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Jyoti Sinha
Ph.D. Forestry, Department of forestry, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya Raipur, Chhattisgarh, India

Dr. Pratap Toppo
Assistant Professor Forestry, Department of forestry, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya Raipur, Chhattisgarh, India

Sandeep Tandav
Ph.D. Forestry, Department of forestry, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya Raipur, Chhattisgarh, India

Corresponding Author:
Jyoti Sinha
Ph.D. Forestry, Department of forestry, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya Raipur, Chhattisgarh, India

Effect of nutrient management on growth and yield performance of chia (*Salvia hispanica L.*) under agroforestry system in plains of Chhattisgarh

Jyoti Sinha, Pratap Toppo and Sandeep Tandav

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Abstract
The experiment was carried out conducted during the rabi seasons of 2023-24 and 2024-25 at the Herbal Garden of Indira Gandhi Krishi Vishwavidyalaya (IGKV), Raipur, Chhattisgarh. The experiment was laid out in a Randomized Block Design (RBD) with 8 treatments and 3 replications. The treatments included various combinations of NPK fertilizers and organic manures (FYM) to (T_1) NPK 30:20:25 kg ha-^{1}, (T_2) NPK 60:40:50 kg ha-^{1}, (T_3) NPK 90:60:75 kg ha-^{1}, (T_4) NPK 120:80:100 kg ha-^{1}, (T_5) NPK 30:20:25 kg ha-^{1} + 5 t fym ha-^{1}, (T_6) NPK 60:40:50 kg ha-^{1} + 5 t fym ha-^{1}, (T_7) NPK 90:60:75 kg ha-^{1} + 5 t fym ha-^{1} and (T_8) 10 t fym ha-^{1} evaluate the effects of integrated and sole nutrient applications on chia performance under partial tree shade. The results revealed that nutrient management significantly influenced the growth, yield, and economic returns of chia. Among all treatments, NPK 90:60:75 kg ha^{-1} (T_3) recorded the highest plant height, No. of branch, No. of leaf, leaf length, leaf width, spike length, No. of spike per plants, leaf area, dry matter accumulation, seed yield (645.20 kg ha^{-1}).Integrated application (T_7: NPK 90:60:75 kg ha^{-1} + 5 t FYM ha^{-1}) also produced competitive results while improving soil organic carbon and supporting tree growth. The study concludes that balanced chemical fertilization and integrated nutrient management enhance chia productivity, profitability, and sustainability under agroforestry systems.

Keywords: Agroforestry system, intercropping, alley cropping, chia crop (*Salvia hispanica*)

Introduction

The word "chia" is derived from the term *chian*, which means oily. *Salvia hispanica*, one of the two plants commonly referred to as "chia," is native to Mexico and Guatemala, belonging to the Lamiaceae family (Ixtaina *et al.*, 2008) [5]. The plant is seasonal that can grow up to 1.5 meters tall, with its main edible part being the seed. Chia is a short-day flowering plant that thrives in light to medium clay or sandy loam soils. Its growing cycle lasts between 100 to 150 days. The plants produce purple or white, self-pollinating flower spikes and require temperatures ranging from 11 °C to 36 °C, with an optimal range of 16-26 °C. Chia can be sown during June-July or November-December (Karim *et al*., 2015) [10].

Chia (*Salvia hispanica L.*) has significant potential for developing gluten-free products with high nutritional value (Kulczynski *et al.*, 2019) [11]. The seeds are rich in omega-3 fatty acids (essential polyunsaturated fatty acids), fibers, and proteins. Chia seeds contain high levels of dietary fiber (18-30%), ash (4-5%), protein (15-25%), fats (30-33%), lipids (31-35%), carbohydrates (26-41%), and various minerals and vitamins. Additionally, chia seeds are rich in antioxidants (Ixtaina *et al*., 2008) [5]. They also have a higher concentration of essential fatty acids, particularly omega-3 (58-64% of total lipids) and omega-6 (Valdivia and Tecante, 2015) [12].

Chia (*Salvia hispanica L.*), a highly nutritious superfood crop, belongs to the Lamiaceae family and is native to Central and Southern Mexico and Guatemala (Ixtaina *et al*., 2008) [5]. It is considered both a pseudo-cereal and an oilseed crop cultivated for its edible seeds. The plant typically grows up to one meter in height and features oppositely arranged leaves with small purple or white flowers (3-4 mm) that have a small corolla and fused flower parts. The chia seeds vary in colour from grey and black to white and have an oval shape, with seed sizes ranging from 1-2 mm (Bresson *et al.*, 2009) [13].

The cultivation of *Chia* (*Salvia hispanica* L.) is gaining global popularity due to its recognized health benefits, making it a superfood with superior nutritional value.

