

Multivariate Assessment of Soil-Plant Relationships and Principal Component Structure in a *Pongamia pinnata* + *Costus igneus* Silvi-Medicinal System under Semi-Arid Alfisols

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Abstract

A multivariate study at PJTSAU, Hyderabad (2019) evaluated variability, inter-parameter relationships, GHG dynamics and tree growth responses under nine INM treatments in a *Pongamia pinnata* + *Costus igneus* silvi-medicinal system on semi-arid alfisols. Correlation analysis showed significant links between plant population and dry matter; plant height, leaf number and leaf area with herbage yield; and soil N, P, K with corresponding plant uptake, confirming a coherent nutrient-growth-yield network. Five principal component models quantified this variability: two for plant growth/yield parameters (91.3% and 94.9% variance explained) and three for soil nutrients, plant nutrient uptake, and *Pongamia* tree parameters (height, girth, canopy spread), explaining 80.5%, 96.1% and 92.9% of variance respectively. Photosynthetically active radiation ranged widely across canopy positions (135.7–1613.3 $\mu\text{mol}/\text{cm}/\text{s}$), reflecting the graded light environment under the *Pongamia* overstorey. GHG analysis revealed significant treatment differences in CO_2 (1325.8 $\text{kg ha}^{-1} \text{ season}^{-1}$), N_2O (649.6 $\text{g ha}^{-1} \text{ season}^{-1}$) and GWP (1527.2 $\text{kg CO}_2\text{-eq ha}^{-1}$), with the sole-crop treatment showing highest emissions. Tree growth and pod yield were largely unaffected by INM treatments, indicating treatment effects operated mainly through the *C. igneus* understorey. This study offers a replicable analytical framework for evaluating silvi-medicinal systems under semi-arid alfisol conditions.

1. INTRODUCTION

In India, major agricultural area is under dryland farming and these regions are characterized by uncertain environmental conditions with poor to average productivity. Integrated approach of land management that utilizes the natural resources more efficiently are essential for such rainfed regions, and tree-based intercropping offers a sustainable path to maximize productivity and farm income per unit area. Agroforestry thus provides an economically and ecologically viable option for agricultural diversification and environmental amelioration. Meta-analytical evidence from Indian agroforestry systems shows that converting to agroforestry can substantially raise soil carbon sequestration relative to conventional cropping, though the magnitude depends on system type, tree age, rainfall and prior land use (Kumara et al., 2023).

In the present context of climate change and the global carbon cycle, agroforestry is significant for two reasons: the tree component fixes and stores atmospheric carbon, and it reduces pressure on natural forests by supplying comparable products. The IPCC estimates agroforestry carbon sequestration at 0.2–3.1 $\text{t C}/\text{ha}/\text{year}$ (Watson et al., 2000), with a global potential of 7 Gt carbon between 1995 and 2050 (Pandey, 2002) and hence there is a need to expand its area and identify agro-techniques that mitigate GHG emissions while improving farmer yield and income. Total area under agroforestry in the world is estimated as 1023 million ha (Nair et al., 2009). In India, major Agroforestry systems are estimated to cover 25.32 million ha, which is about 8.32% of total geographic area of country (Yogesh et al., 2017). Importance of agroforestry for food, fuel, fodder, fruits, fertilizer, timber etc. and in conservation of natural resources is well recognized. Agroforestry systems have greater potential for carbon sequestration than pastures or field crops.

Silvi-medicinal systems represent a newer paradigm integrating trees with medicinal plants, yielding food, fodder, fibre and pharmaceutical raw material while conserving biodiversity and easing pressure on wild resources. Since roughly 90% of medicinal and aromatic plants in developing countries are still wild-harvested, with only 10% cultivated (Karki, 2002), and demand continues to rise, commercial cultivation is increasingly necessary. In India, medicinal and aromatic plants are grown on about 742,000 ha, yielding roughly 645,000 tonnes (Ministry of AYUSH, 2024). As many medicinal species are naturally forest-dwelling and shade-tolerant, agroforestry offers a practical strategy for their cultivation and conservation (Kalaichelv and Arul Swaminathan, 2009).

Pongamia pinnata (Indian beech), a leguminous tree suited to arid and semi-arid regions, sequesters about 13 $\text{t C}/\text{ha}$ (Firdaus et al., 2010) and yields 30–40% seed oil suitable for biodiesel. As a nitrogen-fixer, it enhances soil fertility, while its leaf litter supports microbial activity and nutrient cycling; *Pongamia*-based plantations in semi-arid Telangana were recently shown to maintain elevated surface-soil N and P availability (Gouthami et al., 2026). Declining profitability, productivity and rising pest/disease pressure in traditional cropping are pushing Indian farmers toward alternatives such as medicinal plant cultivation, which tolerates adverse climatic conditions better. India hosts about 6,560 medicinal plant species, of which ~ 960 are traded and 178 are consumed annually above 100 tonnes (Ministry of Health and Family Welfare, 2013); about 70% of Indians rely on traditional plant-based medicine (Saigal et al., 2002), and the global herbal-products market, currently around \$6.2 billion, is projected to reach \$5 trillion by 2050 (Singh, et al., 2024).

Costus igneus (insulin plant), a shade-tolerant perennial herb of the Costaceae, is valued for its anti-diabetic properties, attributed to fibre-, flavonoid- and sapogenin-rich leaves (Annie et al., 2007; Meena, 2014), alongside antibacterial and anticancer activity, making it well suited for intercropping under trees. For quality medicinal plant production, organic fertilization is generally preferred, though complete replacement of inorganic inputs is inadvisable given their low nutrient concentration; integrated nutrient management (INM) combining organic and inorganic sources instead sustains yield, quality and long-term soil health. Locally available organic and green-leaf manures lower production costs and strengthen system resilience in rainfed areas (Ravi and Divya, 2009). Neem cake is an established soil conditioner with pest-repellent and nematicidal action (Abbasi et al., 2005); biochar improves N and P retention, reduces nutrient leaching and enhances productivity (Gul and Whalen, 2016; Kumar et al., 2025); and *Pongamia* green leaf, rich in easily mineralizable N, benefits soil physical properties and nutrient supply in low-fertility dryland soils (Singh et al., 2013).

An agroforestry system is validated only when tree and intercrop components complement one another (Jose, 2011). This study therefore examines INM effects on the growth of *C. igneus* within a *Pongamia* + *Costus* silvi-medicinal system, evaluating its performance as an intercrop, INM's influence on growth, and associated greenhouse gas emissions.

Interactions among soil properties, plant growth, nutrient availability and GHG emissions are inherently complex and multivariate. Conventional univariate analyses detect treatment effects on single parameters but poorly capture interrelationships. For instance, changes in soil organic carbon can simultaneously affect nutrient availability, microbial activity, plant growth and GHG flux. Multivariate approaches such as correlation analysis and principal component analysis (PCA) better capture system functioning by grouping associated variables, identifying principal axes of variation, and isolating

parameters most responsible for treatment differentiation. Recent *Pongamia*-based research has similarly applied multiple regression, PCA and cluster analysis to link soil, growth and biochemical attributes (Vyas et al., 2025).

Despite growing recognition of agroforestry as a climate-smart, soil-restorative strategy, integrated information on soil–plant–GHG relationships in silvi-medicinal systems, particularly those combining *P. pinnata* and *C. igneus* on semi-arid Alfisols, remains scarce. Most existing work addresses productivity, fertility or carbon sequestration in isolation, and the extent to which soil and plant variables jointly explain treatment-level variation is poorly characterized.

This study therefore evaluates the interrelationships among soil and plant parameters, quantifies CO₂, CH₄ and N₂O emissions, and applies PCA to identify the principal dimensions of variation in a *Pongamia* + *Costus* silvi-medicinal system on semi-arid Alfisols, aiming to characterize soil physicochemical, nutrient and growth relationships, assess GHG emissions, and determine the key variables governing system-level variation, thereby offering an integrated understanding of soil–plant–atmosphere interactions underlying the sustainability of *Pongamia*-based silvi-medicinal systems.

2. MATERIALS AND METHODS

Site and experimental details

An integrated nutrient management study was conducted with *Pongamia pinnata* + *Insulin* (*Costus igneus*) silvi medicinal system at Department of Agronomy, Professor Jayashankar Telangana State Agricultural University (PJTSAU), Hyderabad during 2019. The study was conducted with the objective to assess the effects of 9 INM treatments on different soil and plant parameters, the variability and relationships of different parameters and identify significant parameters which influence the productivity and monetary returns from the silvi-medicinal intercropping system under semi-arid alfisols. The experiment was laid out in Randomized block design with three replication and nine treatments which include: T1-Control; T2-100% RDF (75:50:50; NPK); T3-75% RD N + 25% N through neem cake; T4-75% RD N + 25% N through Biochar; T5-75% RD N + PGLM @10 t ha⁻¹; T6-50% RD N + 50% N through neem cake; T7-50% RD N + 50% N through Biochar; T8-50% RD N + PGLM @10 t ha⁻¹; and T9-Sole crop (RDF 75:50:50 NPK kg ha⁻¹). The layout of the experiment along with the plant geometry are given in the Supplementary Fig. 1 (a & b).

Observations recorded

Observations were collected for the *Costus* plant including initial and final population; plant height on 30, 60, 90 DAS and harvest; No. of leaves/plant on 30, 60, 90 DAS and harvest; leaf area on 30, 60, 90 DAS and harvest; dry matter on 30, 60, 90 DAS and harvest; days to 50% flowering; fresh and dry herbage yield; harvest index whereas for the *Pongamia* tree initial and final tree height, girth, canopy spread and pod yield were recorded. Observations were also collected on pH, electrical conductivity (EC), organic carbon, soil nitrogen (N), phosphorus (P₂O₅), potassium (K₂O), plant uptake N on 30, 60, 90 DAS and harvest; uptake P on 30, 60, 90 DAS and harvest; uptake K on 30, 60, 90 DAS and harvest. Initial soil samples were collected from 0–30 cm depth and analyzed for organic carbon (Walkley and Black, 1934), soil N (Subbaiah and Asija, 1956), soil P₂O₅ (Olsen et al., 1954) and soil K₂O (Jackson, 1967). The plant samples were collected from each plot of a treatment and analyzed for plant parameters on different days after sowing and at harvest. PAR incident on the crop canopy was measured using a CI-110 Digital Plant Canopy Analyzer at 30, 60 and 90 DAT and at harvest, expressed as μmol cm⁻² s⁻¹. Readings were recorded between 11:00–13:00 h at the tree base, at 1 m and 2 m from the tree row (north–south direction), and at the plot centre, with corresponding measurements taken in sole-crop plots.

