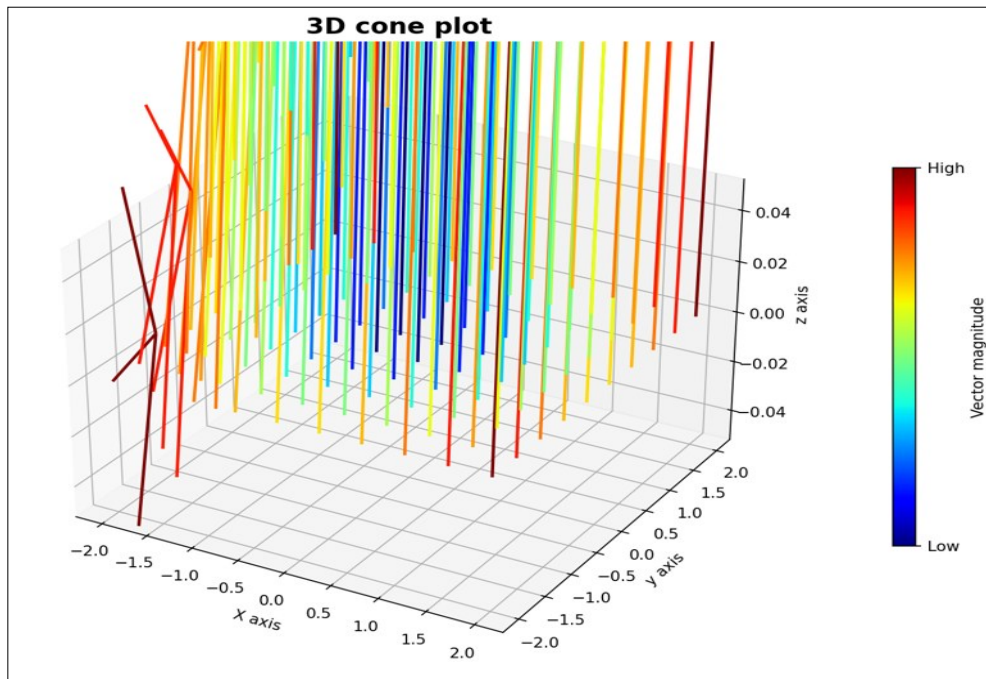


Fig. 4. Cone plot analysis of growth-linked yield and monetary valuation patterns.

