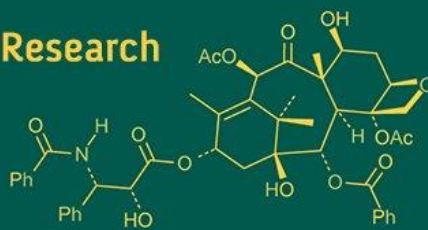
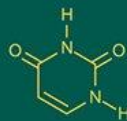
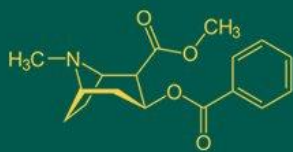


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Optimizing crop geometry (spacing) and nutrient inputs for sustainable cultivation and conservation of black turmeric (*Curcuma caesia* Roxb.)

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Abstract

A field experiment was conducted to evaluate the influence of crop geometry and nutrient management on the growth, yield, and rhizome traits of black turmeric (*Curcuma caesia* Roxb.). The study involved three spacing levels (45 × 30 cm, 30 × 30 cm, and 45 × 45 cm) and four nutrient regimes (no NPK, 25 t FYM + 75% NPK, 25 t FYM + 100% NPK, and 125% NPK). Growth attributes were measured at 210 days after sowing, while rhizome yield and its components were assessed at harvest. Spacing and nutrient levels significantly interacted to influence both vegetative performance and rhizome yield. Wider spacing (45 × 45 cm) combined with higher nutrient input enhanced plant stature and leaf traits, whereas closer spacing (45 × 30 cm) with 25 t FYM and 100% NPK (150:125:250 kg NPK ha⁻¹) produced the highest fresh rhizome yield. This treatment also improved mother, primary, and secondary rhizome production. Root tuber weight was greatest under wider spacing, but the highest tuber number occurred under nutrient omission. Overall, a spacing of 45 × 30 cm with integrated application of FYM and balanced NPK fertilization proved most effective for optimizing fresh rhizome yield and improving rhizome quality. These results highlight the importance of combining appropriate crop geometry with integrated nutrient management to enhance the sustainable cultivation and conservation of black turmeric, a valuable medicinal crop.

Keywords: *Curcuma caesia* Roxb, spacing, rhizome traits, medicinal crop, sustainable production

Introduction

Members of the family Zingiberaceae are valued for their diverse uses as medicines, spices, food, coloring agents, and ornamentals. Several species remain underexploited, and many face the threat of extinction due to habitat loss and other anthropogenic pressures. *Curcuma caesia* Roxb., commonly known as black turmeric because of its bluish-black rhizomes, is one such species. It is an erect, perennial, rhizomatous herb and a lesser-known medicinal plant of the Zingiberaceae. The species occurs in the forests of West Bengal, Madhya Pradesh, Odisha, Chhattisgarh, Uttar Pradesh, and sparsely in the Papi hills of Andhra Pradesh, the Himalayan foothills, Sikkim, and parts of Kerala and Karnataka (Anonymous, 2001, Sabu, 2006, Sharma *et al.*, 2011, Kumar *et al.*, 2021, Spoorti *et al.*, 2025) [2, 4, 5, 3, 1]. It thrives in moist deciduous forest ecosystems. Black turmeric holds considerable medicinal value and is used in traditional systems such as Ayurveda, Unani, and Siddha. Rhizomes are reported to possess diverse pharmacological properties, including blood-purifying, bronchodilating, antioxidant, anxiolytic, anticonvulsant, antibacterial, anthelmintic, and anti-ulcer activities. (Saikia, 2006, Arulmozhi *et al.*, 2006, Mangla *et al.*, 2010, Paliwal *et al.*, 2011, Karmakar *et al.*, 2011, Gill *et al.*, 2011, Das *et al.*, 2012, Paudel *et al.*, 2024, Kotha and Vanitha, 2025, Kumar *et al.*, 2025, Parida *et al.*, 2025, Som *et al.*, 2025, Yigit *et al.*, 2025) [6, 7, 10, 9, 12, 13, 17, 8, 11, 14, 15, 16, 18]. Despite its high economic and medicinal importance, the species has been categorized as *critically endangered* by the National Medicinal Plant Board (NMPB), and its export is regulated by the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India. Given its conservation status and broad-spectrum medicinal properties, cultivation-based conservation is essential. However, agronomic research on *C. caesia* remains scarce. Available information is largely extrapolated from *C.*

longa (turmeric), with only limited studies on soil preference, nutrient requirements, and planting practices (Anonymous, 2016)^[19]. In particular, the influence of crop geometry and nutrient management on growth and rhizome yield of black turmeric has not been systematically evaluated.

