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RESEARCH ARTICLE

# Evaluation of growth, yield and economics of *Stevia rebaudiana* Bertoni under partial shade in a teak-based agroforestry system in the sub-tropical region of Madhya Pradesh

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## Abstract

*Stevia rebaudiana*, a perennial herb prized for its steviol glycosides, is increasingly being cultivated as a natural sweetener. In India, the annual demand for this herb is estimated at approximately 10 metric tons. However, the relationship between agronomic practices and agroforestry systems on leaf yield and economic viability in tropical climates remains underexplored. This study evaluated the effects of spacing and organic amendments on growth, productivity in a teak-based agroforestry system in Central India. A field experiment was conducted in a randomized block design with a factorial concept under a teak-based agroforestry model at the Non Wood Forest Produce (NWFP) nursery, Indian Council of Forestry Research and Education - Tropical Forest Research Institute (ICFRE-TFRI), Jabalpur, Madhya Pradesh. The treatments included plant spacing (S1: 45 × 45 cm, S2: 30 × 30 cm, S3: 20 × 20 cm) and organic nutrient regimes (M7: farmyard manure (FYM) + vermicompost (VC) + poultry manure (PM); M6; VC + PM; M5: FYM + PM; M4: FYM + VC; M3: PM; M2: FYM; M1: VC; M0: control). Growth parameters such as plant height, branch number and leaf count were recorded, along with biomass yield (fresh and dry weight). Economic viability was assessed through input-output ratios. The results indicated enhanced plant height, branching and leaf count per plant under M7. Spacing S3 yielded the maximum fresh and dry biomass. Economic analysis revealed that S3 and M7 are cost-effective with higher net returns. These findings underscore that integrating teak agroforestry and organic amendments enhances both yields, offering a sustainable model for tropical stevia cultivation. This study provides actionable insights into agronomic practices to balance productivity, metabolite quality and profitability in resource-constrained systems.

**Keywords:** agroforestry; farmyard manure; organic nutrient regimes; poultry manure; *Stevia rebaudiana* Bertoni; vermicompost

## Introduction

*Stevia rebaudiana* Bertoni, generally referred to as stevia, is an herbaceous perennial plant of the Asteraceae family. It is indigenous to northeastern Paraguay and extends its natural habitat to neighbouring regions of Brazil and Argentina (1). In recent years, stevia has attracted considerable attention as a commercially viable crop due to its high concentration of steviol glycosides, particularly stevioside and rebaudioside A, which exhibit intense sweetening properties without contributing to caloric intake (2). These compounds, which are approximately 300 to 400 times sweeter than sucrose, serve as an attractive substitute for conventional sugar and artificial sweeteners. Consequently, stevia presents an appealing option for addressing global concerns related to obesity, diabetes and metabolic syndromes (3, 4).

Numerous scientific studies have documented the adverse health effects of consuming large amounts of sugar, which increases the risk of obesity, type 2 diabetes, cardiovascular disease and dental problems. According to a recent meta-analysis, sugar-sweetened beverages are accountable for more than 184000 reportable deaths annually (5). Due to rising demand for natural sweeteners, stevia has expanded beyond its native range. It is now cultivated in China, Japan, Brazil, India and parts of Europe and North America. The global stevia market, valued at USD 0.93 billion in 2025, is projected to expand markedly to USD 1.56 billion by 2030, advancing at a robust compound annual growth rate (CAGR) of 10.78 % (6, 7).

Due to low production costs and the availability of skilled labour, China often plays a significant part in the large production and export of stevia. Initially, it produced 80 % of the world's stevia, accounting for 15000 metric tons of dried leaves annually (5). It is driven by the expanding use of lowcalorie, natural sweeteners in end-use sectors including food and beverages (8). However, despite its economic potential, regions like Brazil face challenges in meeting domestic demand, necessitating substantial imports of stevioside to bridge the supply gap (9). Meanwhile, in India, the annual demand of stevia is approximately 10 metric tons of dried leaves (10).

Globally, sugar production far exceeds that of stevia, with an estimated 185 million metric tons produced each year. This disparity underscores the potential of stevia as a viable natural sweetener to supplement or partially replace conventional sugar in the global market (11, 12). Sugarcane production is associated with substantial food losses and consequent environmental impacts. Sugarcane was found to be one of the largest contributors to water loss due to food waste in India. Sugarcane was the highest contributors to food losses by mass, resulting in significant water waste. Specifically, the total water associated with food losses was 115 ± 4.15 billion $m^3$, with sugarcane being a major contributor (13). To minimize these losses, sustainable substitutes such as stevia, which consume less water and can be integrated with agroforestry systems, should be adopted to improve land-use efficiency.

To address critical global problems including food security, climate change and biodiversity loss, agroforestry systems which integrate trees with crops or livestock on the same piece of land have developed as a sustainable land-use system (14, 15). Especially in tropical and subtropical areas, these systems provide farmers with a variety of advantages, such as increased soil fertility, a better microclimate and additional revenue sources (16, 17). Concerning the different agroforestry models, teak (*Tectona grandis*)-based systems are procuring significance because teak is not only economically valuable but also has great potential for long-term carbon sequestration and works well with understory crops (18). But it all depends on optimizing crop selection, management practices and resource use efficiency for both ecological and economic sustainability.

Despite its potential, growing stevia under teak-based agroforestry system remains insufficiently studied. The incorporation of stevia into such agroforestry systems can offer sustainable and economically profitable options for farmers. Growing stevia requires cautious deliberation of farming practices which includes plant spacing and nutrient regulation to enhance growth, yield and economic returns. Organic manures like vermicompost, farmyard manure (FYM) and poultry manure are well-known for their role in improving soil health and crop productivity (19). Although their efficacy in agroforestry systems, where competition for light, water and nutrients between trees and crops is a critical factor, is not well understood. Moreover, plant spacing plays a crucial part in determining crop performance under agroforestry systems by affecting light interception, root competition and resource utilization (20).

However, there is a lack of research on the combined effects of spacing and organic manure usage on stevia cultivation under teak-based agroforestry systems, especially in tropical India. This knowledge gap limits the ability of farmers and policymakers to make informed decisions about adopting such systems for sustainable and viable agricultural intensification. The present study aims to achieve the following objectives to evaluate stevia growth and production of using organic manure amendments and stevia spacing in an agroforestry system based on teak and to evaluate the economic viability of using organic manure amendments and stevia spacing in an agroforestry system based on teak.