Chia seeds are widely consumed in various countries across Western South America, Western Mexico, and the South-western United States. In recent years, chia cultivation has been expanding in several regions of India. In Southeast Asia and the Caribbean, chia has been used as a medicinal food crop for over three decades, helping to prevent diseases such as diabetes, obesity, and cardiovascular issues (Ayerza and Coates, 2006) [14]. Due to its nutritional properties, chia is gaining popularity globally. It is particularly valued for its low carbohydrate content (42.1 g), high protein (16.5 g), dietary fiber (34.4 g), fat (31 g), and rich mineral content, including potassium (407 mg), phosphorus (860 mg), magnesium (335 mg), and calcium (631 mg). Chia is considered a health food supplement because of its high levels of antioxidants and omega-3 (ω-3) and omega-6 (ω-6) fatty acids, which are essential polyunsaturated fatty acids (PUFAs) in high demand due to their health benefits and market value (Simopoulos, 2008; Capitani *et al*., 2012) [15, 16].

Material and Methods

The experiment was carried out at Raipur, which is located in the South - Eastern part of Chhattisgarh. With 21°.23"39.77"N latitude and 81°.69"44.30"E longitude and having an altitude of 295 m above mean sea level.

The Experiment was started in month of Nov 2023 1st year and Nov 2024 2nd year and crop was finally harvested in March 2024 1st year and 2025 2nd year. The experiment was laid out in a Randomized Block Design with 8 treatments and 3 replications. The treatments included various combinations of NPK fertilizers and organic manures (FYM) to (T_1) NPK 30:20:25 kg ha-^{1}, (T_2) NPK 60:40:50 kg ha-^{1}, (T_3) NPK 90:60:75 kg ha-^{1}, (T_4) NPK 120:80:100 kg ha-^{1}, (T_5) NPK 30:20:25 kg ha-^{1} + 5 t fym ha-^{1}, (T_6) NPK 60:40:50 kg ha-^{1} + 5 t fym ha-^{1}, (T_7) NPK 90:60:75 kg ha-^{1} + 5 t fym ha-^{1} and (T_8) 10 t fym ha-^{1} evaluate the effects of integrated and sole nutrient applications on chia performance under partial tree shade. The soil of experimental field was black clayey soil which belongs to the order Vertisols and it is locally known as Kanhar. The soil of experimental site was very rich in organic carbon and other nutrient because of the addition of litter in the soil every year.

Statistical analysis: The data of all parameters of Chia collected precisely was tabulated, computed and statistical analysis done by using word-excel spreadsheet a randomize block design. The growth parameters data of height and DBH were summarized with standard deviation and presented.

Fig 1: Measurement of chia crop under tree-based Agroforestry system

Result and discussion

Plant Height (cm)

The plant height (cm) of the crop was recorded at various growth stages (30, 60, 90, and 110 DAS) over two consecutive years - Year I (2023-2024) and Year II (2024-25) under different fertilizer treatments comprising varying levels of NPK and FYM. A clear trend of increased plant growth with integrated nutrient management was observed, with noticeable consistency and variation between years. Nutrient management practices are presented in Table 4.1.

Table 1: Plant height of chia as influenced by nutrient management practices

Treatment	Plant Height (cm)							
	2023 - 24				2024-25			
	30 DAS	60 DAS	90 DAS	At Harvest	30 DAS	60 DAS	90 DAS	At Harvest
T_1 NPK 30:20:25 kg ha^{-1}	19.00	64.00	98.30	100.00	18.30	64.00	94.00	100.00
T_2 NPK 60:40:50 kg ha^{-1}	21.30	60.30	89.70	91.30	20.70	60.00	97.71	97.00
T_3 NPK 90:60:75 kg ha^{-1}	31.00	78.70	105.00	106.00	29.00	78.00	103.00	106.00
T_4 NPK 120:80:100 kg ha^{-1}	31.00	78.30	105.70	107.30	29.30	76.30	105.00	107.30
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	22.00	62.00	97.00	98.70	21.00	61.70	95.70	99.00
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	24.00	72.00	96.00	97.70	23.00	73.30	98.30	99.00
T_7NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	28.30	75.30	101.00	102.00	27.70	77.00	101.30	101.70
T_8 10 t fym ha^{-1}	17.00	61.30	90.30	92.00	17.30	61.00	94.30	88.30
SEm±	5.19	7.46	6.73	5.04	3.73	5.52	4.62	5.69
CD @ (P=0.05)	11.96	15.80	14.26	11.26	7.91	11.88	10.76	11.98

Number of branches plant^{-1}

The number of branches per plant is an essential growth attribute that directly influences the plant's capacity for flowering and seed production. In the present study, significant differences in the number of branches were observed under different nutrient management practices across both years (2023-2024 and 2024-2025).