With this background, the present investigation was undertaken with the following objectives:

- To standardize the crop geometry (spacing) of black turmeric for enhanced rhizome yield.
- To determine the optimum nutrient requirement for sustainable cultivation of black turmeric.

Material Methods

Experimental site

The study was conducted during 2023-24 and 2024-25 at the experimental farm of ICAR-Krishi Vigyan Kendra, Chamarajanagar, University of Agricultural Sciences, Bangalore, India. The site is located in the Southern Dry Zone of Karnataka (11.92° N, 76.95° E; 662 m above mean sea level) and is characterized by a semi-arid tropical climate.

Experimental design and treatments

The experiment was laid out in a split-plot design with three replications. The main plots comprised three crop geometry (spacing) levels:

- S₁: 45 × 30 cm
- S₂: 30 × 30 cm
- S₃: 45 × 45 cm

The subplots included four nutrient management levels:

- N₁: Control (no external nutrients)
- N₂: 25 t FYM + 75% NPK (112.5:93.75:187.5 kg ha⁻¹)
- N₃: 25 t FYM + 100% NPK (150:125:250 kg ha⁻¹)
- N₄: 25 t FYM + 125% NPK (187.5:156.25:312.5 kg ha⁻¹)

In total, 12 treatment combinations were evaluated. Each plot measured 3.2 m × 1.8 m.

Planting material and crop management

Well-matured, healthy, and sprouted rhizomes of *Curcuma caesia* (25-35 g) were used for planting. Rhizomes were shade-dried and treated with Mancozeb (75% WP, 3 g L⁻¹)

plus Quinolphos (25% EC, 2 mL L⁻¹) for 15 min before sowing, following standard turmeric practices^[19]. Farmyard manure (25 t ha⁻¹) was incorporated into the soil 20 days before planting. Fertilizer nutrients were supplied through urea, single superphosphate, and muriate of potash. Half of the nitrogen along with the full dose of phosphorus and potassium was applied as basal, and the remaining nitrogen was top-dressed 45 days after planting, following weeding (Anonymous, 2010)^[20].

Planting was done on ridges on 3 June 2023 and 6 June 2024. Irrigation was applied immediately after planting and subsequently at 8-10 day intervals, depending on rainfall and soil moisture. Hand weeding was carried out at 30-day intervals until canopy closure. Earthing-up was performed as needed to cover exposed rhizomes. Pest and disease management included preventive sprays of Mancozeb (0.3%), Quinolphos (0.2%), and neem oil (0.5%).

Harvesting was carried out when crop maturity was indicated by senescence of leaves and tillers. Rhizomes were dug, cleaned, and shade-dried before recording observations.

Observations recorded

Data were collected on growth traits (plant height, number of leaves, clumps per plant, plant diameter, leaf length, and leaf width), yield traits (fresh rhizome yield per plant, plot, and hectare), rhizome components (number and weight of mother, primary, and secondary rhizomes), root tuber weight and number, crop duration, and rhizome constituents (via GC-MS).

Statistical analysis

Experimental data were analyzed using Fisher's method of analysis of variance (ANOVA) (Panse and Sukhatme, 1967)^[21] appropriate for a split-plot design. Treatment effects were considered significant at $P \leq 0.05$. Mean separation was performed using the least significant difference (LSD) test.

The population mean was estimated as:

$$Y = \frac{1}{n} \sum_{i=0}^n Y_i$$

Where Y = population mean, Y_i = individual observation, and n = number of observations.