Greenhouse Gas Emissions

Gas sampling

CO₂ and N₂O fluxes were measured from the soil surface at 15-day intervals during the crop growing season using the closed-chamber technique (Pathak et al., 2002). Chambers (50 × 30 × 100 cm; L × W × H) were fabricated from 6 mm acrylic sheets and fitted onto aluminium anchors (15 cm height, 5 cm internal diameter) pre-installed 10 cm deep in the soil between crop rows. Anchor grooves were filled with water to ensure an airtight seal. Flux measurements were taken between 09:00–11:00 AM to minimize diurnal variation, with treatment sampling order randomized each day to offset temperature-related bias. Gas samples were withdrawn through a 3-way stopcock using a 20 mL syringe (24-gauge needle) at 0, 30 and 60 min after chamber closure.

Gas analysis

Samples were analyzed at CRIDA by gas chromatography. N₂O-N was quantified using a Varian 450-GC fitted with an electron capture detector (ECD) and a 6' × 1/8" stainless steel column (column, injector and detector temperatures: 50, 120 and 320°C; N₂ carrier gas at 14 mL min⁻¹). CO₂ was quantified using a GC fitted with a thermal conductivity detector (TCD). Stage-wise emission values were averaged and multiplied by crop duration to obtain total emissions for the growing period.

Flux calculations

N₂O-N flux (g ha⁻¹ day⁻¹) was calculated as (Prasad et al., 2015):

$$\text{N}_2\text{O-N flux} = (\Delta X \times \text{EBV}(\text{STP}) \times 28 \times 10^3 \times 60) / (10^6 \times 22400 \times T \times A)$$

CO₂-C flux (kg ha⁻¹ day⁻¹) was calculated as (Bhatia et al., 2013):

$$\text{CO}_2\text{-C flux} = (\Delta X \times \text{EBV}(\text{STP}) \times 12 \times 10^3 \times 60) / (10^6 \times 22400 \times T \times A)$$

where ΔX = difference in gas concentration between 60 and 0 min (ppb for N_2O , ppm for CO_2); T = flux time (60 min); A = chamber basal area (m^2); and $EBV(STP)$ = effective box volume at standard temperature and pressure, calculated as:

$$EBV = (H - h) \times L \times B$$

Where, H = chamber height, h = water level in the anchor groove, and L and B = chamber length and breadth (all in cm).

Global warming potential (GWP)

GWP, the cumulative radiative forcing of a unit mass of gas relative to CO_2 over a chosen time horizon, was calculated following Watson et al. (1996) using IPCC (2007) 100-year GWP values ($CO_2 = 1$, $N_2O = 310$):

$$GWP \text{ (kg } CO_2 \text{ eq/ha)} = [CO_2 \text{ emission (kg/ha)} \times 1] + [N_2O \text{ emission} \left(\frac{kg}{ha} \right) \times 310]$$

Statistical analysis

Descriptive statistics viz., minimum, maximum, mean, standard deviation and coefficient of variation were derived for each parameter. Estimates of correlation were derived between different pairs of parameters under each category and were tested for significance (Panse and Sukhatme, 1978). Ranks were assigned to the mean values of parameters under 5 different groups and rank sums were derived viz., RS1, RS2, RS3, RS4 and RS5. Among plant parameters, plant population, Plant height, No. of leaves, Leaf area, Dry matter, Days to 50% flowering, Fresh herbage yield, Dry herbage yield and Harvest index were included in the 1st rank sum group (RS1); Crop growth rate, Relative growth rate, Net assimilation rate, PAR, CO_2 , N_2O and GWP were included in the 2nd rank sum group (RS2). Based on Analysis of Variance (ANOVA), the effects of treatments on different plant parameters were analyzed and tested for significance. A comparison of mean effects of treatments was made based on Least Significant Difference (LSD) criteria and superior treatments were identified.

The estimates of correlation were derived between different plant parameters and were tested for significance (Gomez and Gomez, 1984). The correlation coefficients were used to derive the principal components (PC) of parameters (Dunteman George, 1989; Jolliffe, 1986; Norris, 1972). The principal component models were calibrated with varying combinations of plant and soil parameters. Using plant parameters, two models were calibrated viz., Model-1 was calibrated as a function of initial and final plant population, days to 50% flowering, fresh and dry herbage yield, harvest index, plant height, No. of leaves/plant, leaf area and dry matter on 30, 60, 90 DAS and at harvest; and Model-2 was calibrated as a function of plant height, No. of leaves/plant, leaf area and dry matter on 30, 60, 90 DAS and at harvest. Using soil and plant parameters, 3 models were calibrated viz., Model-1 was calibrated as a function of soil pH, electrical conductivity, organic carbon, N, P and K; Model-2 was calibrated as a function of uptake N, P and K on 30, 60 and 90 DAS and at harvest; and Model-3 was calibrated as a function of initial and final observations of tree height, girth, canopy spread in North-South and East-West directions. A significant PC will have an eigen value more than '1'. The total variance (%) explained by the significant principal components was assessed by considering the eigen values of significant PCs. The parameters were assessed based on their loadings on PCs. Based on the PC analysis, a plant or soil parameter is considered as significant if it has a positive loading of either more than + 0.90 or negative loading of less than - 0.90. An assessment was made by comparing (i) the loadings of parameters on the principal components and (ii) the coefficient of variation of parameters. Significant plant parameters were identified based on the loadings of parameters on the PCs and their variability. Superior INM treatments and significant soil and plant parameters are identified based on the study.

3. Results

3.1. Effect of INM treatments on PAR at varying distances from tree base

Photosynthetically active radiation was recorded at four locations (tree base, 1 m, 2 m, and plot centre) at 30, 60, and 90 DAS to assess treatment effects under the shading gradient of the Pongamia canopy. Mean values with SEM and LSD are presented in Table 1. ANOVA revealed no significant treatment effects on PAR at any location or growth stage, indicating a stable and treatment-independent light environment throughout the cropping period. At the tree base, PAR remained low and consistent across all three stages, ranging from 133.3–136.8 $\mu\text{mol/cm/s}$ (mean 135.2, CV 0.8%) at 30 DAS, 139.6–145.5 $\mu\text{mol/cm/s}$ (mean 143.2, CV 1.5%) at 60 DAS, and 133.9–142.9 $\mu\text{mol/cm/s}$ (mean 138.6, CV 2.2%) at 90 DAS. At 1 m distance, PAR values were similarly stable across stages, ranging from approximately 314–350 $\mu\text{mol/cm/s}$, with means of 328.7, 338.3, and 332.4 $\mu\text{mol/cm/s}$ at 30, 60, and 90 DAS, respectively (CV 2.6–2.8%). At 2 m distance, PAR increased sharply relative to the base and 1 m locations, ranging from approximately 836–870 $\mu\text{mol/cm/s}$ across all three stages, with means of 847.4, 857.0, and 848.6 $\mu\text{mol/cm/s}$ (CV consistently 1.1%). At the centre, PAR values were highest and most variable, ranging from approximately 1519–2119 $\mu\text{mol/cm/s}$, with means of 1604.5, 1608.1, and 1602.5 $\mu\text{mol/cm/s}$ at 30, 60, and 90 DAS, respectively (CV 11.8–12.0%).

Table 1
Effects of INM treatments on PAR at 30, 60 and 90 days after sowing of *Costus igneus*

Treatment	PAR (μ mol/cm/s)				PAR (μ mol/cm/s)				PAR (μ mol/cm/s)			
	on 30 DAS				on 60 DAS				on 90 DAS			
	Tree base	1 m	2 m	Centre	Tree base	1 m	2 m	Centre	Tree base	1 m	2 m	Centre
T1	135.0	340.4	853.1	1545.7	143.7	349.9	867.1	1531.3	138.7	345.4	858.7	1526.0
T2	136.8	331.2	860.9	1553.5	145.5	340.7	869.9	1559.2	142.9	335.3	861.5	1550.2
T3	134.5	322.2	840.9	1530.2	145.2	333.3	848.2	1535.9	139.5	327.2	839.8	1529.2
T4	135.0	334.1	836.0	1545.4	143.7	343.6	853.3	1544.4	140.4	337.4	841.6	1540.0
T5	134.9	336.0	848.0	1540.7	139.6	345.5	855.3	1533.1	133.9	339.3	846.9	1526.4
T6	133.3	314.3	838.1	1518.7	142.0	321.5	845.4	1531.1	137.0	315.3	840.4	1530.4
T7	136.2	323.9	844.3	1540.2	144.9	334.7	851.6	1549.2	141.2	328.5	843.2	1542.6
T8	136.2	327.3	858.1	1557.3	140.6	336.8	865.3	1569.6	134.9	330.6	856.9	1562.9
T9	-	-	-	2108.9	-	-	-	2119.1	-	-	-	2114.6
SEm $\pm$	0.75	5.15	6.98	8.12	4.75	7.53	10.41	31.13	3.4	6.84	8.93	24.03
LSD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

T1-Control; T2-100% RDF (75:50:50; NPK); T3-75% RD N + 25% N through neem cake; T4-75% RD N + 25% N through Biochar; T5-75% RD N + PGLM @10 t ha⁻¹; T6-50% RD N + 50% N through neem cake; T7-50% RD N + 50% N through Biochar; T8-50% RD N + PGLM @10 t ha⁻¹; and T9-Sole crop (RDF 75:50:50 NPK kg ha⁻¹). Data in the column followed by different letters are significantly different at p $\leq$ 0.05.

3.2. Effects of INM treatments on PAR at harvest, CO₂, N₂O and GWP

The effects of INM treatments on PAR at 4 locations viz., tree base, 1 m, 2 m distance and centre on 30, 60 and 90 DAS were tested based on F-test. The mean values of treatments, along with the SEM and LSD values are given in Table 2. At harvest, the PAR ranged from 131.3 to 139.2 μ mol/cm/S with mean of 135.7 μ mol/cm/S (CV of 1.9%) at tree base; while it ranged from 311.0 to 344.5 μ mol/cm/S with mean of 329.0 μ mol/cm/S (CV of 1.9%) at 1 m distance; 834.4 to 856.1 μ mol/cm/S with mean of 843.2 μ mol/cm/S (CV of 1.1%) at 2 m distance; and 1527.6 to 2123.6 μ mol/cm/S with mean of 1613.3 μ mol/cm/S (CV of 11.9%). The CO₂ ranged from 827.0 to 1888.0 kg/ha/season with mean of 1325.8 kg/ha/season (CV of 27.3%); while the N₂O ranged from 227.0 to 1033.0 g/ha/season with mean of 649.6 g/ha/season (CV of 34.8%); and GWP ranged from 897.0 to 2200.0 kg equivalent/ha with mean of 1527.2 kg equivalent/ha (CV of 27.3%).