## Materials and Methods

### Climate and experimental location

The NWFP nursery of the ICFRE-Tropical Forest Research Institute (TFRI), Jabalpur, Madhya Pradesh, India, served as the site of the field experiment in 2022 and 2023 (Fig. 1, 2). The study area exhibits hot summers and cold winters due to its sub-tropical semi-arid climate. Summers have lower relative humidity, while monsoons have higher relative humidity. Most of the soil at the experimental site is sandy loamy with a moderate amount of organic carbon and a pH rated as slightly acidic. The details of climatic conditions and soil are represented in Table 1 and Fig. 3.

### Experimental design and treatments

The four-year-old teak plantation was chosen as an agroforestry model for an experiment where the stevia crop variety CO-Meethi was cultivated using alley cropping. The teak trees were spaced 5 × 5 meters apart. To prepare the field layout, the land was ploughed, harrowed and levelled. The plot was prepared of size 4 × 4 m. The investigation comprised three replications using a factorial randomized block design (FRBD) (21). Factor I consisted of three spacing levels (S1: 45 × 45 cm, S2: 30 × 30 cm and S3: 20 × 20 cm). Factor II comprised eight organic manure treatments: M0: control (no manure), M1: vermicompost (100 % of RDN - recommend dose of nitrogen), M2: farmyard manure (FYM) (100 % of RDN), M3: poultry manure (100 % of RDN), M4: FYM + vermicompost (100 % of RDN), M5: FYM + poultry manure (50 % : 50 %), M6: vermicompost + poultry manure (50 % : 50 %) and M7: FYM + vermicompost + poultry manure (33.3 % +33.3 % + 33.3 % ). To ensure proper randomization and reduce field variability, the entire experimental area was divided into three replications. Each replication contained all 24 treatments [3 spacing × 8 organic manures (including control)] combinations, which were randomly assigned. Three-month-old *S. rebaudiana* seedlings were transplanted on two separate occasions December 2nd, 2022 and December 11th, 2023, corresponding to two consecutive cropping cycles conducted to validate the consistency of results across years. The transplantations were

**Table 1.** Description of the experimental site: Geographical coordinates, climate and soil conditions

| Parameter | | Details |
|---|---|---|
| Latitude | - | 23°05'54.8'' N |
| Longitude | - | 79°59'02.3'' E |
| Altitude | - | 412 meters above sea level |
| Maximum temperature | - | 38-45 °C |
| Minimum temperature | - | 8-12 °C |
| Mean annual precipitation | - | 1358 mm |
| Relative humidity | - | 20-40 % to 70-90 % |
| pH | - | 6.8 |
| Organic carbon content | - | 0.8 % |
| Nutrient levels | - | Nitrogen- 250 kg/ha, Phosphorus- 15 kg/ha Potassium- 180 kg/ha |

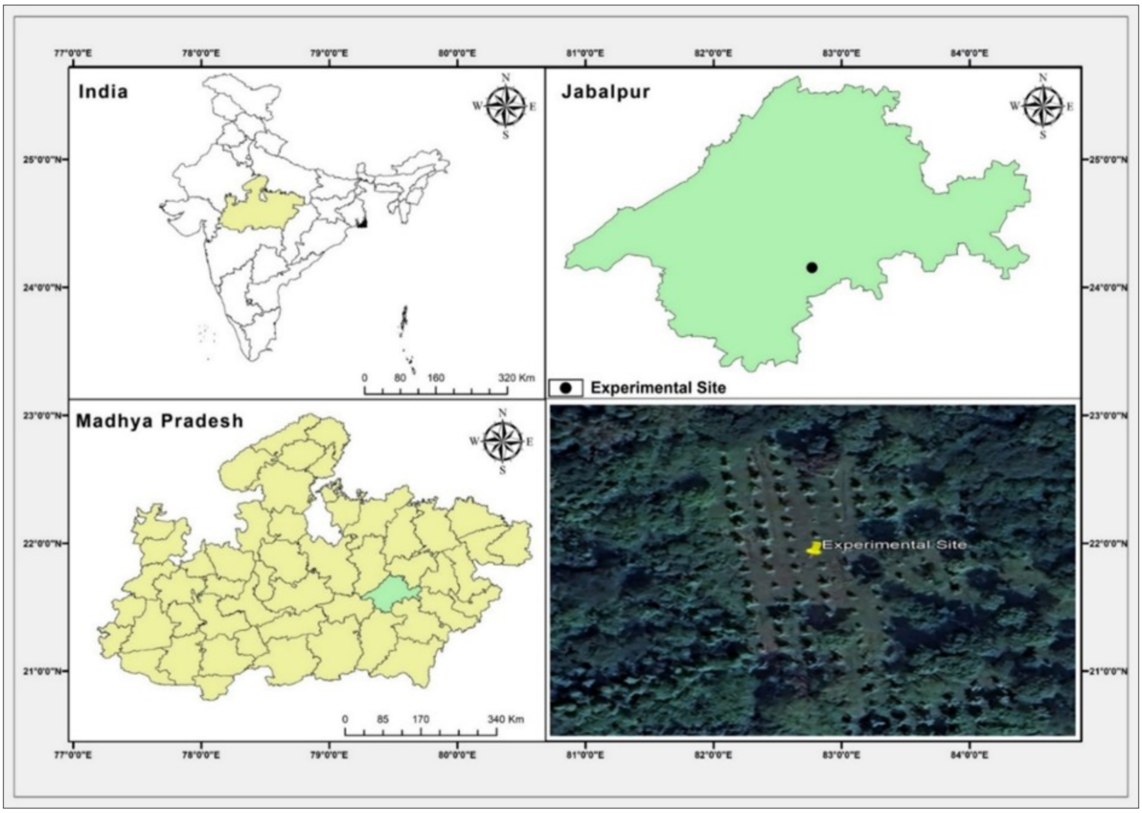



**Fig. 1.** Geographic location of the experimental plot within the NWFP nursery, ICFRE–Tropical Forest Research Institute (TFRI), Jabalpur, Madhya Pradesh, India (Prepared from QGIS version 3.16.0-Hannover).


**Fig. 2.** Experimental site within the NWFP nursery, ICFRE–Tropical Forest Research Institute (TFRI), Jabalpur, Madhya Pradesh, India.