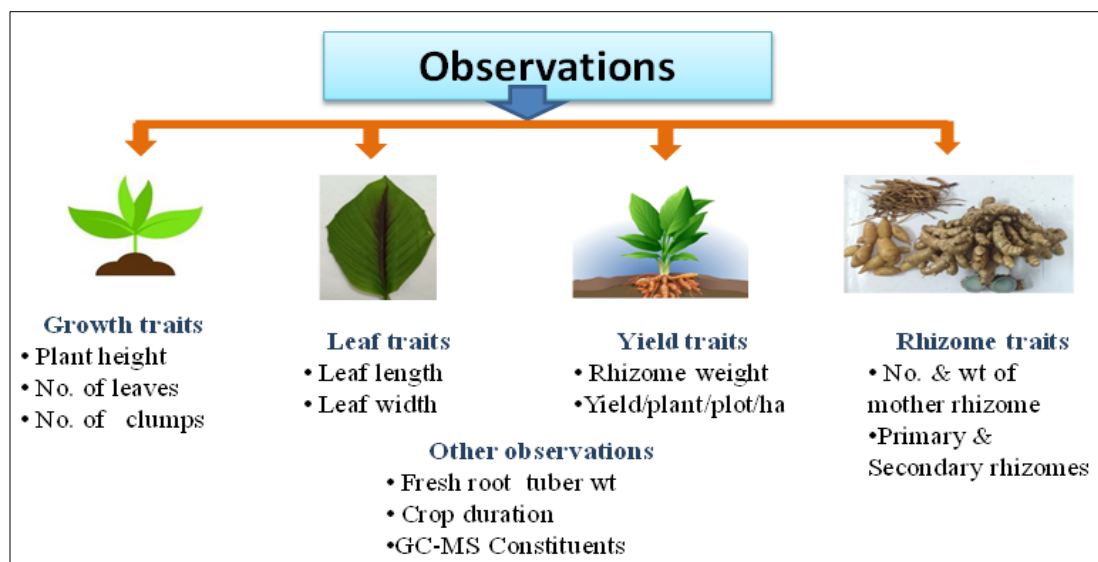


Fig 1: Schematic representation of growth, yield, rhizome, and quality traits recorded in black turmeric (*Curcuma caesia* Roxb.)

Results and Discussion

The observation on growth revealed that there is a significant difference among the spacing and nutrient level on plant growth characters of black turmeric at 210 DAS (Table 1). Tallest plants were observed in S_3 (45 cm X 45 cm) spacing (80.00 cm) followed by S_1 (45 cm x 30 cm) (74.39 cm), least plant height was observed with closer spacing S_2 (30 cm x 30 cm) (73.97 cm). Similar trends was observed with number of leaves per plant (10.32) and number of clumps per plant (3.39) because at lower spacing there is a competition for nutrient, light and moisture availability to the plants, leads stress to the plant.

Spacing has a significant impact on vegetative growth of black turmeric, S_1 : 45 cm x 30 cm level had stable higher number of leaves (11.44) and number of clumps (3.63) and reduction in the number of leaves and number of clumps at lower spacing (S_2 : 30 cm x 30 cm). S_3 : 45 cm x 45 cm

spacing is on par with S_1 , similar results were reported by Sharif and Ismail (2017)^[22] in turmeric.

Number of clumps per plant was significantly differed by different spacing. The plant density has marked influence on the capacity of plants to utilize nutrients and environmental factors in building up of the plant tissues through regulation of absorption capacity of plants due to better utilization of resources and lesser plant to plant competition. Hence, the widely spaced plant produced the greater number of clumps compared to close spacing. In case of wider spacing there was less competition among the plants resulting in greater horizontal spread. This is in agreement with the findings of Mogle (1999), Kelaskar *et al.*, (2020)^[23] in Turmeric.

The sub plot data clearly indicates that increasing the nutrient application from N1 to N4 level increases the vegetative growth, which is evident with plant height, number of leaves and number of clumps per plant at both the season.

Table 1: Effect of different spacing and nutrient level on plant growth characters of black turmeric at 210 DAS.