Table 2
Effects of INM treatments on PAR at harvest, CO₂, N₂O and GWP

Treatment	PAR (μ mol/cm/S) at harvest				CO ₂ (kg/ha/season)	N ₂ O (g/ha/season)	GWP (kg equivalent/ha)
	Tree base	1 m	2 m	Centre			
T1	139.2	344.5	853.3	1534.2	827 ^f	227 ^f	897 ^g
T2	136.1	330.9	856.1	1559.7	1110 ^e	781 ^b	1352 ^e
T3	136.7	325.2	834.4	1540.4	1340 ^d	686 ^c	1552 ^d
T4	136.9	329.8	836.2	1557.9	1094 ^e	656 ^c	1298 ^e
T5	133.8	335.0	841.6	1527.6	1439 ^d	763 ^b	1676 ^{cd}
T6	133.6	311.0	834.9	1541.6	1575 ^c	579 ^d	1755 ^c
T7	137.6	329.2	837.8	1560.4	937 ^f	437 ^e	1073 ^f
T8	131.3	326.3	851.6	1574.2	1722 ^b	684 ^c	1942 ^b
T9	-	-	-	2123.6	1888 ^a	1033 ^a	2200 ^a
SEm $\pm$	2.74	7.1	10.87	26.44	41	21	47
LSD (p = 0.05)	NS	NS	NS	NS	123	64	141

T1-Control; T2-100% RDF (75:50:50; NPK); T3-75% RD N + 25% N through neem cake; T4-75% RD N + 25% N through Biochar; T5-75% RD N + PGLM @10 t ha⁻¹; T6-50% RD N + 50% N through neem cake; T7-50% RD N + 50% N through Biochar; T8-50% RD N + PGLM @10 t ha⁻¹; and T9-Sole crop (RDF 75:50:50

NPK kg ha⁻¹). Data in the column followed by different letters are significantly different at $p \leq 0.05$.

3.3. Effects of INM treatments on initial and final tree height, girth canopy spread and pod yield

The effects of INM treatments on initial and final tree height, girth and canopy spread under North-South and East-West directions and pod yield were tested based on F-test. The mean values of treatments, along with the SEM values are given in Table 3. The initial height ranged from 10.3 to 10.9 cm (mean 10.6 cm, CV of 2.1%), while final height ranged from 10.5 to 11.0 cm (mean 10.7 cm, CV of 1.8%). The initial girth ranged from 52.5 cm to 61.2 cm with mean of 56.9 cm (CV of 5.5%); while the final girth ranged from 47.0 to 63.0 cm with mean of 56.6 cm (CV of 10.6%). The initial canopy spread (North-South) ranged from 3.9 m to 4.8 m with mean of 4.5 m (CV of 6.7%); while the final canopy spread (North-South) ranged from 4.5 to 5.2 m with mean of 5.0 m (CV of 4.7%). The initial canopy spread (East-West) ranged from 4.1 m to 4.9 m with mean of 4.6 m (CV of 5.3%); while the final canopy spread (East-West) ranged from 4.4 to 5.3 m with mean of 5.0 m (CV of 5.9%). The pod yield ranged from 1136 to 1413 kg/ha with mean of 1278 kg/ha (CV of 8.4%).

Table 3
Effects of INM treatments on initial and final tree height, girth canopy spread and pod yield

Treatment	Height (m)		Girth (cm)		Canopy spread (m) (N-S)		Canopy spread (m) (E-W)		Pod yield (kg/ha)
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	
T1	10.7	10.8	53.6	48.7	4.6	5.1	4.8	5.3	1136
T2	10.4	10.6	52.5	54.6	3.9	4.5	4.1	4.4	1385
T3	10.9	11.0	57.0	59.2	4.5	5.0	4.6	5.1	1247
T4	10.8	10.9	55.1	47.0	4.7	5.2	4.8	5.3	1357
T5	10.4	10.5	60.6	61.8	4.3	5.0	4.6	4.9	1191
T6	10.6	10.7	56.4	58.3	4.8	5.2	4.6	4.8	1413
T7	10.8	10.9	61.2	63	4.6	5.2	4.7	5.0	1163
T8	10.3	10.5	58.5	60.5	4.2	4.9	4.9	5.1	1330
T9	-	-	-	-	-	-	-	-	-
SEm±	0.13	0.28	2.6	2.64	0.22	0.34	0.23	0.31	
LSD	NS	NS	NS	NS	NS	NS	NS	NS	

T1-Control; T2-100% RDF (75:50:50; NPK); T3-75% RD N + 25% N through neem cake; T4-75% RD N + 25% N through Biochar; T5-75% RD N + PGLM @10 t ha⁻¹; T6-50% RD N + 50% N through neem cake; T7-50% RD N + 50% N through Biochar; T8-50% RD N + PGLM @10 t ha⁻¹; and T9-Sole crop (RDF 75:50:50 NPK kg ha⁻¹). Data in the column followed by different letters are significantly different at $p \leq 0.05$.

3.4. Testing significance between plant parameters observed on different days after sowing

Temporal changes in plant height, number of leaves/plant, leaf area, dry matter accumulation, and N, P, and K uptake across 30, 60, and 90 DAS and at harvest (Supplementary Tables 1 & 2) were tested using paired t-tests. Mean, standard deviation, and t-calculated values are presented in Table 4. Plant height, leaf area, dry matter, and K uptake showed significant differences across all paired comparisons (30 vs. 60 DAS, 30 vs. 90 DAS, 30 vs. harvest, 60 vs. 90 DAS, 60 vs. harvest, and 90 DAS vs. harvest), indicating continuous, significant growth throughout the crop cycle. Number of leaves/plant and N uptake followed a similar pattern but did not differ significantly between 90 DAS and harvest, suggesting these parameters plateaued in the final growth phase. P uptake showed a more limited pattern of significance, differing significantly only between 30 and 60 DAS and between 30 DAS and harvest, with no significant differences among any other stage comparisons (30 vs. 90 DAS, 60 vs. 90 DAS, 60 vs. harvest, or 90 DAS vs. harvest).

Table 4
Testing significance between plant parameters observed on different days after sowing

Parameters	Mean	SD	Mean	SD	t-cal
Plant height					
30 vs 60 DAS	8.2	1.3	23.0	6.0	-7.249**
30 vs 90 DAS	8.2	1.3	38.1	8.4	-10.574**
30 vs Harvest	8.2	1.3	48.1	9.4	-12.626**
60 vs 90 DAS	23.0	6.0	38.1	8.4	-4.400**
60 vs Harvest	23.0	6.0	48.1	9.4	-6.777**
90 vs Harvest	38.1	8.4	48.1	9.4	-2.402*
No. of leaves/plant					
30 vs 60 DAS	9.8	2.6	20.2	3.6	-7.081**
30 vs 90 DAS	9.8	2.6	39.1	13.1	-6.596**
30 vs Harvest	9.8	2.6	46.8	13.4	-8.130**
60 vs 90 DAS	20.2	3.6	39.1	13.1	-4.172**
60 vs Harvest	20.2	3.6	46.8	13.4	-5.736**
90 vs Harvest	39.1	13.1	46.8	13.4	-1.227
Leaf area					
30 vs 60 DAS	75.9	17.2	154.0	38.4	-5.563**
30 vs 90 DAS	75.9	17.2	300.2	79.0	-8.320**
30 vs Harvest	75.9	17.2	433.9	99.0	-10.693**
60 vs 90 DAS	154.0	38.4	300.2	79.0	-4.990**
60 vs Harvest	154.0	38.4	433.9	99.0	-7.910**
90 vs Harvest	300.2	79.0	433.9	99.0	-3.168**
Dry matter					
30 vs 60 DAS	130	22.8	200	44.3	-4.194**
30 vs 90 DAS	130	22.8	316	84.6	-6.355**
30 vs Harvest	130	22.8	426	123.6	-7.061**
60 vs 90 DAS	200	44.3	316	84.6	-3.643**
60 vs Harvest	200	44.3	426	123.6	-5.168**
90 vs Harvest	316	84.6	426	123.6	-2.207*
Uptake N					
30 vs 60 DAS	4.3	0.7	9.1	1.7	-7.869**
30 vs 90 DAS	4.3	0.7	14.6	3.6	-8.484**
30 vs Harvest	4.3	0.7	14.2	3.5	-8.313**
60 vs 90 DAS	9.1	1.7	14.6	3.6	-4.239**
60 vs Harvest	9.1	1.7	14.2	3.5	-3.993**
90 vs Harvest	14.6	3.6	14.2	3.5	0.249
Uptake P					
30 vs 60 DAS	2.1	0.6	3.9	1.1	-4.310**
30 vs 90 DAS	2.1	0.6	2.7	1.6	-0.927
30 vs Harvest	2.1	0.6	3.3	1.5	-2.300*
60 vs 90 DAS	3.9	1.1	2.7	1.6	1.916
Note: * and ** denote statistical significance at the 5% ($p < 0.05$) and 1% ($p < 0.01$) significance levels, respectively.					

Parameters	Mean	SD	Mean	SD	t-cal
60 vs Harvest	3.9	1.1	3.3	1.5	0.910
90 vs Harvest	2.7	1.6	3.3	1.5	-0.942
Uptake K					
30 vs 60 DAS	2.3	0.6	4.8	1.3	-5.373**
30 vs 90 DAS	2.3	0.6	10.8	3.1	-8.069**
30 vs Harvest	2.3	0.6	15.4	4.9	-8.024**
60 vs 90 DAS	4.8	1.3	10.8	3.1	-5.287**
60 vs Harvest	4.8	1.3	15.4	4.9	-6.288**
90 vs Harvest	10.8	3.1	15.4	4.9	-2.427*
Note: * and ** denote statistical significance at the 5% ($p < 0.05$) and 1% ($p < 0.01$) significance levels, respectively.					

3.5. Assessment of performance of treatments based on mean and CV of plant parameters

An assessment of performance of treatments based on mean and CV of plant height, No. of leaves, leaf area, dry matter, uptake N, P and K nutrients observed on 30, 60, 90 DAS and at harvest is depicted in Fig. 1. In case of plant height and No. of leaves observed on 30, 60, 90 DAS and at harvest, (i) plant height on 30 DAS and No. of leaves on 60 DAS were found to have low mean and low CV; while (ii) plant height on 60 DAS and No. of leaves on 30 DAS have low mean and high CV; (iii) plant height on 90 DAS and at harvest have high mean and low CV; and (iv) No. of leaves on 90 DAS and at harvest have high mean and high CV as indicated in Fig. 1 (Top). In case of leaf area and dry matter observed on 30, 60, 90 DAS and at harvest, (i) leaf area on 30 DAS, dry matter on 30 and 60 DAS were found to have low mean and low CV; while (ii) leaf area on 60 DAS has low mean and high CV; (iii) leaf area at harvest has high mean and low CV; and (iv) leaf area on 90 DAS, dry matter on 90 DAS and at harvest have high mean and high CV as indicated in Fig. 1 (Middle). In case of uptake N, P and K observed on 30, 60, 90 DAS and at harvest, (i) uptake N on 30 DAS, uptake P on 30 and 60 DAS, uptake K on 30 and 60 DAS were found to have low mean and low CV; while (ii) uptake P on 90 DAS and at harvest have low mean and high CV; and (iii) uptake N on 60, 90 DAS and at harvest, uptake K on 90 DAS and at harvest have high mean and low CV as indicated in Fig. 1 (Bottom).