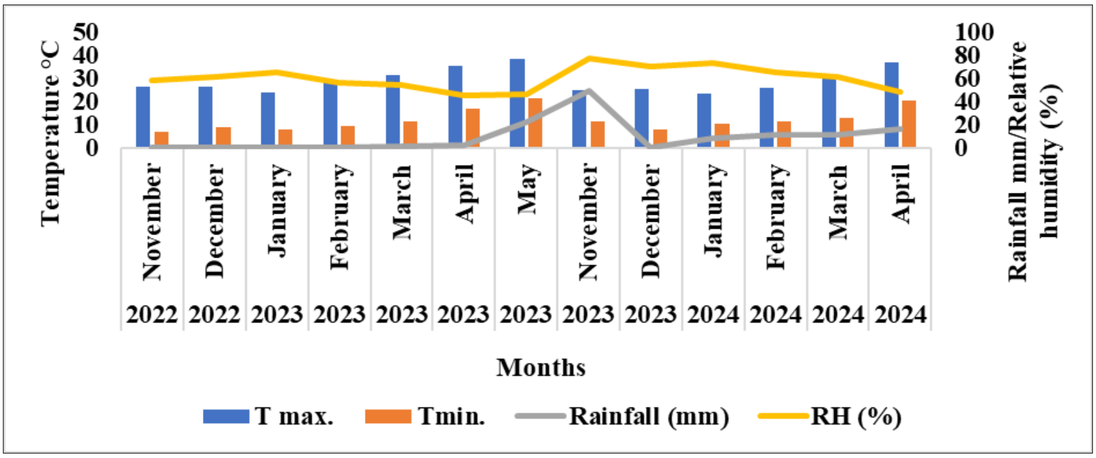



**Fig. 3.** Mean monthly meteorological data at TFRI, Jabalpur (MP), India for the period of experimentation (November 2022 - April 2024). Abbreviations: T max: temperature maximum; T min: temperature minimum; RH (%): relative humidity (%).

carried out using the ridge and furrow method, with plant spacing arranged according to the treatment design. Organic manures were applied based on nitrogen (N) equivalence to the recommended dose of fertilizer (RDF), which is 80 kg N ha$^{-1}$ for stevia under Indian agro-climatic conditions. The amount of each organic manure was calculated to supply an equivalent amount of nitrogen as per RDF, based on their respective nitrogen contents The NPK composition used for calculation and application was: FYM (0.5 % N, 0.2 % P, 0.5 % K), vermicompost (1.5 % N, 0.9 % P, 1.2 % K) and poultry manure (2.5 % N, 1.9 % P, 1.5 % K). Immediately after transplanting, the seedlings were irrigated, followed by light and frequent irrigations, along with periodic weeding and cleaning as required.

### Growth, yield and economical attributes

In this study, five plant samples were randomly selected and labelled for detailed growth observation. The plant height was measured from the soil surface to the tip of the highest shoot using a standard measuring scale, while both primary and secondary branches were counted for each plant. The total number of leaves was recorded to assess the vegetative growth. At harvest, the fresh and dry weights of the leaves were determined using an electronic weighing balance to provide an estimate of the biomass produced.

An economic analysis was conducted to assess the profitability of the cropping system. The cost of cultivation (C) was calculated as the sum of all input costs such as land preparation, seedling, fertilizers, labour, pesticides, irrigation and harvesting, expressed by the formula (22):

$$C = \varepsilon_{c_i} \qquad \text{(Eqn. 1)}$$

Where, $c_i$ represents the cost associated with the i$^{th}$ input.

The market price (P) per unit of yield multiplied by the gross yield (Y), as shown below, is the gross return (GR).

$$GR = P \times Y \qquad \text{(Eqn. 2)}$$

The difference between the cost of cultivation and the gross return was then used to compute net return (NR) i. e.

$$NR = GR - C \qquad \text{(Eqn. 3)}$$

Also, by dividing gross return by cultivation cost, the benefit-cost ratio (BCR) was calculated as follows:

$$BCR = GR/C \qquad \text{(Eqn. 4)}$$

### Statistical analysis

The data analysis was carried out using R software version 4.2.2, which included several packages to handle the various statistical and graphical tasks. The FRBD, a two-way analysis of variance (ANOVA) was conducted to determine the main effects of plant spacing (factor I), organic manure treatments (factor II) and their interaction on the measured growth and yield parameters. When the ANOVA indicated significant treatment effects, means were separated using the least significant difference (LSD) test. Statistical significance for all hypothesis tests was declared at a probability level of $p < 0.05$. The agricolae package was primarily utilized for ANOVA and LSD tests, while the Emmeans package was employed for calculating estimated marginal means and conducting further multiple comparisons where appropriate. Principal component analysis (PCA) was performed using the FactoMineR package. Visualization of data plots, charts and graphs were created using several visualization programs (ggplot2, ggpubr and plotly), including correlation heat maps produced using corrplot and corrgram. These packages, when combined, were essential for the thorough examination of the dataset. The analyses included PCA, FRBD with two factors and a variety of graphical and charting operations that enabled a comprehensive understanding of the variable interactions.

## Results

### Growth parameters

Table 2 shows that various spacing and levels of organic manure affect certain plant growth metrics, such as plant height at harvest, number of primary and secondary branches and number of leaves per plant. Spacing had a significant ($p < 0.05$) impact on plant height at harvest. The S1 (45 × 45 cm) spacing produced the tallest plants (63.38 cm), followed by the S2 (30 × 30 cm) spacing (61.58 cm), while the S3 (20 × 20 cm) spacing produced the smallest plants (57.47 cm). Similarly, the spacing had a substantial ($p < 0.05$) impact on the number of primary and secondary branches and leaves per plant. The

**Table 2.** Pooled plant growth parameters as influenced by crop geometry and organic manure treatments

| Treatments | Growth parameters | | | |
|---|---|---|---|---|
| | Plant height (cm) | No. primary branches | No. secondary branches | Number of leaves |
| **Spacing** | | | | |
| S1 (45 × 45 cm) | 63.38 a | 16.83 a | 34.43 a | 440.88 a |
| S2 (30 × 30 cm) | 61.58 b | 15.37 b | 30.35 b | 381.24 b |
| S3 (20 × 20 cm) | 57.47 c | 14.71 c | 28.48 c | 342.69 c |
| S.E.(m) | 0.27 | 0.07 | 0.14 | 1.66 |
| L.S.D. $_{0.05}$ | 0.76 | 0.19 | 0.40 | 4.67 |
| **Organic manures** | | | | |
| M0 (control) | 57.16 g | 13.65 e | 28.17 f | 346.47 h |
| M1 (vermicompost) | 60.43 de | 15.57 c | 30.98 c | 383.16 e |
| M2 (FYM) | 58.94 f | 14.97 d | 29.46 e | 365.86 g |
| M3 (poultry) | 61.68 bc | 16.19 b | 32.08 b | 402.58 c |
| M4 (FYM + vermicompost) | 59.87 ef | 15.33 c | 30.28 d | 373.50 f |
| M5 (FYM + poultry) | 61.37 cd | 16.02 b | 31.65 b | 392.52 d |
| M6 (vermicompost + poultry) | 62.63 b | 16.55 a | 32.77 a | 413.00 b |
| M7 (FYM + vermicompost + poultry) | 64.38 a | 16.80 a | 33.31 a | 429.03 a |
| S.E.(m) | 0.44 | 0.11 | 0.23 | 2.72 |
| L.S.D. $_{0.05}$ | 1.23 | 0.30 | 0.65 | 7.63 |