Table 2: Number of branches plant^{-1} of chia as influenced by nutrient management practices

Treatment	Number of branches plant^{-1}							
	2023-24				2024-25			
	30 DAS	**60 DAS**	**90 DAS**	**At Harvest**	**30 DAS**	**60 DAS**	**90 DAS**	**At Harvest**
T_1 NPK 30:20:25 kg ha^{-1}	2.00	8.33	16.67	17.67	2.00	7.33	16.33	19.00
T_2 NPK 60:40:50 kg ha^{-1}	2.00	10.33	16.67	20.33	2.00	9.00	16.33	19.33
T_3 NPK 90:60:75 kg ha^{-1}	3.33	16.00	20.05	26.00	3.00	14.33	21.36	26.00
T_4 NPK 120:80:100 kg ha^{-1}	3.27	15.67	20.35	27.00	3.33	14.00	20.37	25.67
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	2.33	8.67	16.20	19.33	2.33	10.67	17.67	19.67
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	3.00	13.00	18.67	20.67	2.33	13.10	18.65	21.33
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	3.00	13.67	20.00	24.33	3.00	14.00	19.67	25.00
T_8 10 t fym ha^{-1}	2.33	6.33	14.67	17.33	2.00	6.69	14.33	16.33
SEm±	0.33	0.57	1.52	1.52	0.33	0.58	1.15	1.15
CD @ (P=0.05)	0.97	1.53	3.24	3.23	0.97	1.61	2.46	2.44

Number of leaves plant $^{-1}$

The highest number of leaves per plant across both years was consistently observed under T_3 (NPK 90:60:75 kg ha^{-1}). In Year I, this treatment recorded 24.00 (30 DAS), 60.00 (60 DAS), 104.30 (90 DAS), and 100.30 (at harvest), while in Year II, the values further improved to 23.00, 59.00, 102.99, and 104.5, respectively. This indicates that a balanced dose of NPK combined with organic manure not only enhances nutrient availability but also sustains leaf production throughout the crop cycle.

Table 3: Number of leaves plant^{-1} of chia as influenced by nutrient management practices

Treatment	Number of leaves plant^{-1}							
	2023-24				2024-25			
	30 DAS	**60 DAS**	**90 DAS**	**At Harvest**	**30 DAS**	**60 DAS**	**90 DAS**	**At Harvest**
T_1 NPK 30:20:25 kg ha^{-1}	15.00	32.30	84.30	82.00	15.00	32.00	83.30	80.30
T_2 NPK 60:40:50 kg ha^{-1}	16.00	34.70	89.70	86.00	15.30	35.00	98.00	85.70
T_3 NPK 90:60:75 kg ha^{-1}	24.00	60.00	104.30	100.30	23.00	59.00	102.00	104.50
T_4 NPK 120:80:100 kg ha^{-1}	23.70	60.00	104.00	100.70	22.90	58.70	101.83	104.00
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	20.30	36.30	92.70	90.30	19.70	37.30	94.00	87.30
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	20.70	46.30	97.30	95.00	20.30	45.30	74.70	97.30
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	22.30	57.00	99.70	97.30	21.70	57.00	100.70	100.70
T_8 10 t fym ha^{-1}	14.30	29.30	63.70	67.30	14.00	30.00	68.70	70.00
SEm±	0.57	0.57	0.40	0.46	0.58	0.57	0.45	0.45
CD @ (P=0.05)	1.22	1.22	0.85	0.86	1.23	1.22	0.86	0.86

Collar diameter (cm)

At harvest, T_7 maintained superior performance with 1.34 cm (Year I) and 1.32 cm (Year II), showcasing the long-term benefit of combining FYM and NPK. Treatments T_7 (1.32 cm and 1.30 cm) and T_6 (1.23 cm and 1.22 cm) also remained high-performing. Meanwhile, T_1 (NPK 30:20:25) and T_4 (NPK 120:80:100 + FYM) recorded moderate collar diameters at 1.12 & 1.10 cm and 1.05 & 1.06 cm, respectively. The lowest again was T_8, with 0.98 cm and 0.97 cm, emphasizing the limited effect of FYM when not paired with chemical fertilizers.