3.6. Grouping of treatments based on mean and standard deviation of plant parameters

Treatments were classified into three performance groups based on mean $\pm$ SD thresholds for each parameter: Group 1 ($< \text{Mean} - \text{SD}$), Group 2 ($\text{Mean} - \text{SD}$ to $\text{Mean} + \text{SD}$), and Group 3 ($> \text{Mean} + \text{SD}$), as summarized in Table 5.

For plant height at 60 DAS, number of leaves/plant (30, 60 DAS, and harvest), leaf area (30, 60, 90 DAS, and harvest), dry matter (90 DAS and harvest), fresh and dry herbage yield, and harvest index (Supplementary table 4), T1 and T9 consistently fell into Group 1 (poorest performers), T2–T5, T7, and T8 into Group 2, and T6 into Group 3 (best performer). A similar pattern was observed for plant height at 90 DAS and dry matter at 60 DAS, except that only T9 occurred in Group 1, with the remaining seven treatments (excluding T6) in Group 2, and T6 again in Group 3.

For initial population (Supplementary table 4), only T9 fell into Group 1, with all other treatments in Group 2. For final population, T4 and T9 fell into Group 1, while T2 and T8 occurred in Group 3. For plant height at 30 DAS, T1 and T9 occurred in Group 1, while T3 and T6 occurred in Group 3. At harvest, T9 alone occurred in Group 1, while T6 and T8 occurred in Group 3. For leaf number at 90 DAS, T1 and T9 fell into Group 1, while T6 and T8 fell into Group 3. Dry matter at 30 DAS showed no differentiation, with all nine treatments in Group 2. For days to 50% flowering, T3 occurred in Group 1 and T9 in Group 3, with the remaining treatments in Group 2.

Table 5
Grouping of treatments based on mean and standard deviation (SD) of their performance for plant parameters

Parameter	< (Mean - SD)	(Mean - SD) to (Mean + SD)	> (Mean + SD)
Initial population	T9	T1, T2, T3, T4, T5, T6, T7, T8	
Final population	T4, T9	T6, T5, T3, T7, T1	T8, T2
Plant height on 30 DAS	T9, T1	T4, T2, T7, T5, T8	T3, T6
Plant height on 60 DAS	T9, T1	T2, T4, T5, T3, T7, T8	T6
Plant height on 90 DAS	T9	T1, T2, T4, T7, T5, T8, T3	T6
Plant height at Harvest	T9	T1, T4, T2, T5, T3, T7	T8, T6
No. of leaves/plant on 30 DAS	T9, T1	T2, T4, T5, T3, T7, T8	T6
No. of leaves/plant on 60 DAS	T9, T1	T2, T4, T5, T3, T7, T8	T6
No. of leaves/plant on 90 DAS	T9, T1	T4, T2, T5, T3, T7	T8, T6
No. of leaves/plant at Harvest	T9, T1	T2, T4, T5, T3, T7, T8	T6
Leaf area on 30 DAS	T9, T1	T2, T4, T5, T3, T7, T8	T6
Leaf area on 60 DAS	T9, T1	T2, T4, T5, T3, T7, T8	T6
Leaf area on 90 DAS	T9, T1	T2, T4, T5, T3, T7, T8	T6
Leaf area at Harvest	T9, T1	T2, T4, T5, T3, T7, T8	T6
Dry matter on 30 DAS		T1, T2, T3, T4, T5, T6, T7, T8, T9	
Dry matter on 60 DAS	T9	T1, T2, T3, T4, T5, T7, T8	T6
Dry matter on 90 DAS	T9, T1	T2, T4, T5, T3, T7, T8	T6
Dry matter at Harvest	T9, T1	T2, T4, T5, T3, T7, T8	T6
Days to 50% flowering	T3	T1, T2, T4, T5, T6, T7, T8	T9
Fresh herbage yield	T9, T1	T2, T4, T5, T3, T7, T8	T6
Dry herbage yield	T9, T1	T2, T4, T5, T3, T7, T8	T6
Harvest index	T9, T1	T2, T4, T5, T3, T7, T8	T6

T1-Control; T2-100% RDF (75:50:50; NPK); T3-75% RD N + 25% N through neem cake; T4-75% RD N + 25% N through Biochar; T5-75% RD N + PGLM @10 t ha⁻¹; T6-50% RD N + 50% N through neem cake; T7-50% RD N + 50% N through Biochar; T8-50% RD N + PGLM @10 t ha⁻¹; and T9-Sole crop (RDF 75:50:50 NPK kg ha⁻¹).

3.7. Grouping of INM treatments based on mean and standard deviation of soil and plant nutrient parameters

Treatments were classified into three performance groups based on mean $\pm$ SD thresholds (Table 6): Group 1 (< Mean–SD), Group 2 (Mean–SD to Mean + SD), and Group 3 (> Mean + SD).

For N uptake at 60 DAS and harvest, P uptake at 60 DAS, and K uptake across all stages (30, 60, 90 DAS, and harvest), T1 and T9 fell into Group 1, T2–T5, T7, and T8 into Group 2, and T6 into Group 3. A similar pattern held for soil K and P uptake at 30 and 90 DAS, except only T1 occurred in Group 1, with T9 joining the remaining treatments in Group 2. For N uptake at 30 and 90 DAS, T1 and T9 occurred in Group 1, while T6 and T8 both occurred in Group 3.

For soil chemical properties (Supplementary table 5), groupings were less consistent: T4 and T6 fell into Group 1 for soil pH, while T7 alone occurred in Group 3; conversely, T7 occurred in Group 1 for electrical conductivity, with T6 in Group 3. For organic carbon, T1 occurred in Group 1 and T3 in Group 3. For soil N, T1 occurred in Group 1, while T6 and T8 occurred in Group 3; for soil P, T1 and T4 occurred in Group 1, with T6 alone in Group 3. All nine treatments fell into Group 2 for P uptake at harvest, indicating no differentiation at this stage.

Table 6
Grouping of treatments based on mean and standard deviation (SD) of their performance for soil and plant nutrient parameters

Parameter	< (Mean - SD)	(Mean - SD) to (Mean + SD)	> (Mean + SD)
Soil pH	T4, T6	T1, T2, T3, T5, T8, T9	T7
Electrical conductivity	T7	T1, T2, T3, T4, T5, T8, T9	T6
Organic carbon	T1	T2, T4, T5, T6, T7, T8, T9	T3
Nitrogen	T1	T2, T3, T4, T5, T7, T9	T8, T6
Phosphorus	T1, T4	T2, T3, T5, T7, T8, T9	T6
Potassium	T1	T2, T3, T4, T5, T7, T8, T9	T6
Uptake N on 30 DAS	T1, T9	T2, T3, T4, T5, T7	T8, T6
Uptake N on 60 DAS	T9, T1	T2, T3, T4, T5, T7, T8	T6
Uptake N on 90 DAS	T9, T1	T2, T3, T4, T5, T7	T8, T6
Uptake N at Harvest	T9, T1	T2, T3, T4, T5, T7, T8	T6
Uptake P on 30 DAS	T1	T2, T3, T4, T5, T7, T8, T9	T6
Uptake P on 60 DAS	T1, T9	T2, T3, T4, T5, T7, T8	T6
Uptake P on 90 DAS	T1	T2, T3, T4, T5, T7, T8, T9	T6
Uptake P at Harvest		T1, T2, T3, T4, T5, T7, T8, T9	T6
Uptake K on 30 DAS	T9, T1	T2, T3, T4, T5, T7, T8	T6
Uptake K on 60 DAS	T1, T9	T2, T3, T4, T5, T7, T8	T6
Uptake K on 90 DAS	T1, T9	T2, T3, T4, T5, T7, T8	T6
Uptake K at Harvest	T1, T9	T2, T3, T4, T5, T7, T8	T6

T1-Control; T2-100% RDF (75:50:50; NPK); T3-75% RDN + 25% N through neem cake; T4-75% RDN + 25% N through Biochar; T5-75% RDN + PGLM @10 t ha⁻¹; T6-50% RDN + 50% N through neem cake; T7-50% RDN + 50% N through Biochar; T8-50% RDN + PGLM @10 t ha⁻¹; and T9-Sole crop (RDF 75:50:50 NPK kg ha⁻¹).

3.8. Correlation between different plant parameters on different days after sowing

Correlation coefficients among plant growth and yield parameters were estimated and tested for significance, as presented in Table 7 (Panse and Sukhatme, 1978).

Initial population showed significant correlations with plant height (90 DAS), leaf area (30 DAS), dry matter (90 DAS and harvest), and harvest index. Plant height at each stage was significantly correlated with height at the preceding stage(s), as well as with number of leaves, leaf area, and dry matter recorded at the same stage; height at harvest was additionally correlated with harvest index and fresh and dry herbage yield (Supplementary table 4).

Number of leaves followed a similar stage-wise pattern, being significantly correlated with leaf number at preceding stages and with leaf area and dry matter at the corresponding stage, while leaf number at harvest was further correlated with harvest index and herbage yield (fresh and dry).

Leaf area showed significant correlations with leaf area at preceding stages and with dry matter at the corresponding stage; leaf area at harvest was additionally correlated with harvest index and fresh and dry herbage yield. Dry matter was significantly correlated with dry matter at preceding stages, and dry matter at harvest was further correlated with harvest index and herbage yield. Fresh herbage yield was significantly correlated with dry herbage yield and harvest index, while dry herbage yield was significantly correlated with harvest index.

3.9. Correlation between different soil and plant nutrient parameters on different days after sowing

Correlation coefficients among soil and plant nutrient uptake parameters were estimated and tested for significance (Table 8).

Soil N was found to be significantly correlated with soil P, soil K, and N uptake at all four stages (30, 60, 90 DAS and harvest). Soil P was also significantly correlated with soil K and P uptake at all stages, while soil K was significantly correlated with K uptake at all stages.