Abbreviations: LSD: least significant difference at 0.05 %, SE(m): sum error of mean.

widest spacing (S1) resulted in a significantly higher number of primary branches (16.83), secondary branches (34.43) and leaves per plant (440.88) compared to the closer spacings (S2 and S3). The application of different organic manures significantly ($p \leq 0.05$) impacted all measured growth parameters. The combined application of FYM, vermicompost and poultry manure (M7) resulted in the tallest plants (64.38 cm), the highest number of primary branches (16.80), secondary branches (33.31) and leaves per plant (429.03). The treatment with vermicompost and poultry manure (M6) also showed significant improvements in all growth parameters compared to the control (M0). The M0, receiving no organic manure, exhibited the lowest values for all measured parameters, with a plant height of 57.16 cm, 13.65 primary branches, 28.17 secondary branches and 346.47 leaves per plant. The other organic manure treatments (M1, M2, M3, M4 and M5) showed intermediate results, with significant improvements over the control but generally lower values than M6 and M7.

## Yield parameters

Fig. 4 illustrate the effects of varying spatial arrangements and organic manure applications on dry leaf yield, dry stem yield and total biomass yield, quantified in quintals per hectare ($qha^{-1}$). Spatial arrangements significantly ($p \leq 0.05$) influenced all yield parameters. The most compact spacing, S3, produced the highest dry leaf yield (33.93 $qha^{-1}$), dry stem yield (73.11 q $ha^{-1}$) and total biomass yield (107.04 $qha^{-1}$). In contrast, the intermediate spacing, S2, yielded moderate values for dry leaf (16.74 $qha^{-1}$), dry stem (37.6 $qha^{-1}$) and total biomass (54.34 q $ha^{-1}$). The most dispersed spacing, S1, exhibited the lowest yields across all parameters, with dry leaf, dry stem and total biomass yields of 8.61 $qha^{-1}$, 20.62 $qha^{-1}$ and 29.23 $qha^{-1}$, respectively. The application of different organic manures also had a significant ($p \leq 0.05$) effect on the yield characteristics. The comprehensive manure strategy, M7, resulted in the highest dry leaf yield (21.53 $qha^{-1}$), dry stem yield (46.41 $qha^{-1}$) and total biomass yield (67.94 $qha^{-1}$). The dual-manure approach, M6, similarly demonstrated substantial enhancements in dry leaf (20.93 $qha^{-1}$), dry stem (45.5 $qha^{-1}$) and total biomass (66.44 $qha^{-1}$) yields. The single manure application, M3, showed notable improvements over M0, with dry leaf, dry stem and total biomass yields of 20.57 $qha^{-1}$, 44.9 $qha^{-1}$ and 65.48 $qha^{-1}$, respectively. M0, registered the lowest values across all parameters, with dry leaf, dry stem and total biomass yields of 18.23 $qha^{-1}$, 41.51 $qha^{-1}$ and 59.74 $qha^{-1}$, respectively. The remaining manure treatments (M1, M2, M4 and M5) displayed intermediary performance, with significant gains over the control but generally lower yields compared to M6 and M7 treatments.

## Correlation and principal component analysis (PCA)

To understand the complex interrelationships among the measured growth, yield and economic parameters and to visualize the effects of different spacing and organic manure treatments, a correlation analysis followed by PCA was performed.

## Correlation analysis

Initial correlation analysis revealed significant relationships among the evaluated parameters. Strong positive correlations ($r > 0.80$) were observed among all three yield components (dry leaves yield, dry stem yield and total biomass yield) and between yield components and economic returns (gross return and net return) (Fig. 5A). Cost of cultivation was also strongly positively correlated with yield and returns, likely to reflect the higher input costs associated with treatments that promoted better growth and yield. The vegetative growth parameters (plant height, number of primary branches, number of secondary branches and number of leaves) were highly positively correlated with each other ($r > 0.90$). Interestingly, while growth parameters showed positive correlations with yield and economic parameters, these correlations were moderate ($r$ ranging from approximately

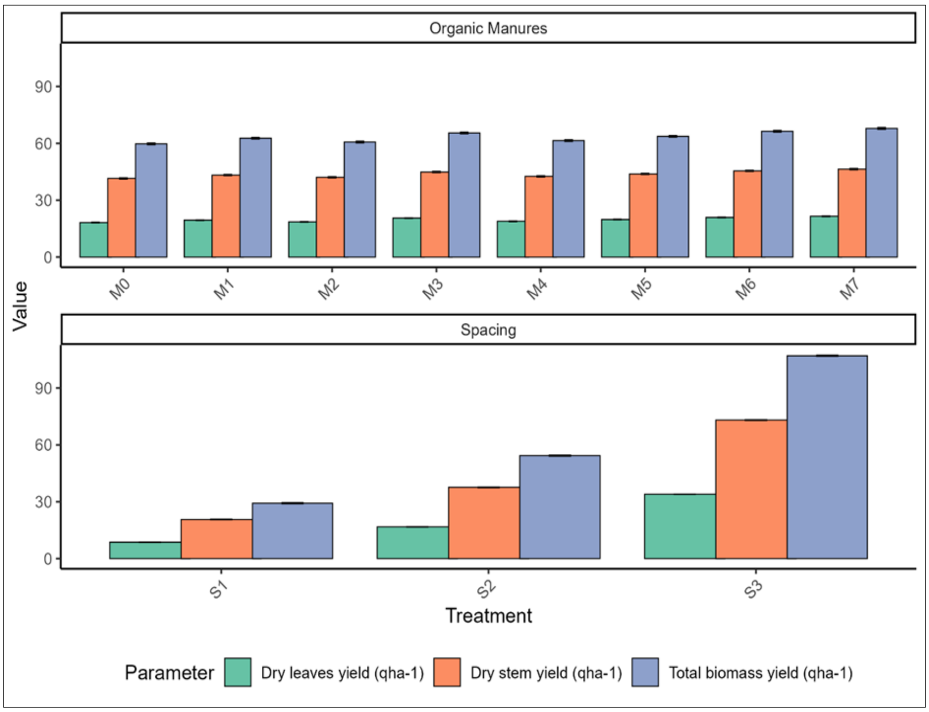



**Fig. 4.** Pooled yield parameters as influenced by crop geometry and organic manure treatments. Abbreviation: q $ha^{-1}$: quintal per hectare

0.30 to 0.70), suggesting that while vegetative growth contributes to yield, other factors or the specific combination of growth characteristics and resource allocation are crucial for maximizing yield and economic returns in this system. Benefit-cost ratio (BCR) showed moderate positive correlations with net return and gross return ($r$ = 0.49 and 0.41, respectively) and weaker correlations with yield and growth parameters, indicating that while yield and returns are important for profitability, efficiency involves a different balance of costs and benefits.