Table 4: Collar diameter of chia as influenced by nutrient management practices

Treatment	Collar diameter (cm)							
	2023-24				2024-25			
	30 DAS	60 DAS	90 DAS	At Harvest	30 DAS	60 DAS	90 DAS	At Harvest
T_1 NPK 30:20:25 kg ha^{-1}	0.53	0.85	1.08	1.12	0.55	0.83	1.07	1.10
T_2 NPK 60:40:50 kg ha^{-1}	0.56	0.89	1.16	1.17	0.57	0.88	1.14	1.16
T_3 NPK 90:60:75 kg ha^{-1}	0.66	1.06	1.35	1.34	0.64	1.04	1.29	1.32
T_4 NPK 120:80:100 kg ha^{-1}	0.54	0.83	1.00	1.05	0.55	0.84	1.01	1.06
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	0.57	0.88	1.14	1.16	0.57	0.89	1.15	1.18
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	0.62	0.98	1.21	1.23	0.60	0.99	1.19	1.22
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	0.65	1.05	1.29	1.32	0.64	1.02	1.28	1.30
T_8 10 t fym ha^{-1}	0.52	0.82	0.95	0.98	0.51	0.80	0.94	0.97
SEm±	0.01	0.016	0.016	0.018	0.02	0.015	0.017	0.018
CD @ (P=0.05)	0.03	0.032	0.032	0.038	0.04	0.031	0,036	0.038

No. of spikes plant^{-1}

Number of spikes plant^{-1} varied significantly due to methods of establishment and nutrient levels shown in table 4.5.

At 60 days after sowing, In Year I, T_4 lead (14.66), followed by T_3 (14). Integrated treatments (T_5, T_6, T_7) showed 6.00, 9.66 and 4.00. In Year II, T_3 remained high (13.67), with T_4 at 13.00, T_6 at 9.33. Integrated treatments (T_5, T_6, T_7) recorded 5.33, 9.33 and 3.67. T_8 remained low (2.00).

Table 5: Number of spikes plant^{-1} as influenced by nutrient management practices

Treatment	Number of spikes plant^{-1}					
	2023-24			2024-25		
	60 DAS	90 DAS	At Harvest	60 DAS	90 DAS	At Harvest
T_1 NPK 30:20:25 kg ha^{-1}	3.66	24.66	25.33	3.33	23.67	24.00
T_2 NPK 60:40:50 kg ha^{-1}	7.33	24.66	25.33	6.67	24.00	25.33
T_3 NPK 90:60:75 kg ha^{-1}	14.00	35.00	35.33	13.67	33.67	34.00
T_4 NPK 120:80:100 kg ha^{-1}	14.66	34.66	35.36	13.00	32.60	34.33
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	6.00	21.33	22.33	5.33	20.00	21.33
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	9.66	30.00	30.66	9.33	29.33	29.67
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	4.00	33.66	34.33	3.67	31.67	34.00
T_8 10 t fym ha^{-1}	2.33	19.66	21.66	2.00	18.67	20.00
SEm±	1.17	3.21	5.20	1.25	3.19	5.19
CD @ (P=0.05)	3.49	6.09	11.08	4.15	6.08	11.07

No. of seed spike^{-1}

When comparing the two years, it is evident that T_3 consistently maintained superior performance across both 90-day and harvest stages, reflecting its suitability for maximizing seed spike production. The treatment T_6 (NPK 60:40:50 + 5 t FYM) also showed reliable improvement in the second year (945 to 950 spikes in 2023-24; 1010 in 2024-25), suggesting positive cumulative effects of FYM. On the contrary, T_8 (10 t FYM ha^{-1}) consistently recorded the lowest spike count (660 and 700 in year one; 710 in year two), highlighting that FYM alone is insufficient to support optimal spike development.

Table 6: Number of seed spike^{-1} as influenced by nutrient management practices

Treatment	Number of seed spike^{-1}			
	2023-24		2024-25	
	90 DAS	At Harvest	90 DAS	At Harvest
T_1 NPK 30:20:25 kg ha^{-1}	774.66	780.00	770.00	840.00
T_2 NPK 60:40:50 kg ha^{-1}	790.33	788.33	790.00	845.00
T_3 NPK 90:60:75 kg ha^{-1}	1110.66	1107.66	1020.00	1211.80
T_4 NPK 120:80:100 kg ha^{-1}	1110.65	1106.66	1019.00	1211.65
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	865.00	868.33	855.00	900.15
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	945.00	950.00	931.66	1010.00
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	1000.66	1005.00	997.33	1102.10
T_8 10 t fym ha^{-1}	660.00	700.00	784.00	710.00
SEm±	8.45	9.29	8.43	9.46
CD @ (P=0.05)	21.85	26.88	21.84	27.86

Length of spike

In contrast, T_8 (10 t FYM ha^{-1}) recorded the shortest spike lengths (20.00-23.00 cm across stages and years), consistently under per forming in comparison to all other treatments. This highlights that organic manure alone may not be sufficient to meet the nutrient demands of chia during peak growth phases, especially for spike development. Interestingly, a general increase in spike length from 90 days to harvest across treatments indicates continued spike elongation post-90 days. The most prominent gains were observed in treatments with higher nutrient levels (e.g., T_3 and T_7), emphasizing the importance of sustained nutrient availability for full spike development.