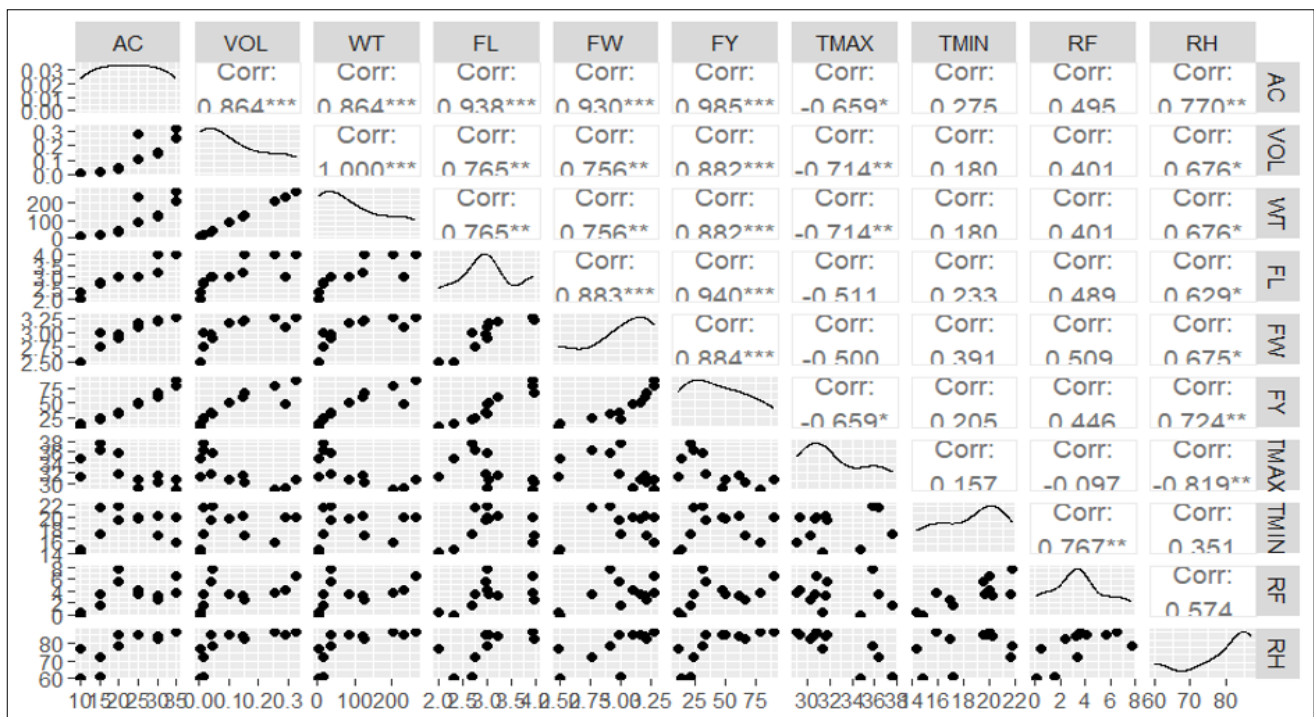


Fig. 5. Scatterplot correlation matrix of biometrics and climatic factors.

AC: acid content; VOL: volume; WT: weight; FL: fruit length; FW: fruit width; FY: fruit yield; TMAX: maximum temperature; TMIN: minimum temperature; RF: rainfall; RH: relative humidity.

across the two agro-climatic zones studied (29, 30).

Principal component analysis (PCA) biplots resolved the primary axes of growth and economic yield variation into two components that together captured 85.2 % of total variance, with the first-dimension alone accounting for 68.5 % and the second contributing a further 16.7 % (Fig. 6). Productivity-related variables, including age class, stem volume, biomass, fruit yield and fruit size, loaded strongly on Dim1, confirming that tree growth forms the dominant axis of yield variation in plantation systems (12, 13). Principal component analysis is widely used to reduce dimensionality and identify dominant patterns of variability in complex datasets (31, 32). Dim2 captured climatic influences, with rainfall and humidity loading positively and maximum temperature negatively, suggesting that moisture availability supports productivity while heat stress constrains it (29). These results confirm that growth traits are the primary yield determinants, with climate serving a secondary but meaningful regulatory role, justifying the inclusion of both variable classes in zonal yield and economic valuation models (29, 30).

The climate-growth correlation matrix (Fig. 7) further affirmed DBH as the strongest single predictor of merchantable volume ($r=0.99$), reinforcing its centrality in yield table development (12, 13). Total height maintained moderate positive associations with both DBH ($r=0.48$) and stem volume ($r=0.57$), a finding that is consistent with established allometric growth expectations. Among the environmental variables, relative humidity showed notably strong positive links with DBH ($r=0.72$) and stem volume ($r=0.75$), while maximum temperature worked in the opposite direction, pulling down both height ($r=-0.63$) and volume ($r=-0.57$), a response pattern that points to thermal limitation as a real constraint on radial and vertical growth under tropical field conditions. These findings reinforce DBH and moisture availability as the key drivers of productivity estimation across contrasting agro-climatic zones (29, 30).

K-means clustering resolved observations into three statistically distinct yield classes, primarily differentiated along Dim1 (68.5 %) (Fig. 8). Cluster 1 represented low-yielding stands with limited biomass accumulation, Cluster 3 captured high-performing stands with superior volume and economic value and Cluster 2 reflected intermediate productivity likely governed by site quality and climatic variability. This classification provides a structured framework for partitioning plantations into homogeneous yield classes, directly improving the precision and applicability of yield and monetary yield tables (12, 33).