## Principal component analysis

PCA was applied to the standardized data of all measured parameters to reduce dimensionality and identify underlying patterns of variation driven by the experimental treatments. The analysis revealed that the first two principal components (PC1 and PC2) collectively explained a substantial proportion of the total variance in the dataset, accounting for 61.6 % and 32.1 %, respectively, for a cumulative explanation of 93.7 % (Fig. 5B-D). This high cumulative variance indicates that the two-dimensional PCA plane effectively captures most of the variability present in the original multidimensional data.

### Contribution to principal components

The contribution of individual variables to the principal components provides insights into what each component represents (Fig. 5B). PC1 (Dim1), explaining the largest proportion of variance (61.6 %), was primarily driven by variables related to yield and economic performance. Variables such as dry leaves yield, dry stem yield, total biomass yield, gross return, net return and cost of cultivation showed strong positive loadings on PC1, clustering together on the right side of the PCA plot. This suggests that PC1 represents a gradient of overall productivity and profitability, with higher values on PC1 indicating better yield and economic returns, albeit often associated with higher costs.

PC2 (Dim2), explaining 32.1 % of the variance, was strongly associated with vegetative growth parameters. Plant height, number of primary branches, number of secondary branches and number of leaves exhibited high positive loadings on PC2, located towards the top of the PCA plot. This indicates that PC2 primarily captures the variation in vegetative vigor and structural development of the stevia plants. The near-orthogonal relationship between the clusters of yield/economics variables (aligned with PC1) and growth variables (aligned with PC2) in the variable contribution plot (Fig. 5 B). The observation further supports from the correlation matrix that while related, yield/economics and vegetative growth represent somewhat distinct dimensions of performance influenced differently by the treatments. BCR showed a moderate positive loading on PC1 and a slight negative loading on PC2, positioning it somewhat independently from the main clusters of yield/economics and growth variables.

### Treatment effects on the PCA

The projection of the treatment combinations onto the PCA biplot (Fig. 5C) allows for the visualization of their relative performance and the variables driving their position. Treatments positioned towards the positive end of PC1 (right side) are associated with higher yield and economic returns, while those towards the positive end of PC2 (top side) are associated with greater vegetative growth.

### Spacing effect

The spacing treatments showed a clear separation primarily along PC1. The S1 treatment was located on the far left (negative PC1), indicating the lowest overall productivity and economic returns. S2 was positioned more centrally, while S3 was located on the far right (positive PC1), strongly associated with the highest yield, total biomass, gross return, net return and cost of cultivation. This demonstrates that increased planting density up to 20 × 20 cm significantly enhances per-area productivity and profitability, which aligns with the strong positive correlations observed between S3 treatments and the yield/economics variables.

### Organic manure amendment effects

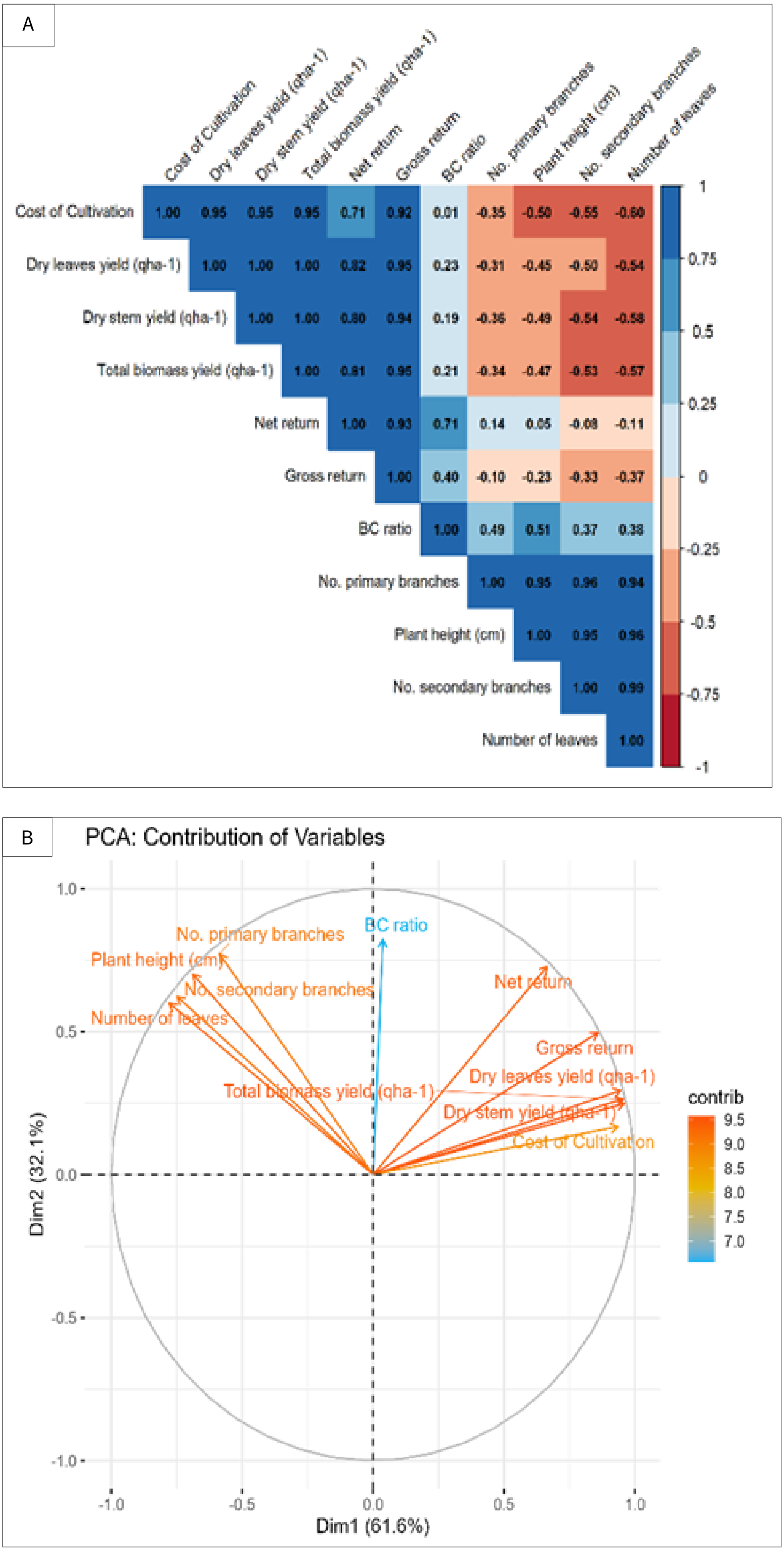
The organic manure treatments (M0-M7) showed variation across the PCA space, generally shifting performance compared to M0. M0 was positioned alongside S1, confirming its low performance across most parameters. Manure treatments, in general, moved the data points towards the right (positive PC1) and/or upwards (positive PC2) compared to M0. Several manure treatments (M1, M2, M4, M5 and M6) were primarily positioned towards the positive PC1, indicating improvements in yield and economic returns. Treatments M3 and M7 were in the upper-right quadrant, suggesting they promoted both strong vegetative growth (positive PC2) and high yield and economic returns (positive PC1). This indicates that certain organic manure types or combinations are more effective in simultaneously enhancing different aspects of stevia performance.