Uptake of N, P, and K each showed significant correlations with their own values at preceding stages. N uptake at 30 DAS was correlated with P and K uptake at the same stage, this cross-nutrient correlation, along with correlation with N uptake at preceding stages, persisted at 60, 90 DAS, and harvest. A similar pattern held for P uptake, which was significantly correlated with K uptake at the corresponding stage in addition to its own preceding-stage values, from 30 DAS through harvest. K uptake showed significant

Table 7
Correlation between different plant parameters on different days after sowing

	Population		Plant Height				No. of Leaf / Plant				Leaf Area				Dry matter	
	Initial	Final	30	60	90	Hr	30	60	90	Hr	30	60	90	Hr	30	60
IP	1															
FP	0.34	1														
PH30	0.62	0.08	1													
PH60	0.53	0.16	0.86**	1												
PH90	0.71*	0.13	0.97**	0.91**	1											
PHH	0.60	0.28	0.87**	0.99**	0.92**	1										
NL30	0.54	0.05	0.85**	0.98**	0.90**	0.95**	1									
NL60	0.55	0.30	0.82**	0.97**	0.88**	0.98**	0.93**	1								
NL90	0.53	0.15	0.84**	0.99**	0.89**	0.98**	0.98**	0.96**	1							
NLH	0.54	0.18	0.82**	0.99**	0.89**	0.99**	0.97**	0.97**	0.99**	1						
LA30	0.71*	0.15	0.87**	0.95**	0.92**	0.95**	0.95**	0.90**	0.96**	0.95**	1					
LA60	0.60	0.14	0.89**	0.99**	0.93**	0.98**	0.98**	0.94**	0.99**	0.98**	0.98**	1				
LA90	0.52	0.14	0.86**	0.99**	0.91**	0.98**	0.97**	0.97**	0.99**	0.99**	0.94**	0.98**	1			
LAH	0.65	0.28	0.84**	0.97**	0.92**	0.98**	0.93**	0.95**	0.97**	0.97**	0.96**	0.97**	0.97**	1		
DM30	0.54	0.24	0.86**	0.98**	0.91**	0.98**	0.95**	0.94**	0.98**	0.98**	0.95**	0.98**	0.97**	0.96**	1	
DM60	0.65	0.22	0.84**	0.97**	0.89**	0.97**	0.93**	0.95**	0.97**	0.97**	0.98**	0.97**	0.97**	0.96**	0.95**	1
DM90	0.69*	0.18	0.85**	0.96**	0.89**	0.96**	0.94**	0.93**	0.96**	0.96**	0.99**	0.97**	0.95**	0.96**	0.93**	0.99**
DMH	0.67*	0.16	0.83**	0.96**	0.89**	0.96**	0.95**	0.95**	0.97**	0.98**	0.98**	0.97**	0.96**	0.96**	0.93**	0.99**
D50F	-0.48	-0.34	-0.56	-0.51	-0.62	-0.58	-0.44	-0.42	-0.50	-0.50	-0.55	-0.54	-0.51	-0.64	-0.62	-0.47
FHY	0.64	0.16	0.86**	0.98**	0.91**	0.98**	0.96**	0.96**	0.99**	0.99**	0.98**	0.99**	0.98**	0.97**	0.96**	0.99**
DHY	0.58	0.03	0.90**	0.96**	0.94**	0.95**	0.95**	0.95**	0.96**	0.96**	0.94**	0.96**	0.98**	0.94**	0.92**	0.95**
HI	0.72*	0.10	0.86**	0.92**	0.89**	0.92**	0.92**	0.88**	0.93**	0.93**	0.99**	0.96**	0.91**	0.93**	0.90**	0.97**

* Correlation is significant at the 0.05 level of significance, ** Correlation is significant at the 0.01 level of significance.

D50F: Days to 50% flowering, FHY: Fresh herbage yield, DHY: Dry herbage yield, HI: Harvest index, Hr: Harvest

Table 8
Correlation between soil and plant nutrient parameters

Soil		N Content						P Content						K Content			
	pH	EC	OC	N	P	K	30	60	90	Hr	30	60	90	Hr	30	60	
Soil	pH	1															
	EC	-0.47	1														
	OC	-0.12	0.23	1													
	N	0.05	0.26	0.41	1												
	P	0.09	0.38	0.48	0.97**	1											
	K	0.09	0.24	0.54	0.97**	0.98**	1										
N Content	30	-0.13	0.39	0.44	0.94**	0.96**	0.95**	1									
	60	0.03	0.27	0.47	0.96**	0.97**	0.97**	0.97**	1								
	90	0.12	0.21	0.35	0.95**	0.95**	0.95**	0.94**	0.99**	1							
	Hr	0.05	0.37	0.35	0.97**	0.98**	0.96**	0.97**	0.96**	0.96**	1						
P Content	30	-0.08	0.37	0.38	0.97**	0.97**	0.96**	0.99**	0.96**	0.94**	0.98**	1					
	60	-0.09	0.28	0.41	0.96**	0.94**	0.95**	0.98**	0.99**	0.97**	0.95**	0.98**	1				
	90	-0.33	0.53	0.34	0.87**	0.87**	0.85**	0.94**	0.84**	0.81**	0.90**	0.95**	0.89**	1			
	Hr	-0.20	0.55	0.36	0.91**	0.92**	0.88**	0.92**	0.86**	0.83**	0.93**	0.94**	0.89**	0.97**	1		
K Content	30	-0.03	0.44	0.42	0.94**	0.97**	0.96**	0.96**	0.94**	0.93**	0.97**	0.97**	0.94**	0.93**	0.96**	1	
	60	-0.02	0.22	0.52	0.85**	0.88**	0.89**	0.93**	0.94**	0.91**	0.87**	0.89**	0.92**	0.77*	0.72*	0.82**	1
	90	-0.01	0.19	0.55	0.79*	0.84**	0.85**	0.88**	0.90**	0.87**	0.81**	0.83**	0.88**	0.70*	0.64	0.76*	0.9
	Hr	-0.06	0.25	0.55	0.84**	0.87**	0.88**	0.92**	0.94**	0.91**	0.86**	0.88**	0.92**	0.76*	0.71*	0.82**	0.9
N Uptake	30	-0.15	0.14	0.44	0.91**	0.84**	0.89**	0.87**	0.89**	0.87**	0.84**	0.89**	0.93**	0.82**	0.84**	0.87**	0.7
	60	-0.13	0.09	0.29	0.88**	0.79*	0.85**	0.84**	0.87**	0.87**	0.82**	0.86**	0.92**	0.79*	0.80**	0.84**	0.7
	90	-0.13	0.11	0.29	0.89**	0.80**	0.85**	0.85**	0.89**	0.88**	0.83**	0.87**	0.93**	0.79*	0.80**	0.84**	0.7
	Hr	-0.23	0.16	0.25	0.88**	0.79*	0.83**	0.86**	0.86**	0.85**	0.83**	0.89**	0.92**	0.85**	0.84**	0.85**	0.7
P Uptake	30	-0.13	0.25	0.42	0.96**	0.91**	0.94**	0.94**	0.93**	0.91**	0.92**	0.96**	0.96**	0.91**	0.92**	0.94**	0.8
	60	-0.18	0.23	0.34	0.92**	0.86**	0.90**	0.92**	0.92**	0.91**	0.89**	0.93**	0.96**	0.88**	0.89**	0.91**	0.7
	90	-0.33	0.46	0.29	0.88**	0.85**	0.84**	0.92**	0.84**	0.81**	0.89**	0.94**	0.90**	0.99**	0.97**	0.92**	0.7
	Hr	-0.29	0.41	0.31	0.89**	0.85**	0.86**	0.91**	0.85**	0.82**	0.89**	0.93**	0.91**	0.96**	0.97**	0.92**	0.7
K Uptake	30	-0.12	0.21	0.43	0.92**	0.86**	0.90**	0.87**	0.88**	0.86**	0.86**	0.89**	0.91**	0.85**	0.88**	0.90**	0.7
	60	-0.16	0.13	0.35	0.90**	0.83**	0.88**	0.89**	0.91**	0.90**	0.85**	0.90**	0.96**	0.83**	0.82**	0.87**	0.8
	90	-0.18	0.11	0.34	0.88**	0.80**	0.86**	0.87**	0.89**	0.89**	0.82**	0.88**	0.95**	0.81**	0.79*	0.84**	0.8
	Hr	-0.24	0.17	0.33	0.89**	0.81**	0.86**	0.89**	0.89**	0.87**	0.84**	0.90**	0.95**	0.85**	0.83**	0.85**	0.7
* Correlation is significant at the 0.05 level of significance, ** Correlation is significant at the 0.01 level of significance, Hr: Harvest																	

* Correlation is significant at the 0.05 level of significance, ** Correlation is significant at the 0.01 level of significance, Hr: Harvest

correlations with its own values at preceding stages at 60, 90 DAS, and harvest.

3.10. Eigen values and variance explained by the principal components of plant parameters

Two models were calibrated to assess variability in plant parameters using principal component analysis (Jolliffe, 1986). Model-1 included initial and final population, days to 50% flowering, fresh and dry herbage yield, harvest index, and plant height, leaf number, leaf area, and dry matter at 30, 60, 90 DAS and

harvest. Model-2 included only plant height, leaf number, leaf area, and dry matter across the same growth stages. Eigen values and variance explained are presented in Table 9.

Two principal components (PCs) were significant under Model-1, while only one PC was significant under Model-2. Under Model-1, eigenvalues were 18.784 (PC1) and 1.309 (PC2), together explaining 91.3% of total variance (85.4% and 5.9%, respectively). Under Model-2, PC1 alone had an eigenvalue of 15.193, explaining 94.9% of variance.

Under Model-1, PC1 loadings ranged from – 0.556 (days to 50% flowering) to 0.993 (leaf area at 60 DAS and fresh herbage yield), with all loadings significant except initial and final population and days to 50% flowering. PC2 loadings ranged from – 0.858 (final population) to 0.531 (days to 50% flowering), with only the final population loading being significant. Under Model-2, loadings ranged from 0.889 (plant height at 30 DAS) to 0.995 (leaf area at 60 DAS).

Table 9
Eigen values and Variance explained by Principal Component models of plant parameters

Model	Principal component model	Eigen value	Variance (%)	Cumulative variance (%)
1	PC1 = 0.652 (IPOP) + 0.195 (FPOP) + 0.893* (PH30) + 0.986* (PH60) + 0.942* (PH90) + 0.989* (PHHAR) + 0.965* (NOL30) + 0.959* (NOL60) + 0.984* (NOL90) + 0.984* (NOLHAR) + 0.983* (LA30) + 0.993* (LA60) + 0.982* (LA90) + 0.984* (LAHAR) + 0.974* (DM30) + 0.983* (DM60) + 0.982* (DM90) + 0.983* (DMHAR) – 0.556 (DF50) + 0.993* (FHY) + 0.971* (DHY) + 0.962* (HI)	18.784	85.4	91.3
	PC2 = -0.410 (IPOP) – 0.858* (FPOP) + 0.013 (PH30) + 0.087 (PH60) – 0.046 (PH90) – 0.060 (PHHAR) + 0.175 (NOL30) + 0.002 (NOL60) + 0.092 (NOL90) + 0.071 (NOLHAR) + 0.006 (LA30) + 0.057 (LA60) + 0.095 (LA90) – 0.106 (LAHAR) – 0.035 (DM30) + 0.019 (DM60) + 0.027 (DM90) + 0.061 (DMHAR) + 0.531 (DF50) + 0.061 (FHY) + 0.170 (DHY) + 0.057 (HI)	1.309	5.9	
2	PC1 = 0.889* (PH30) + 0.993* (PH60) + 0.935* (PH90) + 0.990* (PHHAR) + 0.972* (NOL30) + 0.966* (NOL60) + 0.991* (NOL90) + 0.990* (NOLHAR) + 0.977* (LA30) + 0.995* (LA60) + 0.989* (LA90) + 0.981* (LAHAR) + 0.978* (DM30) + 0.981* (DM60) + 0.978* (DM90) + 0.981* (DMHAR)	15.193	94.9	94.9
#Indicates the significance of loading on a principal component- IPOP: Initial population; FPOP: Final population; PH: Plant height; NOL: No. of leaves; LA: Leaf area; DM: Dry matter; DF50: Days to 50% flowering; FHY: Fresh herbage yield; DHY: Dry herbage yield; HI: Harvest index; HAR: Harvest; PC: Principal component				

3.11. Eigen values and variance explained by the principal components of soil and plant nutrient parameters

Three models were calibrated to assess variability in soil and plant nutrient status and tree growth parameters using principal component analysis (Norris, 1972). Model-1 comprised soil pH, electrical conductivity, organic carbon, N, P, and K; Model-2 comprised N, P, and K uptake at 30, 60, 90 DAS and harvest; and Model-3 comprised initial and final tree height, girth, and canopy spread (North–South and East–West). Eigen values and variance explained are presented in Table 10.