The validation analysis revealed substantial discrepancies between observed and predicted tree volumes. The model produced a mean predicted volume (0.2011 m^3) nearly double the mean observed volume (0.1018 m^3), resulting in a high percentage bias (PBIAS = +97.62 %). The RMSE (0.1116 m^3) and MAE (0.0993 m^3) further indicated considerable prediction errors. These findings suggest that the developed equation systematically overestimates volume under NEZ conditions (Table 4). Such overprediction may arise from differences in site productivity, climatic conditions, stand structure and management practices between calibration and validation datasets. Similar observations have been reported in forest biometric studies, where generalised allometric equations (12, 34) often exhibit reduced accuracy when transferred across regions. Therefore, local calibration or development of region-specific models is recommended to improve volume estimation accuracy in *P. emblica* plantations of the NEZ (35, 36).

The validation of the yield model for *P. emblica* in the NWZ (Table 5) demonstrated satisfactory predictive performance across plantations aged 5–35 years. The mean predicted volume (0.1012 m^3) was slightly higher than the mean observed volume (0.0901 m^3), indicating a tendency toward moderate overestimation (37). The model produced a low RMSE (0.0260 m^3) and MAE (0.0197 m^3), suggesting that prediction errors were relatively small and that the model effectively captured the volume growth pattern

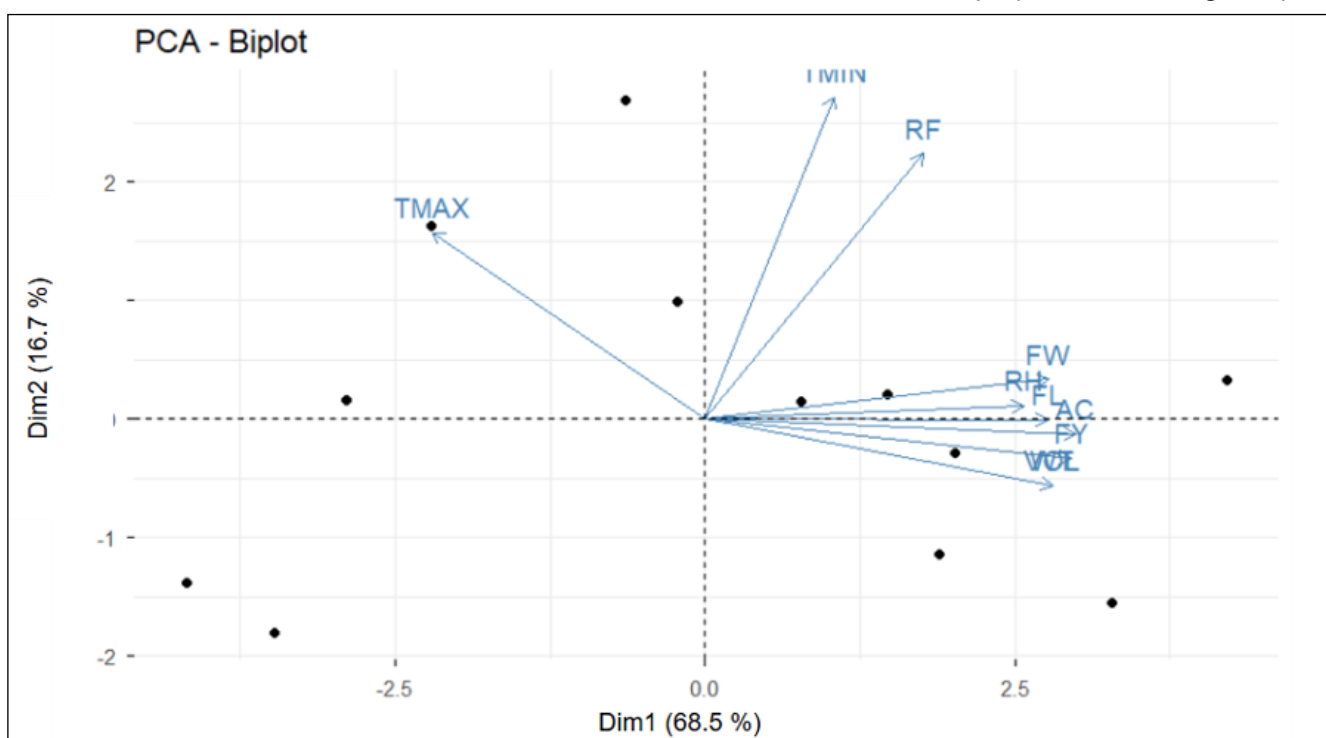


Fig. 6. Principal component biplot of yield-related and climatic variables.