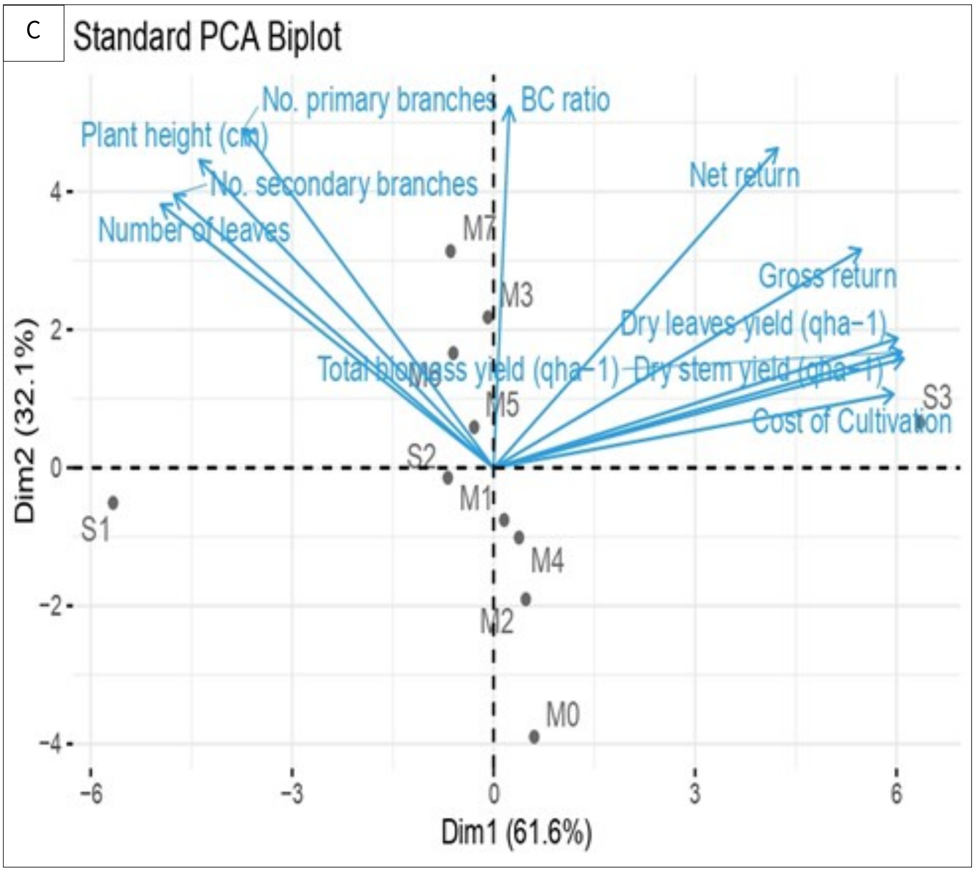
### Grouping by treatment type

Visualizing the data points grouped by the main treatment factors further elucidates their impact (Fig. 5D). The ellipses representing spacing treatments (S1, S2 and S3) are largely separated along the PC1 axis, with the S3 ellipse clearly positioned on the positive side of PC1, distinct from S1 and S2. This reinforces the finding that spacing is a primary driver of variation in yield and economic performance (PC1). The ellipse encompassing all organic manure treatments shows a wider spread, particularly along PC1 and PC2, indicating that variation within the manure treatments contributes significantly to both productivity and profitability and vegetative growth dimensions. The distinct separation between the overall spacing and organic manures groups in the PCA space highlights that both factors contribute uniquely to the observed variability in stevia performance, with spacing dictating the primary productivity level (PC1) and manure management fine-tuning both productivity and growth (PC1 and PC2).

## Economics

Fig. 6 illustrates the economic implications of varying spatial arrangements and organic manure applications on the cost of cultivation, net return, gross return and BCR. For spatial arrangements, increasing plant density from S1 to S3 led to a substantial increase in the cost of cultivation, ranging from ₹142709.20/ha for S1 to ₹357384.50/ha for S3. This escalation in costs is attributable to the heightened input requirements for denser planting. Despite the increased costs, both gross


A
Cost of Cultivation
Dry leaves yield (qha-1)
Dry stem yield (qha-1)
Total biomass yield (qha-1)
Net return
Gross return
BC ratio
No. primary branches
Plant height (cm)
No. secondary branches
Number of leaves
Cost of Cultivation 1.00 0.95 0.95 0.95 0.71 0.92 0.01 -0.35 -0.50 -0.55 -0.60
Dry leaves yield (qha-1) 1.00 1.00 1.00 0.82 0.95 0.23 -0.31 -0.45 -0.50 -0.54
Dry stem yield (qha-1) 1.00 1.00 0.80 0.94 0.19 -0.36 -0.49 -0.54 -0.58
Total biomass yield (qha-1) 1.00 0.81 0.95 0.21 -0.34 -0.47 -0.53 -0.57
Net return 1.00 0.93 0.71 0.14 0.05 -0.08 -0.11
Gross return 1.00 0.40 -0.10 -0.23 -0.33 -0.37
BC ratio 1.00 0.49 0.51 0.37 0.38
No. primary branches 1.00 0.95 0.96 0.94
Plant height (cm) 1.00 0.95 0.96
No. secondary branches 1.00 0.99
Number of leaves 1.00
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
B
PCA: Contribution of Variables
No. primary branches
Plant height (cm)
No. secondary branches
Number of leaves
BC ratio
Net return
Gross return
Dry leaves yield (qha-1)
Total biomass yield (qha-1)
Dry stem yield (qha-1)
Cost of Cultivation
contrib
9.5
9.0
8.5
8.0
7.5
7.0
Dim2 (32.1%)
1.0
0.5
0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.0
Dim1 (61.6%)