Treatments	Plant height (cm) @ 210 DAS			Number of leaves per plant @ 210 DAS			Number of clumps per plant @ 210 DAS		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Main plot									
S_1	73.65	75.15	74.39	11.45	11.44	11.44	3.49	3.76	3.63
S_2	75.88	72.05	73.97	10.29	10.35	10.32	3.44	3.33	3.39
S_3	79.38	80.63	80.00	10.96	11.44	11.20	2.96	4.14	3.55
SEM	1.05	1.55	1.02	0.19	0.24	0.16	0.12	0.12	0.05
CD@5%	4.11	6.07	4.00	0.75	0.94	0.63	0.48	0.47	0.18
Sub plot									
N1	64.11	61.34	62.72	8.93	7.93	8.43	2.20	2.49	2.35
N2	71.55	70.81	71.18	10.06	9.94	10.00	2.84	3.43	3.12
N3	83.66	83.54	83.61	11.50	12.70	12.10	3.95	4.41	4.18
N4	85.88	88.08	86.98	13.11	13.71	13.41	4.22	4.66	4.44
SEM	2.17	1.64	1.75	0.36	0.55	0.32	0.10	0.19	0.09
CD@5%	6.44	4.87	5.20	1.06	1.63	0.94	0.29	0.55	0.28
Interaction S X N									
S_1 N1	57.94	56.60	57.26	8.85	8.18	8.51	2.08	2.51	2.30
S_1 N2	68.63	71.63	70.13	10.02	9.16	9.59	3.00	3.51	3.26
S_1 N3	84.31	84.01	84.16	13.24	13.78	13.51	4.22	4.38	4.30
S_1 N4	83.69	88.38	86.04	13.68	14.63	14.15	4.66	4.65	4.66
S_2 N1	65.68	60.65	63.16	8.37	7.30	7.83	2.36	2.18	2.27
S_2 N2	76.94	69.31	73.12	9.48	9.75	9.62	2.71	2.88	2.79
S_2 N3	77.85	75.54	76.71	10.68	11.50	11.09	4.30	4.05	4.18
S_2 N4	83.08	82.71	82.90	12.65	12.83	12.74	4.40	4.23	4.32
S_3 N1	68.71	66.77	67.74	9.57	8.33	8.95	2.17	2.79	2.48

S ₃ N ₂	69.10	71.50	70.30	10.69	10.91	10.80	2.73	3.88	3.31
S ₃ N ₃	88.84	90.09	89.96	10.60	12.83	11.71	3.33	4.80	4.07
S ₃ N ₄	90.86	93.16	92.01	13.01	13.68	13.34	3.60	5.10	4.35
Total	915.66	911.38	913.52	130.86	132.91	131.87	39.59	45.00	42.32
Mean	76.30	75.94	76.12	10.91	11.07	10.98	3.29	3.75	3.52
SEM	3.41	2.90	2.82	0.57	0.86	0.50	0.19	0.30	0.15
CD@5%	10.14	8.63	8.37	1.68	2.55	1.49	0.57	0.90	0.44
CV (%)	8.52	6.47	6.90	9.78	14.87	8.65	8.87	14.82	7.94

Higher level of nutrient application (N₄-125%) favoured the luxuriant plant growth of black turmeric. Highest plant height (86.98 cm), more number of leaves (13.71) and more number of clumps (4.44) was evident at N₄ level. It clearly shows that black turmeric is a heavy feeder, requires good amount of nutrients for the better vegetative growth.

The interaction clearly shows the significant influence of spacing and nutrient levels on vegetative growth. Tallest plant height (90.86 cm, 93.16 cm and 92.01 cm) was recorded in S₃N₄ (45 cm x 45 cm and 125% NPK) treatment, while the minimum (57.94 cm, 56.60 cm and 57.26 cm) was observed in S₁ N₁ (45 cm x 30 cm and no NPK). Similar trend was observed with Number of leaves per plant and Number of clumps per plant @ 210 DAS also. The interaction clearly shows that irrespective of spacing more number of leaves and more number of clumps per plant @ 210 DAS was observed in higher nutrient i.e., S₁ N₄, S₂N₄ and S₃N₄ levels. This clearly indicates that application of higher nutrient level promotes luxuriant vegetative growth at different level of spacing. The present findings were in accordance with the findings of Khedkar *et al* (2023); Modupeole *et al* (2021); Nautial *et al* (2016) in turmeric.

Table 2 shows that, there is a significant difference among the different level of spacing and nutrient on plant diameter of black turmeric at 210 DAS. S₁: 45 cm x 30 cm had highest plant diameter (10.37 cm, 10.06 cm and 10.21 cm) followed by S₃: 45 cm x 45 cm (9.82 cm, 10.32 cm and 10.07 cm). While S₂ (30 cm x 30 cm) had consistently lower plant diameter (8.91 cm; 9.29 cm and 9.10 cm). N₁ had very low plant spread (7.79 cm, 7.73 cm and 7.76 cm) while N₄ had the maximum (11.48 cm, 11.60 cm and 11.54 cm)

followed by N₃ nutrient level. This clearly shows that increasing the nutrient improves the plant diameter.