TMAX: maximum temperature; TMIN: minimum temperature; RF: rainfall; RH: relative humidity; AC: acid content; FL: fruit length; FW: fruit width; FY: fruit yield; VOL: volume; WT: weight.

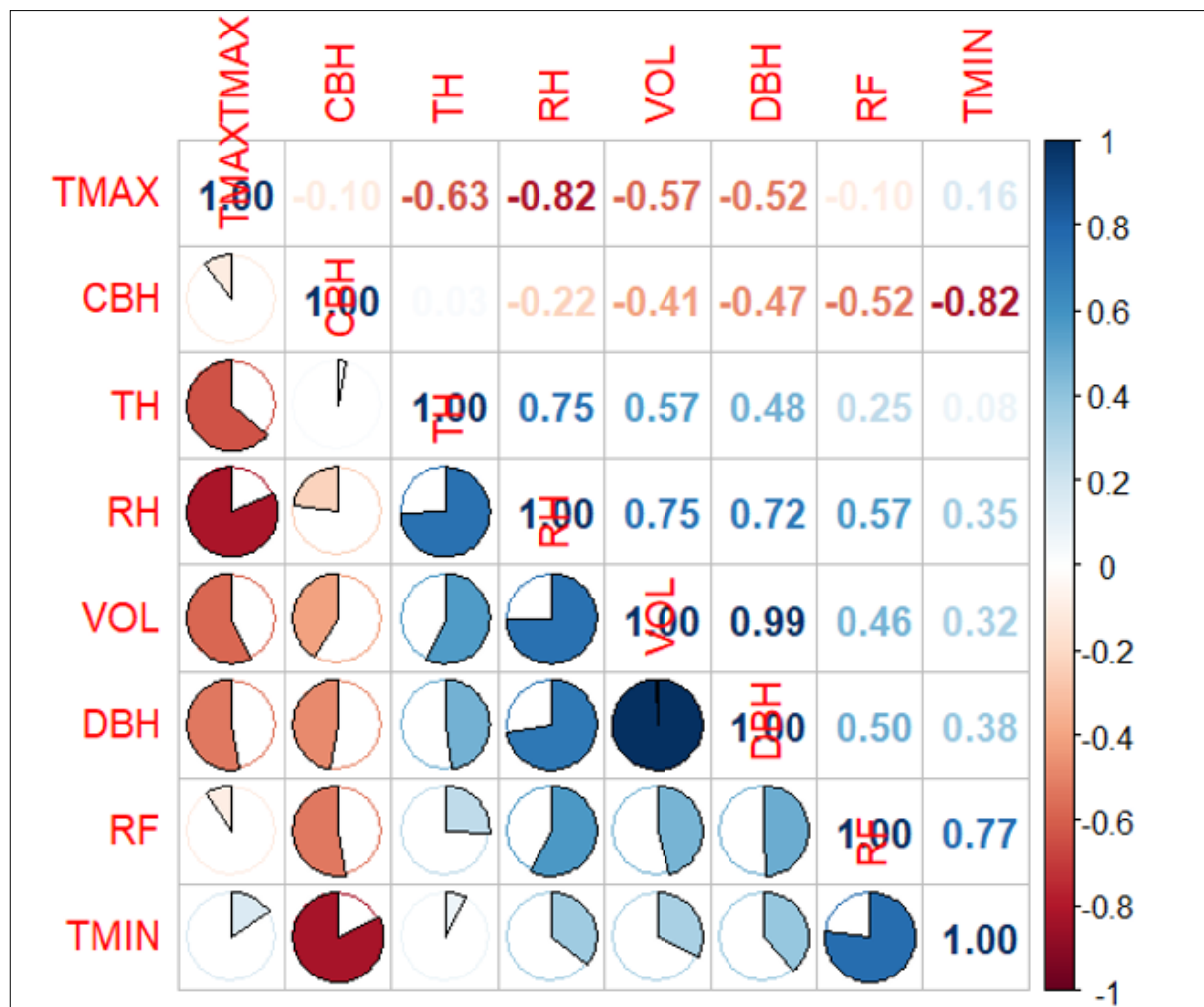


Fig. 7. Correlation matrix of growth vs climatic factors.