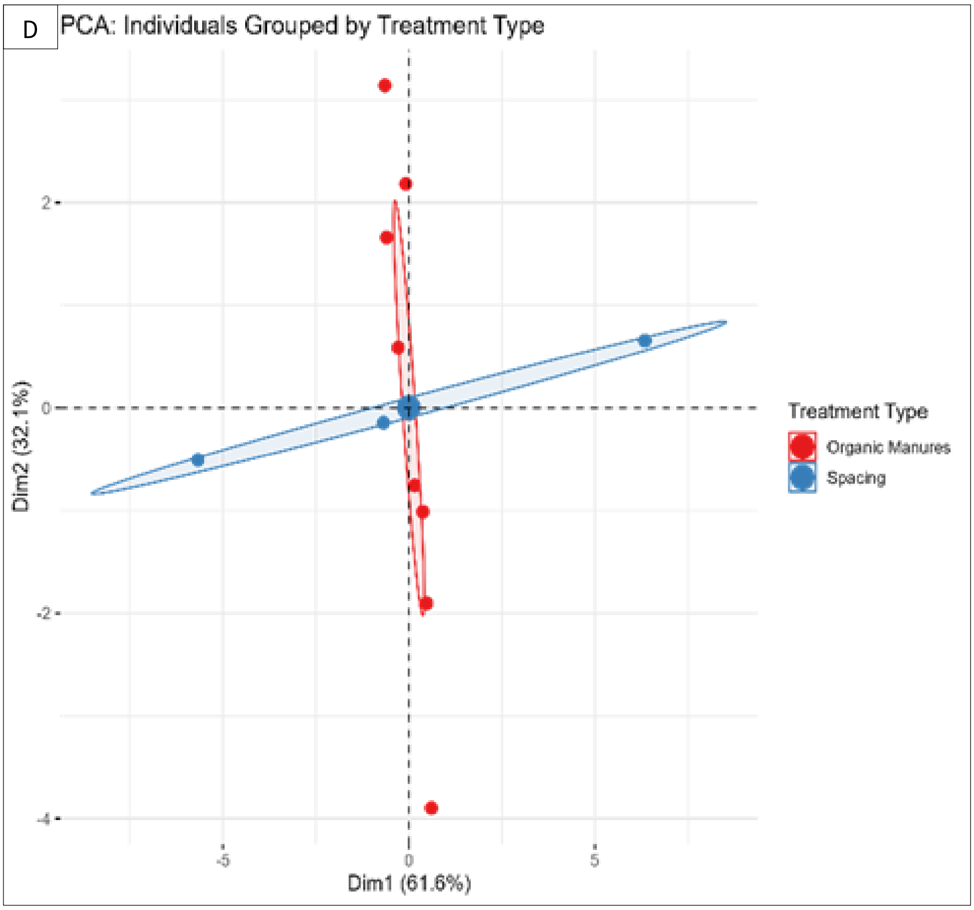




**Fig. 5.** Principal component analysis (PCA) and correlation analysis of growth, yield and economic parameters of stevia. (A) correlation matrix between all measured variables. (B) PCA correlation circle showing the contribution of variables to the first two principal components (Dim1 and Dim2). (C) standard PCA biplot showing the projection of treatment combinations (spacing treatments S1, S2, S3 and organic manure treatments M0-M7) and variables onto the plane defined by the first two principal components (Dim1 and Dim2). (D) PCA plot showing individual data points (treatment combinations) grouped by treatment type (organic manures and spacing).
Abbreviations: PCA: Principal component analysis; Dim1: Dimension 1; Dim2: Dimension 2.

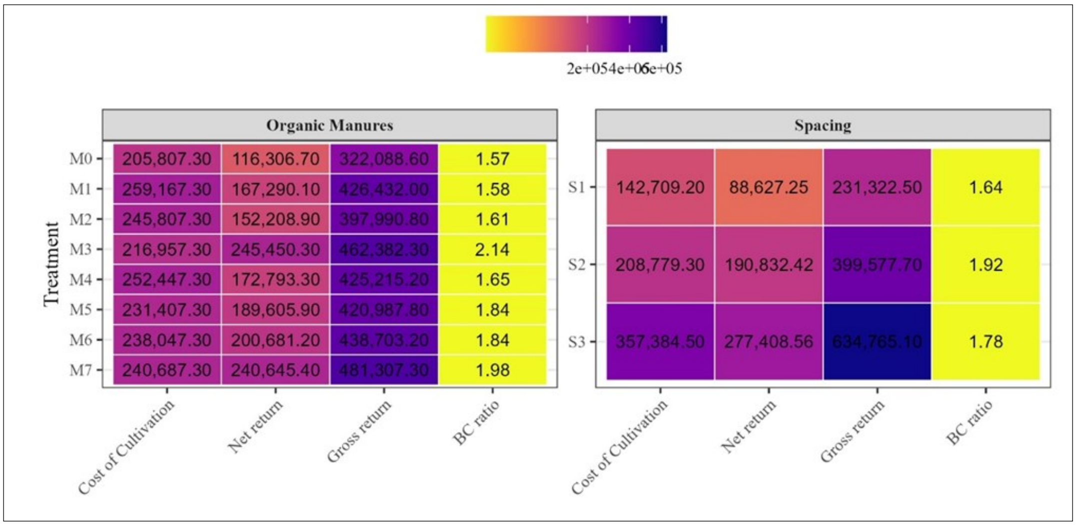



**Fig. 6.** Influence of crop geometry and different organic manure on pooled economics of agroforestry model.

and net returns also showed significant increments with higher plant density. S1 yielded a gross return of ₹231322.50/ha and a net return of ₹88627.25/ha, while S3 produced a gross return of ₹634765.10/ha and a net return of ₹277408.56/ha. However, the BCR increased from 1.635 for S1 to 1.775 for S3. This indicates that, within the range of densities tested, the economic efficiency per unit of cost improved with the densest planting (S3), alongside the higher net returns. Regarding organic manures, the cost of cultivation was slightly higher compared to the control (M0), which stood at ₹205807.30/ha. The most comprehensive manure strategy, M7, incurred the highest cost of cultivation at ₹240687.30/ha but also generated the highest gross return (₹481307.30/ha) and net return (₹240645.40/ha), with a BCR of 1.984. The control group exhibited the lowest gross and net returns. Among the manure treatments, M3 and M7 both provided the highest net returns and BCR, with M3 having a BCR of 2.144. While M6 showed a comparable BCR to M7, the inclusion of all three manures (M7) presented the most favorable economic outcome.