Leaf characters revealed that the leaf length and width were significantly influenced by spacing and nutrient levels. The highest leaf length (49.84 cm) was recorded in S₃ and N₄ nutrient levels (54.08 cm). In both the years the highest leaf length was recorded at wider spacing and higher nutrient level which was superior over other spacing and nutrient levels. There is a close relationship with planting density, nutrient availability and growth of the plant, under wider spacing availability of more nutrients, moisture, space and better interception of sunlight within the plant canopy than the closely spaced plant hence, wide spaced plants have produced maximum leaf length as compared to other spacing. Combined effect of spacing and nutrients variations significantly influenced the leaf length, Similar trend is observed with leaf width characters also in both the seasons (Table 2).

The interaction effect showed significant effect on plant diameter, leaf length and leaf width. The treatment combination of S₃N₄ was found significantly superior over rest of the treatment combinations and recorded the highest plant diameter (12.33 cm), Leaf length (59.82 cm) and leaf width (11.75), where as the minimum was observed in S₂ N₁ (7.61 cm; 30.43 cm & 7.43 cm respectively). Under wider spacing plants absorbs the sufficient resources and increased their photosynthetic efficiency that further increased the vegetative growth and ultimately increased leaf length and width. The findings agreed with Manjunathgoud *et al.*, (2002)^[27]; Kelaskar *et al.*, (2020)^[23] in turmeric.

Table 2: Effect of different spacing and nutrient level on plant diameter and leaf characters of black turmeric.

Treatments	Plant diameter (cm) @ 210 DAS			Leaf length (cm) @ 210 DAS			Leaf width (cm) @ 210 DAS		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Main plot									
S ₁	10.37	10.06	10.21	45.90	45.85	45.87	9.84	9.67	9.75
S ₂	8.91	9.29	9.10	39.15	39.24	39.19	9.00	9.02	9.01
S ₃	9.82	10.32	10.07	50.32	49.36	49.84	10.22	10.28	10.24
SEM	0.20	0.16	0.16	0.77	0.70	0.68	0.30	0.28	0.28
CD@5%	0.77	0.65	0.64	3.01	2.74	2.65	1.18	1.08	1.10
Sub plot									
N ₁	7.79	7.73	7.76	34.96	35.31	35.13	7.49	7.35	7.42
N ₂	9.12	9.16	9.13	41.70	41.55	46.62	9.31	9.30	9.30
N ₃	10.40	11.07	10.73	49.23	48.85	49.04	10.78	10.88	10.83
N ₄	11.48	11.60	11.54	54.59	53.57	54.08	11.16	11.10	11.13
SEM	0.20	0.20	0.17	0.98	1.12	1.01	0.20	0.29	0.23
CD@5%	0.59	0.59	0.51	2.91	3.33	2.99	0.61	0.86	0.69
Interaction S X N									
S ₁ N ₁	8.25	7.71	7.98	36.34	36.80	36.57	7.82	7.58	7.69
S ₁ N ₂	9.80	9.50	9.64	42.11	42.35	42.23	9.03	8.86	8.94
S ₁ N ₃	11.08	11.35	11.21	48.16	47.96	48.06	10.99	11.01	11.00
S ₁ N ₄	12.35	11.67	12.01	56.98	56.31	56.64	11.53	11.25	11.39
S ₂ N ₁	7.51	7.73	7.61	30.11	30.75	30.43	7.29	7.58	7.43
S ₂ N ₂	8.12	8.61	8.36	37.62	38.80	38.20	8.64	8.48	8.56