Two PCs were significant under Model-1, one PC under Model-2, and three PCs under Model-3. Under Model-1, eigenvalues were 3.382 (PC1) and 1.447 (PC2), together explaining 80.5% of variance (56.4% and 24.1%, respectively). Under Model-2, PC1 alone had an eigen value of 11.530, explaining 96.1% of variance. Under Model-3, eigen values were 4.206 (PC1), 2.058 (PC2), and 1.170 (PC3), together explaining 92.9% of variance (52.6%, 25.7%, and 14.6%, respectively).

3.12. Loadings of soil and plant nutrient parameters on the principal components

Under Model-1, PC1 loadings ranged from – 0.018 (soil pH) to 0.981 (soil P), with soil N, P, and K loading significantly. PC2 loadings ranged from – 0.746 (electrical conductivity) to 0.897 (soil pH), with soil pH and electrical conductivity loading significantly.

Under Model-2, loadings ranged from 0.928 (P uptake at 90 DAS) to 0.997 (P uptake at 60 DAS), with all parameter loadings significant.

Under Model-3, PC1 loadings ranged from – 0.260 (final tree girth) to 0.913 (final canopy spread, North–South), with initial and final canopy spread (North–South) loading significantly. PC2 loadings ranged from – 0.396 (final tree height) to 0.931 (initial tree girth), with initial tree girth loading significantly. PC3 loadings ranged from – 0.514 (initial canopy spread, East–West) to 0.490 (final tree height), with no significant loadings.

Table 10
Eigen values and variance explained by principal components of soil and plant nutrient parameters

Model	Principal component model	Eigen value	Variance (%)	Cumulative variance (%)
1	PC1 = -0.018 (pH) + 0.420 (EC) + 0.626 (OC) + 0.950* (N) + 0.981* (P2O5) + 0.974* (K2O)	3.382	56.4	80.5
	PC2 = 0.897 (pH) - 0.746 (EC) - 0.144 (OC) + 0.146 (N) + 0.107 (P2O5) + 0.180 (K2O)	1.447	24.1	
2	PC1 = 0.988* (UN-30) + 0.986* (UN-60) + 0.985* (UN-90) + 0.992* (UN-HAR) + 0.987* (UP-30) + 0.997* (UP-60) + 0.928* (UP-90) + 0.955* (UP-HAR) + 0.979* (UK-30) + 0.990* (UK-60) + 0.982* (UK-90) + 0.991 (UK-HAR)	11.530	96.1	96.1
3	PC1 = 0.798 (Initial-TH) + 0.739 (Final-TH) + 0.197 (Initial-TG) - 0.260 (Final-TG) + 0.905* (Initial-CS-NS) + 0.913* (Final CS-NS) + 0.737 (Initial-CS-EW) + 0.848 (Final-CS-EW)	4.206	52.6	92.9
	PC2 = -0.333 (Initial-TH) - 0.396 (Final-TH) + 0.931* (Initial-TG) + 0.833 (Final-TG) + 0.011 (Initial-CS-NS) + 0.269 (Final CS-NS) + 0.393 (Initial-CS-EW) + 0.054 (Final-CS-EW)	2.058	25.7	
	PC3 = 0.481 (Initial-TH) + 0.490 (Final-TH) + 0.222 (Initial-TG) + 0.449 (Final-TG) + 0.080 (Initial-CS-NS) - 0.009 (Final CS-NS) - 0.514 (Initial-CS-EW) - 0.422 (Final-CS-EW)	1.170	14.6	

#Indicates the significance of loading on a principal component- EC: electrical conductivity; OC: Organic carbon; N: Nitrogen; P₂O₅: Phosphorus; K₂O: Potassium; UN: Uptake N; UP: Uptake P; UK: Uptake K; HAR: Harvest; TH: Tree height; TG: Tree girth; CS: Canopy spread; NS: North-South; EW: East-West; PC: Principal component.

3.13. Assessment of superiority of treatments based on the rank sums of parameters

To assess treatment superiority, ranks were assigned to soil and plant parameters under five groups, and rank sums (RS) were derived for each treatment within each group. The treatment with the minimum rank sum was considered superior for that group and overall (Sankar et al., 2014). Group-1 comprised population, growth, and yield parameters (initial and final population, plant height, leaf number, leaf area, dry matter, days to 50% flowering, fresh and dry herbage yield, and harvest index); Group-2 comprised growth rate and gas exchange parameters (CGR, RGR, NAR, PAR, CO₂, N₂O, and GWP); Group-3 comprised soil chemical properties (pH, EC, organic carbon, N, P, K); Group-4 comprised nutrient uptake (N, P, K); and Group-5 comprised economic parameters (cost of cultivation, gross returns, net returns, and benefit-cost ratio). Rank sums for each treatment under each group are given in Table 11.

Rank sums ranged from 20–75 (Group-1), 17–59 (Group-2), 15–45 (Group-3), 3–26 (Group-4), and 9–29 (Group-5), with overall rank sums ranging from 70 to 219. T₆ recorded the minimum (best) rank sum in Group-1 (20), Group-3 (15), and Group-4 (3), while T₈ recorded the minimum rank sum in Group-2 (17) and Group-5 (9). T₈ was the second-best treatment in Group-1, Group-3, and Group-4, while T₆ was second-best in Group-2 and Group-5. Based on overall rank sum, T₈ was the superior treatment (70), followed by T₆ (73). Group-wise rank sums (RS1–RS5) are depicted in Fig. 2.

Table 11
Rank sums of INM treatments based on ranking of treatments under 5 groups

Treatments	RS1	RS2	RS3	RS4	RS5	Total
T ₁ - Control	67	59	44	25	24	219
T ₂ -100% RDF (75:50:50 NPK)	51	35	27	19	22	154
T ₃ - 75% RD N + 25% N through neem cake	40	39	26	12	16	133
T ₄ - 75% RD N + 25% N through Biochar	54	36	45	19	24	178
T ₅ - 75% RD N + PGLM @10 t ha ⁻¹	43	31	34	16	16	140
T ₆ - 50% RD N + 50% N through neem cake	20	23	15	3	12	73
T ₇ - 50% RD N + 50% N through Biochar	32	37	24	9	28	130
T ₈ - 50% RD N + PGLM @10 t ha ⁻¹	21	17	17	6	9	70
T ₉ - Sole crop (RDF 75:50:50 NPK kg ha ⁻¹)	75	27	25	26	29	182
#RDN: Recommended dose of nitrogen; RDF: Recommended dose of fertilizer; PGLM: Pongamia green leaf manure						

4. Discussion

4.1. Effects of treatments on PAR at varying distances from tree base

The non-significant treatment effects across all locations and growth stages confirm that INM practices, which act on soil nutrient dynamics, have no influence on canopy light interception or the resulting radiation microclimate. Instead, PAR distribution was governed entirely by the fixed structural characteristics of the Pongamia canopy, with values increasing progressively from the tree base to the centre as that of the typical radial pattern of light

attenuation seen in tree-based agroforestry systems. This pattern remained stable across 30, 60, and 90 DAS, consistent with *Pongamia*'s relatively unchanging canopy structure over a single cropping season.

The higher CV observed at the plot centre, despite comparable or greater PAR, suggests greater spatial heterogeneity in light availability farther from the tree, possibly due to variable canopy density or sun-angle effects across the more open plot area. The overall results confirm that tree canopy position, not nutrient management, is the primary determinant of light availability in this system, and should guide the spatial arrangement of shade-tolerant intercrops. These findings are consistent with those of Verma et al. (2010) and Joy et al. (2004), who similarly reported reduced PAR beneath tree canopies in agroforestry systems alongside satisfactory or enhanced performance of shade-tolerant understorey crops.

4.2. Effects of treatments on PAR at harvest, CO₂, N₂O and GWP

The non-significance of treatment effects on PAR at harvest confirms that INM practices do not alter the canopy-driven light environment, which remains governed by tree structural characteristics rather than soil nutrient management.

In contrast, significant treatment effects on CO₂, N₂O, and GWP indicate that nutrient source strongly influenced soil microbial activity and greenhouse gas dynamics. The consistently higher emissions under T9 across all three parameters likely reflect a nutrient composition dominated by readily mineralizable sources (higher inorganic fertilizer proportions), which stimulate microbial respiration and denitrification. Elevated emissions under T8 and T6 (CO₂) and T5 and T2 (N₂O) suggest comparable nutrient intensities promoting active decomposition and nitrogen transformation. Conversely, the lower emissions under T1 (and T7 for CO₂) suggest greater reliance on organic or slow-release nutrient sources, promoting gradual mineralization and reduced GHG flux, a pattern mirrored in GWP, where T1 was lowest and T9 highest, confirming CO₂ and N₂O as the primary drivers of GWP.

These results highlight a key trade-off in INM strategy: treatments maximizing nutrient availability (T9) may carry a higher environmental cost. Thus, the need for combinations such as those resembling T1 or T7 will ultimately balance productivity with lower emission intensity in climate-smart agroforestry systems. These findings align with Saravanan et al. (2008), who similarly used ANOVA to assess the influence of environmental factors on physiological and yield parameters in *Andrographis paniculata*.

4.3. Effects of INM treatments on initial and final tree height, girth canopy spread and pod yield

Based on the F-test, there was no significant difference in the effects of treatments on different tree parameters and pod yield. The lack of significant treatment effects likely reflects the short trial duration and the buffering capacity of an already-established tree crop, which responds more slowly to nutrient management than annual species; residual soil fertility may have further masked treatment differences.

The higher CV in final girth (10.6%) and pod yield (8.4%) compared to height and canopy spread indicates these traits were more sensitive to plant-to-plant and micro-site variability than the treatment effects which is in consistent with yield-related traits integrating a broader range of physiological and environmental influences over the crop cycle.