TMAX: maximum temperature; CBH: clear bole height; TH: total height; RH: relative humidity; VOL: stem volume; DBH: diameter at breast height; RF: rainfall; TMIN: minimum temperature.

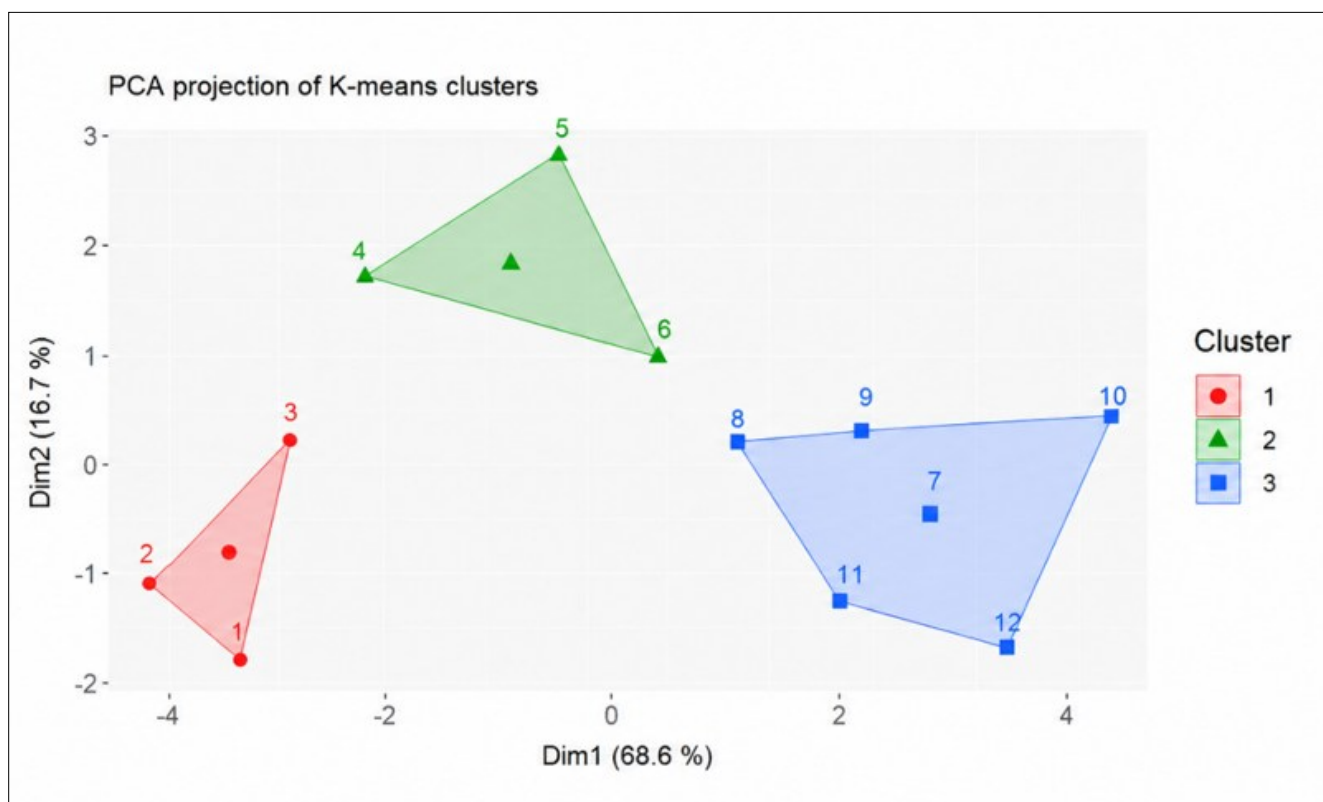


Fig. 8. Principal component analysis-based K-means clustering of yield classes.