## Discussion

### Growth parameters

Wider spacing (S1) significantly enhanced plant height, primary and secondary branching and the number of leaves per plant compared to closer spacings (S2 and S3). This finding is consistent with established principles where reduced inter-plant competition for resources (light, nutrients and water) at wider spacings promotes more extensive individual vegetative development, representing a known trade-off against the higher total biomass per unit area typically achieved with denser plant populations (23). Similar findings in stevia were described, while the general principle applies broadly across many crops (24, 25). The application of organic manures, particularly the combination of FYM, vermicompost and poultry manure (M7), significantly improved all measured growth parameters compared to the control (M0). This synergistic effect can be attributed to the combined benefits of each manure type. FYM improves soil structure and provides a slow release of nutrients, vermicompost is rich in readily available nutrients and growth-promoting substances and poultry manure provides a rapid boost of nitrogen and phosphorus (26-28). These findings align with previous studies demonstrate the positive impact of integrated nutrient management on stevia growth (29).

### Yield parameters

In contrast to growth, however, the production of dry leaves, stems and total biomass increased significantly with decreasing spacing (S3). The reason for this was most likely because even while the individual plants were smaller, the significantly larger number of plants per hectare in S3 may compensate for the smaller individual plants, leading to higher biomass yields per hectare (30-32). This suggests that, even at the expense of individual plant size, maximizing biomass output in stevia requires optimizing plant density. Like the growth characteristics, the mixed organic manure treatment (M7) produced the maximum fresh and dry leaf yields. To increase stevia yield, this also emphasizes the necessity of balanced nutrition and improved soil health. A comparable rise in yield is reported previously (33).

### Correlation and principal component analysis (PCA)

The findings of the correlation and PCA illustrated the relationship between growth, yield and economic traits of stevia plants under various spacing and organic manure treatments. The significant positive associations ($r$ > 0.80) observed among yield components (dry leaf yield, dry stem yield and total biomass yield) and between yield and economic returns (gross return and net return) indicate a strong and direct relationship, where higher yields are associated with greater economic performance. However, the cost of cultivation also increased with higher yields, suggesting that while productivity boosts profitability, it may also require greater input. This underscores the importance of balancing yield gains with input efficiency to maximize economic returns. This result is consistent with previous reports, indicating that crop yield is directly related to the economic profitability of agricultural systems (34). While vegetative growth is significant, other factors also influence yield and economic returns, as shown by the moderate correlations ($r$ = 0.30-0.70) between growth parameters and yield/economic parameters. This implies that other factors, such as the efficiency of resource distribution, nutrient uptake and environmental interactions, are also important in determining the ultimate yield and financial results. Similar findings have been documented for other crops, where production was influenced by different factors, but vegetative growth metrics exhibited moderate to significant associations with yield (35).

The first two principal components (PC1 and PC2) contributing to 93.7 % of the variance, the PCA results further clarify the basic trends in the dataset. The distribution of productivity and profitability, driven by yield and economic characteristics, is represented by PC1, which is responsible for 61.6 % of the variance. This highlights the significance of these characteristics in determining the overall performance and is in accordance with the correlation study. Vegetative vigor and structural development were linked to PC2, which accounted for 32.1 % of the variance. This suggests that vegetative growth is a distinctive component of performance. The high cumulative variance explained by PC1 and PC2 indicates that most of the variation in the dataset is captured by these two components, with minimal residual variability. This suggests strong patterns in the data and limited noise or outliers. Variables with very low contributions had a minimal influence on the overall PCA structure and were retained to preserve completeness. No variables were excluded from the analysis, as all measured parameters contributed meaningfully to either yield and economic (PC1) or growth-related (PC2) dimensions.

The PCA treatment effects showed that spacing had a major impact on profitability and productivity, with the 20 × 20 cm spacing (S3) performing best on PC1. Studies showing the advantages of ideal planting density in maximizing agricultural output and financial returns lend credibility to this conclusion (35). Furthermore, organic manure amendments were significant. Some treatments (such as M3 and M7) improved both the vegetative growth and yield/economic returns. This implies that organic manures or their mixtures can enhance several aspects of plant performance, most likely because of their benefits to soil health and a balanced supply of nutrients (36, 37).

According to BCR, which has a moderately favorable association with both net return and gross return ($r$ = 0.49 and 0.41, respectively), efficiency requires a different cost-benefit balance than profitability, even if yield and returns are crucial for profitability. The BCR values and PCA results indicate that treatments like M7 and S3 are not only profitable but also efficient at increasing yield and vegetative development. Similar findings have been observed in previous studies (38-40).

According to the economic study, closer spacing (S3) had the highest gross and net returns because of the significantly higher biomass output, even if it was associated with a higher cultivation cost. But when density increases, the BCR decreases, indicating that S3's economic efficiency may be less than that of S1 or S2. This emphasizes how crucial it is to optimize planting density while taking the cost-benefit ratio into account in addition to yield. With the largest gross and net returns as well as the highest BCR, the mixed organic manure application (M7) produced the best economic results. This demonstrates that the investment in a comprehensive organic nutrient management strategy can be economically justifiable, leading to both higher yields and greater profitability. The superior performance of M7 underscores the synergistic benefits of combining different organic amendments, potentially enhancing nutrient availability, soil health and overall plant performance (41).

## Conclusion

This study comprehensively demonstrated that both planting density and organic manure application profoundly influence the growth, yield and economic returns of *S. rebaudiana* cultivated within a teak-based agroforestry system. Wider spacing (45 × 45 cm) fostered superior individual with specific growth parameter, specifically resulting in significantly greater plant height, a higher number of primary and secondary branches and more leaves per plant, attributable to reduced inter-plant competition for resources. Conversely, the closest spacing (20 × 20 cm), despite yielding smaller individual plants, resulted in the highest dry leaf yield, dry stem yield and total biomass yield per hectare. This underscores the significant impact of increased plant population density in compensating for reduced individual plant size to maximize overall area productivity. The integrated application of farmyard manure, vermicompost and poultry manure (M7) consistently surpassed other treatments, significantly enhancing all measured growth parameters and yield components. This highlights the synergistic benefits of a diversified organic nutrient strategy, improved soil health, enhanced nutrient availability and sustained nutrient release, promoting stevia development and productivity. Stevia producers can therefore tailor planting density and employ comprehensive organic fertilization to achieve specific production targets and maximize economic viability in such intercropping systems. Future investigations could further explore the precise mechanisms by which specific architectural traits influence light capture and productivity under varying agroforestry canopy conditions. While this study supports the sustainability of organic amendments in improving productivity, it did not directly assess long-term soil health impacts. Future long-term studies should include soil quality indicators such as organic carbon content, microbial activity and nutrient dynamics to validate the ecological sustainability of such practices over time.

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## Authors' contributions

DA conducted the field experiment, collected the data and prepared the draft of the manuscript. HOS and PKT were involved in framing the research objectives, designing the experimental layout and developing the methodology. DA performed the statistical analysis of the data. AJ and AKY carried out necessary modifications and final draft preparation. All authors read, edited and approved the final version of the 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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