These findings align with those of Mehta et al. (2017), who evaluated the performance of *Chlorophytum borivillanum* accessions for treatment superiority under a Moringa-based agroforestry system, where treatment effects were similarly assessed but did not necessarily translate into pronounced, consistent differences across all measured parameters. Likewise, Sehgal and Thakur (2008) evaluated organic fertilizer treatments using analysis of variance to assess growth and production of medicinal herbs under an agroforestry system, reinforcing the observation that nutrient management responses in agroforestry systems can be gradual and may require longer evaluation periods, or larger treatment contrasts, before significant differences in tree growth and yield parameters become statistically detectable.

4.4. Testing significance between plant parameters observed on different days after sowing

The sustained, significant increases in plant height, leaf area, dry matter, and K uptake across all stages reflect continuous vegetative growth and active potassium assimilation, consistent with K's role in osmoregulation and assimilate translocation throughout plant development.

The plateauing of leaf number and N uptake near harvest likely reflects the shift from vegetative to reproductive growth, as nitrogen is increasingly remobilized from vegetative tissues rather than taken up fresh from the soil.

The restricted significance pattern for P uptake that is confined to early growth suggest that uptake was concentrated during initial root establishment, which is in consistent with phosphorus's known role in early root proliferation and energy transfer (Liu, 2021).

4.5. Assessment of performance of treatments based on mean and CV of plant parameters

The mean-CV classification (Gomez and Gomez, 1984) shows that growth stability varied markedly across parameters and stages. Plant height showed a high mean-low CV pattern at 90 DAS and harvest, indicating consistent height gain with maturity, while leaf number remained high mean-high CV at these stages, likely due to uneven leaf senescence and abscission despite overall growth stabilization.

Leaf area and dry matter shifted from low mean-low CV during early establishment (30–60 DAS) to high mean-high CV at 90 DAS, suggesting micro-site heterogeneity and differential treatment responses intensified as canopy and biomass expanded; leaf area reverted to low CV at harvest, indicating some convergence among plants by maturity.

Nutrient uptake patterns further distinguished the three elements: N and K uptake shifted to a high mean-low CV pattern by 90 DAS and harvest, reflecting substantial yet consistent late-stage assimilation, whereas P uptake remained low and increasingly variable (low mean–high CV) at later stages, corroborating the earlier finding that P uptake plateaus early in the crop cycle.

These contrasting patterns indicate that plant height and late-stage N and K uptake are the most stable and reliable indicators of crop performance. In contrast, leaf-related traits and P uptake were inherently more variable. Future field evaluations of similar agroforestry systems should therefore use larger sample sizes or more targeted management to improve precision for these traits.

4.6. Grouping of treatments based on mean and standard deviation of plant parameters

This grouping approach consistently identified T6 as the top-performing treatment and T9 (often alongside T1) as the weakest across most growth, yield, and nutrient-related parameters, corroborating the LSD-based rankings reported earlier for crop growth rate and related traits. The recurrence of this T6-superior, T9-inferior pattern across a wide range of independent parameters strengthens confidence that these rankings reflect genuine, biologically consistent treatment effects rather than parameter-specific artifacts.

Notably, T2 and T8 emerged among the better performers specifically for final population and late-stage height and leaf number, suggesting these treatments may have particularly favored plant survival and structural development in the later growth phase, even where they did not lead for other traits. The uniform Group 2 classification for dry matter at 30 DAS indicates negligible treatment differentiation at this very early stage, consistent with the generally low variability observed for early-stage growth parameters throughout this study.

This mean-SD grouping method serves as a practical, complementary approach to ANOVA and LSD analysis, enabling identification of consistently superior or inferior INM treatments across multiple parameters simultaneously, and reinforces T6 as the most agronomically promising treatment tested.

4.7. Grouping of treatments based on mean and standard deviation of soil and plant nutrient parameters

The recurrence of T6 in Group 3 (superior) and T1/T9 in Group 1 (inferior) across N, P, and especially K uptake closely mirrors the pattern observed for plant growth and yield parameters, confirming that T6's growth advantage was underpinned by genuinely greater nutrient acquisition rather than growth alone.

In contrast, groupings for soil chemical properties (pH, EC, organic carbon, soil N and P) were comparatively inconsistent, with different treatments occupying the extreme groups for each property. This divergence suggests that soil physicochemical parameters responded to INM treatments somewhat independently of plant nutrient uptake, likely reflecting the buffering capacity of soil and the influence of factors such as native soil fertility, treatment-specific organic-to-inorganic nutrient ratios, and microbial activity, which do not necessarily translate proportionally into enhanced plant-available nutrients or uptake.

The emergence of T6 and T8 in Group 3 for soil N, alongside their superior N uptake performance, points to a more targeted, nitrogen-oriented nutrient release pattern under these treatments rather than a broad enhancement of overall soil fertility status. The uniform grouping of all treatments for P uptake at harvest further supports the earlier finding that phosphorus dynamics stabilize across treatments by crop maturity, regardless of the nutrient management strategy applied. These contrasting patterns between plant nutrient uptake and soil property responses underscore the value of examining both compartments independently when evaluating INM efficacy in agroforestry systems, as favorable plant-level outcomes do not necessarily imply parallel improvements in the broader soil nutrient status.

4.8. Correlation between different plant parameters on different days after sowing

The consistent pattern of significant correlations between a given parameter and its own values at preceding growth stages reflects the cumulative, sequential nature of plant growth, wherein early vegetative attainment sets the trajectory for subsequent development. Similarly, the strong within-stage correlations among height, leaf number, leaf area, and dry matter indicate that these traits developed in a coordinated manner, consistent with their shared dependence on overall plant vigor and resource capture at each growth stage.

The significant correlations of height, leaf number, leaf area, and dry matter at harvest with harvest index and herbage yield (fresh and dry) indicate that vegetative growth parameters late in the crop cycle were closely linked to final biomass productivity, suggesting that these traits could serve as useful indirect selection criteria for herbage yield in this system. The correlation of initial population with several later-stage parameters further suggests that establishment density had a lasting influence on subsequent plant development and final yield attributes.

These relationships are consistent with those reported by Suvera et al. (2015), who examined the variability and relationships of herbage and essential oil yield among *Ocimum* species intercropped under *Pongamia pinnata* in a silvi-medicinal system in Gujarat. Similarly, our findings align with those of Suvera and Thakur (2016), who reported comparable trait relationships in *Ocimum* species grown under *Pongamia*-based silvi-medicinal systems in the same region, reinforcing the consistency of these growth–yield relationships across related intercropping systems.

4.9. Correlation between different soil and plant nutrient parameters on different days after sowing

The significant correlations of soil N, P, and K with their corresponding plant uptake values confirm that soil nutrient status was a direct driver of nutrient acquisition, as expected from basic soil–plant nutrient dynamics. The consistent cross-correlation among N, P, and K uptake within each growth stage further suggests coordinated, non-independent nutrient absorption, wherein uptake of one nutrient was closely linked to the availability and uptake of the others which is a pattern consistent with the interdependent nature of nutrient transport and assimilation processes in plants.

These relationships are consistent with Parama et al. (2018), who examined soil parameter variability and its effects on crop yield under semi-arid alfisols in Chamarajanagara district, Karnataka, prior to developing yield prediction models. The convergence of relationship patterns between the two studies supports the reliability of these soil–plant nutrient correlations as a foundation for developing predictive models of crop performance based on soil and plant nutrient status.

4.10. Eigen values and variance explained by the principal components of plant parameters

The high variance explained by PC1 alone in both models (85.4% and 94.9%, respectively) indicates that a single underlying growth gradient, reflecting overall plant vigor and biomass accumulation, accounted for the majority of variability among plant parameters, with most traits (height, leaf number, leaf area, and dry matter across stages) loading strongly and consistently in the same direction on this component.

The non-significant loadings of initial and final population and days to 50% flowering on PC1 under Model-1 suggest that these parameters varied comparatively independently of the main vegetative growth gradient. However, final population loaded significantly and negatively on PC2, indicating that this second, minor component captured a distinct source of variability related specifically to plant establishment and survival, separate from overall vegetative performance.

The markedly higher variance explained by a single PC in Model-2 (94.9%) compared to Model-1 (85.4% for PC1 alone) suggests that restricting the analysis to core vegetative growth parameters (height, leaf number, leaf area, dry matter) yields a more parsimonious and cohesive representation of plant growth variability, whereas incorporating yield and phenological traits in Model-1 introduces additional, partially independent sources of variation. This distinction supports using Model-2 when the objective is to characterize vegetative growth dynamics specifically, and Model-1 when a broader assessment incorporating yield and population-related traits is required.

4.11. Eigen values and variance explained by the principal components of soil and plant nutrient parameters

Across all three models, a small number of principal components captured the large majority of total variance, consistent with the general utility of PCA in reducing dimensionality while retaining most of the informative variability in multivariate soil and plant datasets (Norris, 1972).

The single dominant PC explaining 96.1% of variance under Model-2 indicates that N, P, and K uptake across all growth stages varied along a single, highly cohesive gradient, reflecting the interdependent nature of nutrient uptake dynamics noted in the correlation analysis. In contrast, the requirement for two and three significant PCs under Model-1 and Model-3, respectively, suggests that soil fertility parameters and tree growth attributes each comprise more than one distinct, partially independent source of variability, likely reflecting the more heterogeneous nature of soil chemical properties and the distinct growth dimensions (vertical height/girth vs. lateral canopy spread) captured in tree architecture.

These findings are consistent with Parama et al. (2018), who similarly used PCA to evaluate soil fertility parameters under long-term watershed management in semi-arid alfisols, identifying a limited number of significant components that explained the majority of variance in their dataset. The convergence of results between the two studies reinforces the reliability of PCA as a tool for simplifying complex, multi-parameter soil and plant nutrient datasets into a smaller set of interpretable underlying growth or fertility gradients.

4.12. Loadings of soil and plant nutrient parameters on the principal components

The strong loading of soil N, P, and K on PC1 under Model-1 indicates that this component primarily represents a soil nutrient-availability gradient, while the distinct loading of pH and electrical conductivity on PC2 suggests a separate dimension related to soil chemical reaction and salinity status, largely independent of nutrient content. Under Model-2, the uniformly high and significant loadings across all P uptake stages confirm that phosphorus uptake behaved as a single, tightly coupled process throughout the crop cycle. Under Model-3, the dominant loading of canopy spread (North–South) on PC1 and tree girth on PC2 suggests that lateral canopy expansion and radial stem growth represent largely distinct dimensions of tree development, rather than a single unified growth process.

These results align with Anderson and Furley (1975), who used PCA to relate surface soil properties to slope form, and with Deka et al. (2017), who grouped soil physical and chemical parameters into distinct factors using PCA in rice-based systems of the Brahmaputra valley. The findings are further consistent with Sankar et al. (2014), who applied PCA to identify significant soil, weather, and crop production factors influencing long-term cotton yield and returns under semi-arid vertisols. Across these studies, PCA similarly distinguished nutrient-related and physicochemical soil dimensions as separate underlying components, supporting the consistency of this pattern across diverse soil and cropping systems.