Table 7: Length of spike as influenced by nutrient management practices

Treatment	Length of spikes (cm)					
	2023-24			2024-25		
	60 DAS	90 DAS	At Harvest	60 DAS	90 DAS	At Harvest
T_1 NPK 30:20:25 kg ha^{-1}	7.33	25.67	26.00	7.00	25.00	26.67
T_2 NPK 60:40:50 kg ha^{-1}	8.33	24.33	25.00	7.67	26.33	27.67
T_3 NPK 90:60:75 kg ha^{-1}	12.67	33.00	33.33	11.68	31.35	33.69
T_4 NPK 120:80:100 kg ha^{-1}	12.33	31.00	32.67	12.67	31.02	33.29
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	7.49	21.33	22.00	9.33	22.00	24.33
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	9.66	28.00	28.67	9.67	27.33	29.00
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	11.33	31.33	31.50	11.33	30.67	32.33
T_8 10 t fym ha^{-1}	7.33	20.00	21.33	6.67	21.33	23.00
SEm±	3.11	5.11	7.11	3.11	5.11	8.11
CD @ (P=0.05)	9.24	14.24	21.24	9.24	14.24	22.24

Leaf length (cm)

The results clearly demonstrate that integrated nutrient management, particularly T_7 (NPK 90:60:75 kg ha^{-1} + 5 t FYM ha^{-1}), significantly enhances leaf length at all growth stages over two years. This indicates a synergistic effect between chemical fertilizers and organic manure, improving both early growth and final plant vigor.

Higher doses of NPK without FYM (e.g., T_3) also resulted in strong performance, but the addition of FYM (in T_7) provided better consistency and sustainability. Sole application of FYM or lower fertilizer levels showed limited potential. Thus, for sustainable agricultural practices aiming at optimized crop growth and yield, a balanced integration of organic and inorganic nutrient sources is strongly recommended.

Table 8: Leaf length (cm) as influenced by nutrient management practices

Treatment	Leaf length (cm)							
	2023-24				2024-25			
	30 DAS	60 DAS	90 DAS	At Harvest	30 DAS	60 DAS	90 DAS	At Harvest
T_1 NPK 30:20:25 kg ha^{-1}	4.50	8.00	10.00	11.00	4.20	7.00	9.50	11.00
T_2 NPK 60:40:50 kg ha^{-1}	3.80	8.00	10.00	10.00	3.90	7.50	10.50	12.00
T_3 NPK 90:60:75 kg ha^{-1}	7.00	13.00	13.00	14.00	7.00	10.00	13.00	15.00
T_4 NPK 120:80:100 kg ha^{-1}	6.50	13.01	13.00	15.00	7.40	10.00	13.50	15.50
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	5.50	8.00	8.50	9.50	4.00	7.20	9.00	12.00
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	4.00	9.50	12.50	12.00	4.00	8.50	11.00	13.00
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	5.90	12.00	13.00	13.00	5.89	9.95	12.00	14.00
T_8 10 t fym ha^{-1}	3.80	7.00	8.00	10.00	3.90	7.00	8.75	10.00
SEm±	0.06	0.07	0.08	1.02	0.06	0.07	0.08	1.02
CD @ (P=0.05)	0.17	0.20	0.24	2.38	0.14	0.21	0.27	2.38

Leaf width (cm)

At the final stage, T_3 and T_7 again delivered the highest leaf width: 5.33 cm and 5.00 cm in 2023-24; 5.06 cm and 4.83 cm in 2024-25, respectively. These values are significantly higher than T_1 (4.00 and 3.85 cm) and T_4 (3.69 and 3.55 cm). The improvement in T_6 and T_7 can be attributed to the synergistic effect of inorganic NPK and organic FYM, which supports nutrient release throughout the growing period.

The data across both years revealed a consistent trend where treatments with balanced and moderate levels of NPK particularly T_3 (NPK 90:60:75 kg ha^{-1}) and T_7 (same NPK + 5 t FYM ha^{-1}) significantly enhanced both leaf length and leaf width at all growth stages compared to other treatments. The integration of FYM with chemical fertilizers in T_6 and T_7 not only improved leaf metrics but also sustained growth across the crop cycle, emphasizing the benefit of integrated nutrient management. In contrast, T_4 (NPK 120:80:100 kg ha^{-1} + FYM) consistently showed poor performance, likely due to nutrient imbalances or antagonism. The lowest leaf measurements were observed in control or lower-NPK treatments (T_1), confirming the necessity of adequate nutrient supply for optimal vegetative growth.