Table 4. Validation of yield model for *Phyllanthus emblica* in North Eastern Zone

Age (years)	DBH (m)	Height (m)	CBH (m)	Actual volume (m ³)	Predicted volume (m ³)
5	0.0634	3.92	2	0.0056	0.0079
7	0.0605	4.24	2.1	0.0055	0.0133
8	0.0688	3.97	1.8	0.0066	0.0184
9	0.0605	3.96	1.7	0.0051	0.0192
10	0.0648	4.14	1.6	0.0061	0.0246
11	0.0951	5.6	1.7	0.0179	0.0782
12	0.0936	5.93	3.2	0.0184	0.0578
13	0.094	6.13	2.4	0.0191	0.0820
14	0.0959	6.15	2.1	0.02	0.0955
15	0.0949	6.3	2.5	0.02	0.0966
16	0.1268	8.08	3.4	0.0459	0.1444
17	0.1158	9.22	2.8	0.0437	0.1533
18	0.1257	9.81	3.1	0.0548	0.1724
19	0.1319	8.95	2.4	0.055	0.1800
20	0.1318	10.3	3.5	0.0632	0.1926
21	0.2486	13.1	4.3	0.286	0.3423
22	0.1859	8.51	4.1	0.1039	0.2402
23	0.1991	9.15	5	0.1281	0.2628
24	0.1566	12.6	3.9	0.1092	0.2315
25	0.1225	8.23	3.8	0.0436	0.1876
26	0.1835	12.4	4.1	0.1475	0.2817
27	0.1899	12.8	4.2	0.1631	0.2951
28	0.1869	13.5	4.6	0.1666	0.3049
29	0.1917	11.9	3.9	0.1545	0.2980
30	0.1898	14.2	4.9	0.1807	0.3128
31	0.199	13.39	4.8	0.1873	0.3164
32	0.2239	14.17	3.4	0.2509	0.4280
33	0.2216	14.16	3.9	0.2456	0.3928
34	0.2236	14.13	4.4	0.2496	0.3992
35	0.2222	14.29	4	0.2492	0.4031
Mean				0.1018	0.2011
Root mean square error (RMSE)					0.1116
Mean absolute error (MAE)					0.0993
Mean bias error (MBE)					+0.0993
Bias percentage (PBIAS)					+97.62 %

DBH: diameter at breast height; CBH: clear bole height.

Table 5. Validation of yield model for *Phyllanthus emblica* in North Western Zone

Age (years)	DBH (m)	Height (m)	CBH (m)	Actual volume (m ³)	Predicted volume (m ³)
5	0.0635	3.98	1.7	0.0057	0.0038
7	0.0644	3.99	1.6	0.0058	0.0134
8	0.0686	4.11	1.9	0.0066	0.0025
9	0.0648	4.25	1.8	0.0063	0.0099
10	0.0679	4.14	1.7	0.0067	0.0157
11	0.0968	6.36	2.9	0.0211	0.0164
12	0.1	6.78	2.8	0.024	0.0318
13	0.0971	6.99	2.4	0.0233	0.0530
14	0.0936	7.01	2.6	0.0217	0.0440
15	0.0917	7.12	2.9	0.0211	0.0261
16	0.1193	9.84	2.9	0.0495	0.0554
17	0.1235	9.92	3.5	0.0534	0.0421
18	0.1193	9.44	2.8	0.0475	0.0611
19	0.129	10.1	3.3	0.0594	0.0621
20	0.1271	9.43	2.5	0.0538	0.1045
21	0.11	13.1	4.3	0.039	0.0411
22	0.1248	8.51	4.1	0.0416	0.0582
23	0.1411	9.15	5	0.0587	0.0657
24	0.1661	12.6	3.9	0.1277	0.1623
25	0.1069	8.23	3.8	0.0585	0.0185
26	0.1863	12.6	4.1	0.1545	0.1785
27	0.192	13.8	4.7	0.1797	0.1798
28	0.1984	12.1	4	0.1682	0.2277
29	0.1863	14.9	5.2	0.1827	0.1420
30	0.1908	13.2	4.4	0.1698	0.2026
31	0.224	13.98	4.1	0.2478	0.3026
32	0.2539	14.43	4	0.3286	0.3602
33	0.2511	14.49	4.1	0.3227	0.3579
34	0.2545	14.58	4.3	0.3336	0.3505
35	0.256	14.48	4.4	0.3352	0.3510
Mean				0.0901	0.1012
Root mean square error (RMSE)					0.0260
Mean absolute error (MAE)					0.0197
Mean bias error (MBE)					0.0129
Bias percentage (PBIAS)					12.24 %