4.13. Assessment of superiority of treatments based on the rank sums of parameters

The complementary ranking pattern between T6 and T8 — with T6 excelling in vegetative growth, soil fertility, and nutrient uptake (Groups 1, 3, 4), and T8 excelling in growth efficiency/emissions and economic returns (Groups 2, 5) which indicates that no single treatment dominated across all evaluation criteria, and that treatment superiority is sensitive to which aspect of performance is prioritized. Despite this, T8's superior overall rank sum, achieved through consistently strong (if not always top) performance across all five groups, suggests that a more balanced treatment profile can outperform one that excels narrowly in a subset of parameters, an outcome consistent with the additive nature of the rank-sum method.

Practically, this suggests that T6 may be preferred where maximizing vegetative growth and soil nutrient status is the primary objective, whereas T8 offers the best overall balance of agronomic, environmental, and economic performance, making it the more broadly recommendable treatment under the conditions of this study.

These findings align with Madhavi Lata et al. (2012), who identified superior treatments for maximizing monetary returns from *Andrographis* in tree-based dryland systems, and with Sankar et al. (2014), who ranked INM treatments for yield, returns, and soil fertility changes under semi-arid vertisols. The results are further consistent with Kumar et al. (2015), who ranked treatments for growth, herb yield, and returns in a teak–*Ocimum* silvi-medicinal system in Gujarat, and are comparable to findings under litchi-based intercropping (Kumar et al., 2014) and guava-based horti-pasture systems (Kumar et al., 2016) in semi-arid India, collectively supporting rank-sum analysis as a robust approach for identifying agronomically and economically superior treatments across diverse tree-based cropping systems.

5. Conclusion

This study demonstrates that soil and plant nutrient parameters in the *Pongamia-Costus* silvi-medicinal system are governed by strong, stage-wise interrelationships, with nutrient uptake closely coupled to corresponding soil nutrient status and later-stage growth traits strongly correlated with earlier-stage measurements. Grouping treatments based on mean $\pm$ SD consistently identified T6 (and, for several parameters, T8) as the highest-performing treatments, while T1 and T9 (control/sole crop) consistently ranked lowest; notably, T9 also recorded the highest CO₂, N₂O, and GWP emissions, highlighting a potential trade-off between nutrient input intensity and environmental cost. Principal component analysis effectively reduced data dimensionality, with condensed components explaining 80.5–96.1% of total variance across soil, plant nutrient, and tree growth datasets, confirming their reliability as robust indicators of system-wide variability.

The key novelty of this work lies in its integrated multivariate framework which combine correlation analysis, mean $\pm$ SD-based grouping, and PCA so as to simultaneously characterize soil–plant nutrient dynamics, tree growth relationships, and greenhouse gas emissions within a single analytical structure. To our knowledge, this combined statistical and emission-based assessment has not previously been applied to the *Pongamia-Costus* silvi-medicinal system under semi-arid Alfisols, offering a novel, replicable approach for evaluating both productivity and environmental sustainability in tree-based intercropping systems. These findings provide a methodological and practical foundation for identifying INM strategies that optimize agronomic performance while minimizing greenhouse gas footprints in similar agroforestry systems.

Declarations

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

A.M.L. and A.A. performed the data analysis and drafted the manuscript. L.P.R. contributed to manuscript revision, data validation, and preparation of the tables and figures. All authors reviewed and approved the final version of the manuscript.

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Figures

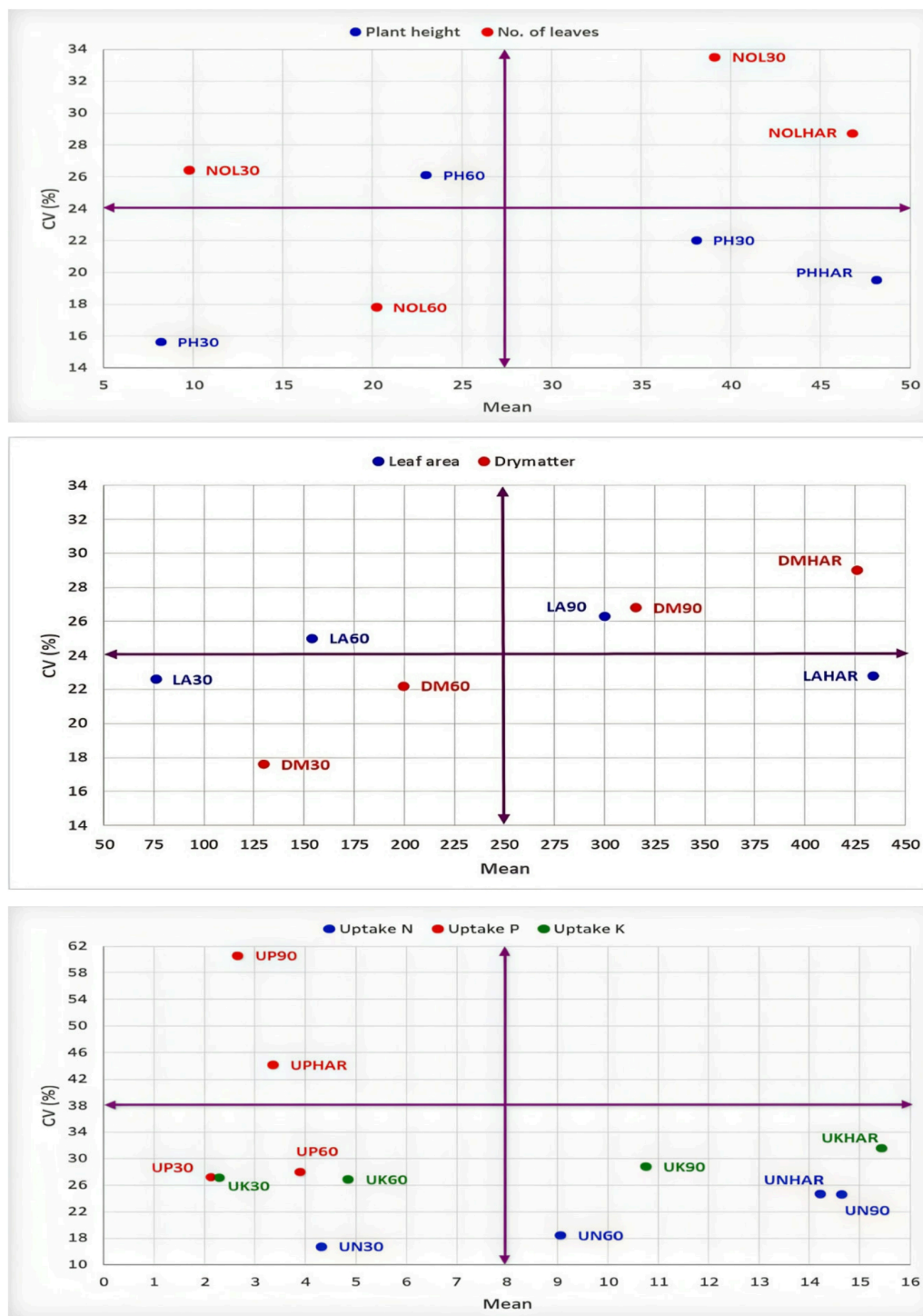


Figure 1

Assessment of performance of treatments based on mean and CV of plant height, No. of leaves, leaf area, dry matter, uptake N, P and K nutrients

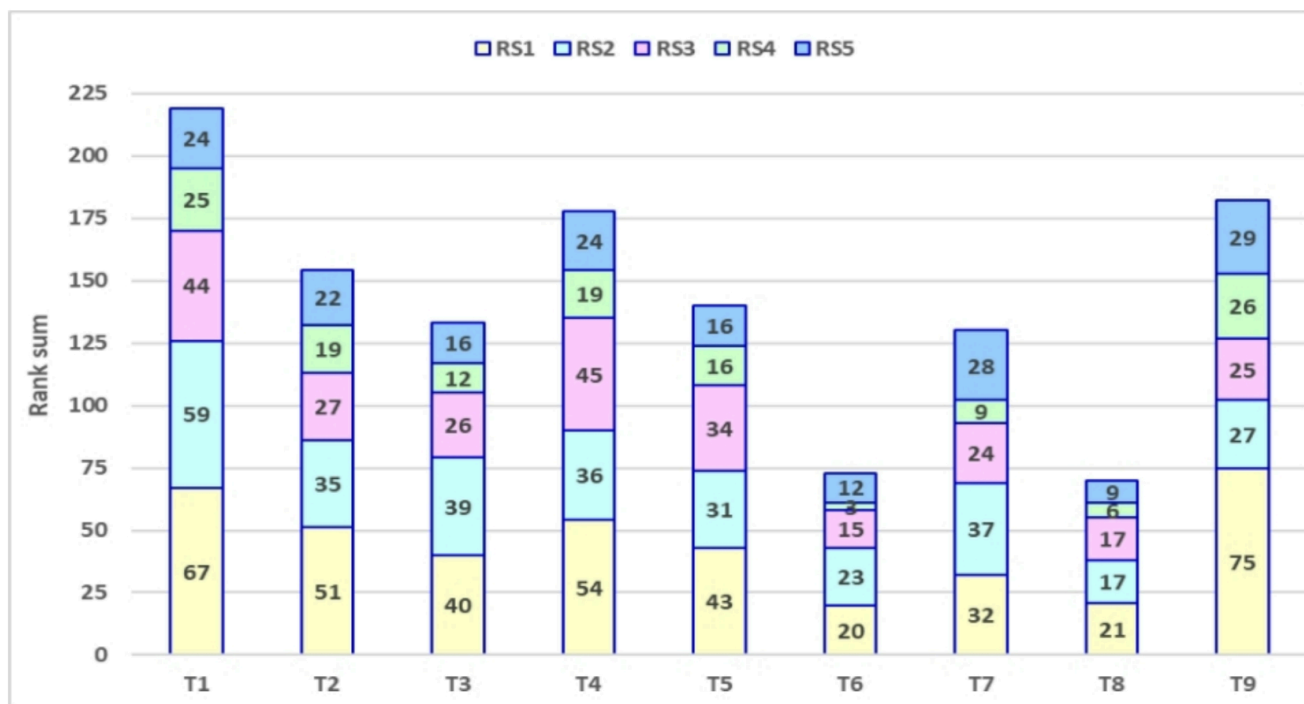


Figure 2

Ranking of treatments based on their performance for soil and plant parameters under 5 groups

#RS1 = Initial population, Final population, Plant height, No. of leaves, Leaf area, Dry matter, Days to 50% flowering, Fresh herbage yield, Dry herbage yield and Harvest index; RS2 = Crop growth rate, Relative growth rate, Net assimilation rate, PAR, CO₂, N₂O and GWP; RS3 = Soil pH, Electrical conductivity, Organic carbon, Nitrogen, Phosphorus and Potassium; RS4 = Uptake N, Uptake P and Uptake K; RS5 = Cost of cultivation, Gross returns, Net returns and Benefit-Cost ratio.

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