Table 9: Leaf width (cm) as influenced by nutrient management practices

Treatment	Leaf width (cm)							
	2023-24				2024-25			
	30 DAS	60 DAS	90 DAS	At Harvest	30 DAS	60 DAS	90 DAS	At Harvest
T_1 NPK 30:20:25 kg ha^{-1}	2.67	3.50	3.83	4.00	2.50	3.35	3.67	3.85
T_2 NPK 60:40:50 kg ha^{-1}	2.83	3.66	4.00	4.17	2.67	3.50	3.83	4.01
T_3 NPK 90:60:75 kg ha^{-1}	3.83	4.68	5.00	5.33	3.67	4.55	4.86	5.03
T_4 NPK 120:80:100 kg ha^{-1}	2.50	3.17	3.50	3.69	3.33	3.00	3.33	3.55
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	2.83	3.67	4.00	4.17	2.67	3.51	3.88	4.00
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	3.33	4.18	4.50	4.67	3.17	4.00	4.35	4.50
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	3.67	4.50	4.83	5.00	3.50	4.33	4.67	4.83
T_8 10 t fym ha^{-1}	2.33	3.00	3.33	3.50	2.17	2.83	3.17	3.33
SEm±	0.074	0.072	0.073	0.074	0.072	0.074	0.072	0.073
CD @ (P=0.05)	0.157	0.153	0.155	0.158	0.154	0.156	0.153	0.156

Leaf area (cm^2)

The statistical analysis supports the visual trends from the raw data. The Standard Error of Mean (SEm±) and Critical Difference (CD) at P = 0.05 indicate that differences among treatments were statistically significant. For example: At 90 DAS in the first year, the SEm± was 0.4164, and CD was 0.8813. T_3 and T_7 were well above this margin compared to T_4 and T_8, confirming true treatment effects. Similarly, in the second year, the CD at harvest was 0.8919, validating the significant superiority of T_3, T_6, and T_7 over the control and low-performing treatments. The low SEm± values across stages (ranging from 0.2173 to 0.4335) indicate reliable experimental precision and low variability among replicates.

Table 10: Leaf area (cm^2) as influenced by nutrient management practices

Treatment	Leaf area (cm^2)							
	2023-24				2024-25			
	30 DAS	60 DAS	90 DAS	At Harvest	30 DAS	60 DAS	90 DAS	At Harvest
T_1 NPK 30:20:25 kg ha^{-1}	8.65	16.65	20.06	22.00	7.50	14.99	18.33	20.06
T_2 NPK 60:40:50 kg ha^{-1}	9.90	18.37	22.00	23.93	8.66	15.99	19.14	22.00
T_3 NPK 90:60:75 kg ha^{-1}	9.20	30.60	36.25	40.00	17.32	29.01	33.75	36.25
T_4 NPK 120:80:100 kg ha^{-1}	8.50	18.37	15.75	18.37	6.41	12.00	14.25	16.50
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	9.90	18.37	22.00	25.01	8.66	15.99	19.14	22.00
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	14.17	23.96	29.25	31.50	12.63	21.99	27.18	29.25
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	17.39	28.08	32.62	36.33	15.75	25.99	30.33	33.75
T_8 10 t fym ha^{-1}	6.41	11.9	15.00	17.06	5.41	10.63	13.50	15.18
SEm±	0.21	0.38	0.41	0.43	0.22	0.39	0.40	0.42
CD @ (P=0.05)	0.46	0.81	0.88	0.91	0.47	0.83	0.85	0.89

Dry matter accumulation (gm)

The differences in DMA across treatments were statistically significant at all growth stages, as evidenced by the CD (P=0.05) values: At harvest: CD = 0.1394 (Year I) and CD = 0.1417 (Year II), At 90 DAS: CD = 0.1300 (Year I) and CD = 0.1272 (Year II). The SEm+ values ranged between 0.0278-0.0669 across all stages, indicating low experimental error and high reliability of the data. Treatments T_3 and T_7 consistently exceeded these thresholds, affirming their superior performance as statistically valid.

The study conclusively shows that NPK 90:60:75 kg ha^{-1}, especially when combined with 5 t FYM ha^{-1} (T_7), significantly enhances dry matter accumulation in plants. These treatments consistently outperformed all others in both years and across all growth stages, indicating that optimal nutrient supply both chemical and organic maximize biomass production.

Table 11: Dry matter accumulation plant (gm) as influenced by nutrient management practices