DBH: diameter at breast height; CBH: clear bole height.

across age classes. The positive mean bias error (MBE) (0.0129 m³) and percentage bias (12.24 %) further confirmed a systematic but acceptable level of overprediction. Such bias may be attributed to site-specific variations in soil fertility, moisture availability, stand density and management practices that were not fully represented in the model structure. Nevertheless, the overall validation statistics indicate that the model provides reliable and accurate volume estimates for *P. emblica* plantations in the NWZ and can be confidently applied for yield prediction, plantation management and resource assessment purposes (38–40).

The validation of the money yield model for *P. emblica* in the NEZ showed high predictive accuracy, with the mean predicted yield (37.72) closely matching the mean observed yield (38.17). The model produced low error values (RMSE = 1.9702; MAE = 0.8513), indicating minimal deviation between observed and predicted yields (41). The negative MBE (-0.5240) and PBIAS (-1.18 %) revealed only a slight underestimation tendency, which was negligible and within acceptable limits. Overall, the validation results confirm that the model reliably estimates economic yield and can be effectively used for yield forecasting and plantation management of *P. emblica* in the NEZ (Table 6).

The validation of the monetary yield table for *P. emblica* in the NWZ indicated moderate predictive performance with a mean observed yield of 42.62 m³ and a mean predicted yield of 32.17 m³. The model consistently underestimated actual yield across age classes, as reflected by the negative MBE = -12.19 and PBIAS = -24.51 %. The RMSE = 16.71 m³ and MAE = 13.97 m³ further suggest considerable deviations between observed and predicted values, particularly in older and high-yielding plantations. Despite

capturing the general increasing trend of yield with age, the model showed reduced accuracy in estimating higher yield levels (42, 43), indicating that site-specific factors and age-related growth variations may not be fully represented in the prediction equation. Therefore, while the yield table provides a useful framework for estimating monetary yield in NWZ plantations, further calibration using additional field data and inclusion of relevant growth variables would improve its reliability and applicability for plantation management and economic planning (Table 7).

Conclusion

Zone-specific yield and monetary yield models developed for *Phyllanthus emblica* L. across the NWZ and NEZ of Tamil Nadu demonstrated strong predictive performance ($R^2 = 0.929$), with stem diameter identified as the primary determinant of physical and economic productivity. Tree age, moisture availability and maximum temperature acted as important secondary growth regulators. Validation results confirmed satisfactory model accuracy within acceptable error limits, although periodic recalibration is recommended for mature stands. The developed yield and monetary yield tables provide a reliable tool for investment planning, harvest scheduling and sustainable management of *P. emblica*-based farm forestry systems. Future research should focus on validating these models across broader agro-climatic regions and integrating additional environmental and management variables to improve long-term predictive accuracy and adaptability under changing climatic conditions.