Treatment	Dry matter accumulation (gm)							
	2023-24				2024-25			
	30 DAS	60 DAS	90 DAS	At Harvest	30 DAS	60 DAS	90 DAS	At Harvest
T_1 NPK 30:20:25 kg ha^{-1}	3.33	8.61	11.87	13.50	3.60	8.47	11.97	11.73
T_2 NPK 60:40:50 kg ha^{-1}	4.83	7.54	11.30	12.68	4.00	7.10	12.16	12.30
T_3 NPK 90:60:75 kg ha^{-1}	6.96	12.43	18.04	19.10	6.90	12.40	17.50	18.50
T_4 NPK 120:80:100 kg ha^{-1}	6.30	12.97	17.77	19.00	6.19	12.60	17.25	18.43
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	5.55	7.65	8.32	13.20	5.20	8.00	12.66	12.51
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	6.48	9.80	11.21	15.50	6.10	10.35	14.16	14.40
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	6.90	11.24	17.50	17.90	6.40	11.59	16.93	17.89
T_8 10 t fym ha^{-1}	3.20	8.34	9.02	11.00	3.50	8.38	10.98	11.55
SEm±	0.027	0.052	0.061	0.065	0.028	0.053	0.060	0.066
CD @ (P=0.05)	0.059	0.111	0.130	0.139	0.060	0.114	0.127	0.141

CGR (Crop Growth Rate) and RGR (Relative Growth Rate)

CGR was recorded as 0.086 gm/plant/day in the first year and 0.083 gm/plant/day in the second year, indicating a consistent and robust vegetative growth phase. The growth rate peaked during the 60-90 days interval, showing 0.094 gm/plant/day in the first year and a slightly lower but comparable rate of 0.093 gm/plant/day in the second year. This peak suggests that this period may correspond to the active reproductive phase, where nutrient uptake and biomass accumulation are at their highest. However, a notable decline in CGR was observed from 90 days to harvest, with values dropping to 0.019 gm/plant/day and 0.017 gm/plant/day for the first and second years, respectively.

Table 12: Crop Growth Rate (gm/plant/day) as influenced by nutrient management practices

Interval	Crop Growth Rate (gm/plant/day) 2023-24 2024-25	
	CGR (gm/plant/day)	CGR (gm/plant/day)
30-60 DAS	0.086	0.833
60-90 DAS	0.094	0.093
90-Harvest	0.019	0.017

Table 12.1: Relative Growth Rate (gm/gm/day) as influenced by nutrient management practices

Interval	Relative Growth Rate (gm/gm/day) 2023-24 2024-25	
	RGR (gm/gm/day)	RGR (gm/gm/day)
30-60 DAS	0.0335	0.0331
60-90 DAS	0.0175	0.0178
90-Harvest	0.0026	0.0025

4.2. Yield Parameters

Test Weight (1000 seed, gm)

Across both years, treatments with combined NPK and FYM (T_5 to T_7) consistently outperformed those with only chemical (T_1-T_4) or only organic inputs (T_8). The slight year-to-year variation (e.g., T_2: 1.43 gm to 1.40 gm) may be attributed to environmental factors like rainfall, temperature, or soil nutrient carryover effects. The best performing treatments (T_3 and T_7) balance efficient nutrient supply with soil conditioning benefits, leading to better grain filling and kernel weight.

Table 13: Test Weight (1000 seed, gm) as influenced by nutrient management practices

Treatments	Test Weight (1000 seed, gm)	
	2023-24	2024-25
T_1 NPK 30:20:25 kg ha^{-1}	1.42	1.41
T_2 NPK 60:40:50 kg ha^{-1}	1.43	1.42
T_3 NPK 90:60:75 kg ha^{-1}	1.45	1.45
T_4 NPK 120:80:100 kg ha^{-1}	1.42	1.41
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	1.44	1.43
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	1.43	1.42
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	1.44	1.44
T_8 10 t fym ha^{-1}	1.40	1.40
SEm±	0.014	0.013
CD @ (P=0.05)	0.029	0.028

Seed yield (Kg ha^{-1})

The statistical analysis further validates these differences. For the first season, the Standard Error of Mean (SEm) was 26.64, and the Critical Difference (CD @ P=0.05) was 63.00 kg ha^{-1}, indicating that any yield difference greater than 63 kg ha^{-1} between treatments is statistically significant. In the second season, the SEm was 25.18, and the CD was 59.54 kg ha^{-1}, reflecting similar levels of statistical reliability. For the pooled data, the SEm was 25.91 and CD was 61.17 kg ha^{-1}.

Table 14: Seed yield (Kg ha^{-1}) as influenced by nutrient management practices

	Seed yield (Kg ha^{-1})		
Treatments	2023-24	2024-25	Pooled
T_1 NPK 30:20:25 kg ha^{-1}	469.11	455.30	462.30
T_2 NPK 60:40:50 kg ha^{-1}	491.00	483.05	487.00
T_3 NPK 90:60:75 kg ha^{-1}	648.90	641.50	645.20
T_4 NPK 120:80:100 kg ha^{-1}	591.00	585.10	588.05
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	516.10	523.50	519.70
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	603.10	547.30	575.20
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	573.30	599.10	586.20
T_8 10 t fym ha^{-1}	425.50	436.10	444.30
SEm±	26.64	25.18	25.91
CD @ (P=0.05)	63.00	59.54	61.17