Table 6. Validation of monetary yield table for *Phyllanthus emblica* in North Eastern Zone

Age (years)	Weight (kg)	Fruit length (cm)	Fruit width (cm)	Actual yield (m ³)	Predicted yield (m ³)
5	4.56	2	2.48	10.92	11.10
7	4.50	2.31	2.49	13.96	14.13
8	5.44	2.35	2.43	11.52	11.81
9	4.20	2.47	2.99	15.78	16.04
10	5.04	2.88	2.67	13.89	14.05
11	14.67	2.7	2.99	21.44	21.82
12	15.05	2.75	2.76	23.44	23.68
13	15.69	2.76	2.78	23.77	23.99
14	16.38	2.79	2.79	24.77	25.04
15	16.44	2.8	2.75	25.77	25.93
16	37.63	2.99	2.91	31.57	31.70
17	35.81	2.98	2.98	33.54	33.77
18	44.90	2.97	2.99	35.66	35.91
19	45.10	2	2.96	36.77	37.38
20	51.83	2.11	2.94	38.44	38.72
21	234.51	3.01	3.1	47.56	47.84
22	85.19	3.03	3.16	49.88	49.92
23	105.07	3.02	3.18	50.99	50.93
24	89.51	3.17	3.19	52.99	53.03
25	35.77	3.08	3.18	53.88	54.02
26	120.95	3.21	3.2	61.23	61.38
27	133.71	3.29	3.25	62.54	62.52
28	136.60	3.89	3.24	64.78	64.88
29	126.67	3.78	3.21	65.99	66.32
30	148.18	3.88	3.2	66.63	65.97
31	153.60	3.99	3.26	72.33	66.62
32	205.77	3.96	3.27	78.83	72.36
33	201.42	3.96	3.28	79.77	78.99
34	204.64	3.97	3.29	80.44	79.76
35	204.37	3.98	3.21	86.77	80.52
Mean				38.17	37.72
Root mean square error (RMSE)				1.9702	
Mean absolute error (MAE)				0.8513	
Mean bias error (MBE)				-0.5240	
Bias percentage (PBIAS)				-1.18 %	

Table 7. Validation of monetary yield table for *Phyllanthus emblica* in North Western Zone

Age (years)	Weight (kg)	Fruit length (cm)	Fruit width (cm)	Actual yield (m ³)	Predicted yield (m ³)
5	4.65	2.9	2.67	14.54	11.68
7	4.79	2.88	2.89	14.59	11.64
8	5.45	2.65	2.75	13.59	11.03
9	5.17	2.65	2.78	12.99	10.95
10	5.53	2.64	2.98	14.44	11.02
11	17.26	2.84	2.7	26.77	15.28
12	19.64	2.88	2.76	26.72	16.14
13	19.09	2.9	2.72	29.53	16.05
14	17.76	2.97	2.71	29.55	15.89
15	17.34	2.56	2.78	30.44	14.31
16	40.57	2.89	2.9	39.77	22.49
17	43.83	2.76	2.91	40.65	23.02
18	38.92	2.99	2.9	41.22	22.35
19	48.69	2.97	2.97	42.66	25.23
20	44.13	2.65	2.99	42.76	22.72
21	31.97	3.09	3.16	55.57	20.60
22	34.11	3.99	3.18	56.79	24.44
23	48.10	3.23	3.17	57.77	25.97
24	104.69	3.21	3.18	58.86	42.99
25	48.00	3.2	3.19	59.78	25.83
26	126.68	3.99	3.21	66.9	52.40
27	147.36	3.78	3.23	67.33	57.90
28	137.96	3.96	3.24	64.76	55.70
29	149.80	3.49	3.22	69.53	57.61
30	139.20	3.77	3.21	70.83	55.40
31	203.19	3.76	3.28	87.33	74.69
32	269.46	3.98	3.29	88.98	95.48
33	264.64	3.96	3.27	89.94	93.96
34	273.55	3.92	3.26	89.22	96.51
35	274.88	3.9	3.25	87.9	96.84
Mean				42.62	32.17
Root mean square error (RMSE)					16.71
Mean absolute error (MAE)					13.97
Mean bias error (MBE)					-12.19
Bias percentage (PBIAS)					-24.51 %

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Authors' contributions

All authors contributed to the conceptualisation of the research work, design of the experiments, execution of field and laboratory experiments, data collection, data analysis, interpretation of results and preparation of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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