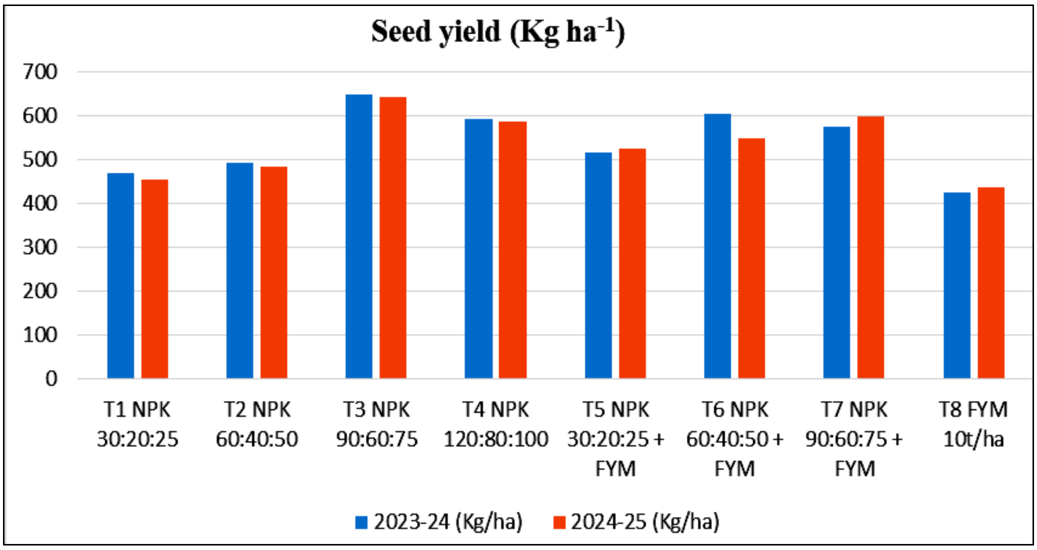

Fig 2: Seed yield (Kg ha^{-1}) as influenced by nutrient management practices

4.2.3. Halum yield (Kg ha^{-1})

Pooled across both years, T_3 remained the superior treatment with a mean dry weight yield of 1.53 kg ha^{-1}, followed by T_6 (1.35 kg ha^{-1}) and T_7 (1.13 kg ha^{-1}). Treatments with combined organic and inorganic nutrients generally performed better than sole applications. Based on the statistical analysis, the standard error of mean (SEm) was 0.096, and the critical difference (CD at 5%) was 0.21. Hence, the differences among T_3, T_6, and T_1 are statistically significant, confirming the effectiveness of high and balanced NPK rates, especially when supplemented with FYM, in increasing dry matter production.

Table 15: Halum yield (Kg ha^{-1}) as influenced by nutrient management practices

Treatments	Halum yield (Kg ha^{-1})	
	2023-24	2024-25
T_1 NPK 30:20:25 kg ha^{-1}	0.93	1.00
T_2 NPK 60:40:50 kg ha^{-1}	1.00	1.10
T_3 NPK 90:60:75 kg ha^{-1}	1.50	1.56
T_4 NPK 120:80:100 kg ha^{-1}	1.10	1.21
T_5 NPK 30:20:25 kg ha^{-1} + 5 t fym ha^{-1}	1.10	1.10
T_6 NPK 60:40:50 kg ha^{-1} + 5 t fym ha^{-1}	1.40	1.30
T_7 NPK 90:60:75 kg ha^{-1} + 5 t fym ha^{-1}	1.00	1.26
T_8 10 t fym ha^{-1}	0.96	1.10
SEm±	0.09	0.09
CD @ (P=0.05)	0.21	0.021

Conclusion

In terms of vegetative growth, the best performance was observed in NPK 120:80:100 kg ha^{-1} (T_4) and NPK 90:60:75 kg ha^{-1} (T_3). These treatments recorded the tallest plants, most leaves, and maximum dry matter accumulation. Leaf size and area were also significantly larger in these treatments, confirming the importance of macronutrient availability. The integration of FYM (particularly in T_7: NPK 90:60:75 kg ha^{-1} + 5 t FYM ha^{-1}) further improved plant development and sustained growth across both years.

Reproductive traits such as the number of spikes, spike length, and seed count per spike were highest in T_3 and closely followed by T_4 and T_7. The maximum seed yield of 648.90 kg ha^{-1} (2023-24) and 641.50 kg ha^{-1} (2024-25) was recorded under NPK 90:60:75 kg ha^{-1}, followed by 588.05 kg ha^{-1} in NPK 120:80:100 and 586.20 kg ha^{-1} in the integrated treatment with FYM. The lowest yields were observed in FYM only (T_8), indicating that sole organic nutrient application was insufficient under agroforestry shade conditions.

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