S ₂ N ₃	9.93	10.33	10.13	42.56	42.18	42.37	9.80	9.78	9.79
S ₂ N ₄	10.07	10.50	10.29	46.32	45.25	45.78	10.27	10.25	10.25
S ₃ N ₁	7.62	7.75	7.68	38.44	38.38	38.41	7.36	6.90	7.13
S ₃ N ₂	9.43	9.37	9.40	45.38	43.50	44.44	10.26	10.55	10.40
S ₃ N ₃	10.19	11.55	10.86	56.99	56.41	56.70	11.55	11.86	11.70
S ₃ N ₄	12.03	12.63	12.33	60.49	59.15	59.82	11.70	11.81	11.75
Total	116.42	118.73	117.54	541.53	537.86	539.67	116.28	115.95	116.08
Mean	9.70	9.89	9.79	45.13	44.82	44.97	9.69	9.66	9.68
SEM	0.36	0.34	0.30	1.66	1.82	1.65	0.43	0.52	0.45
CD@5%	1.06	1.01	0.90	4.93	5.40	4.91	1.27	1.53	1.33
CV (%)	6.10	6.02	5.23	6.51	7.49	6.71	6.33	9.01	7.17

Black turmeric whole rhizome consists of rhizome, root tubers along with roots. All the parts has commercial importance, but more emphasis on rhizome production, it may influenced by spacing and nutrient availability. There is a significant difference for the production of whole rhizome at different level of spacing and nutrients. The wider spacing (S₃) had highest whole rhizome production (757.16g; 739.91g & 748.53g at 2023, 2024 & pooled respectively), followed by S₁ (747.07g; 749.19g & 748.13g at 2023, 2024 & pooled respectively). At lower spacing S₂: 30 cmx 30 cm restrict rhizome growth at underground was evident in both the years (689.44g; 691.90g & 690.67g at 2023, 2024 & pooled respectively).

At different nutrient levels N₄ had maximum rhizome weight per plant (757.06g; 771.45g & 749.98g) and lowest was recorded in N₂ (687.21g; 6692.58g & 674.89g). This clearly shows that for rhizome development sufficient nutrient supply is required. The correlation data clearly denotes that optimum spacing with high level of nutrient favours the rhizome growth and development in black turmeric. The treatment combination S₁ N₄ was found significantly superior over rest of the treatment combinations and recorded the highest Whole rhizome weight (837.32g; 842.28g and 839.80g respectively) per plant, whereas the minimum was observed in S₂ N₂ (633.62; 640.13 and 636.87g respectively).

Production of rhizome is one of the economic trait is majorly influenced by the spacing and nutrients in black turmeric, Table 3 clearly shows the significant differences among the treatments for rhizome yield per plant (g). The spacing S₁ has highest rhizome yield per plant (280.62g; 307.49g & 294.05g at 2023, 2024 & pooled respectively) followed by S₃. Sherif and Ismail (2017) ^[22] confirms the

effect of spacing on yield in turmeric. At different nutrient levels N₃ had maximum rhizome yield per plant (423.32g; 437.31g and 430.32g respectively) and lowest was recorded in N₁ level. N₃: 25t FYM +100% NPK (150:125:250kg/ha) has influence on the rhizome yield per plant production, it clearly shows that application of optimum nutrient levels reduces the production of root tubers and improves the rhizome production. The treatment combination S₁ N₃ was found significantly superior over rest of the treatment combinations and recorded the highest rhizome yield per plant (441.76g; 458.44g and 450.10g respectively), and least was recorded in S₂ N₁ (125.03g, 130.12g and 128.25g respectively). High amount of nutrition and optimum population which favours the accumulation of more substrates and good rhizome development. The findings are in line with the findings of Khedkar *et al* (2023) in turmeric. Production of root tubers is the common feature of rhizomatous crops, in black turmeric root tubers are one of the major feature, whether that can be influenced by different spacing and nutrient supplement is studied here, the data clearly indicate that (Table 3) root tuber production is significantly influenced by spacing and availability of nutrients. The spacing S₃ had highest root tuber production (489.04g; 484.34g & 486.69g at 2023, 2024 & pooled respectively) followed by S₂. At different nutrient levels N₁ had maximum root tubers per plant (601.38g; 591.92g and 585.54g respectively) and lowest was recorded in N₃ followed by N₄ levels. N₃: 25t FYM +100% NPK(150:125:250kg/ha) has influence on the root tuber production, lowest level of root tubers production is evident at N₃ level (345.45g; 339.73g and 345.81g respectively), clearly shows that application of optimum nutrients reduces the root tuber production.

Table 3: Effect of different spacing and nutrient level on rhizome yield characters of black turmeric.

Treatments	Whole rhizome weight per plant (g)			Root tuber weight per plant (g)			Rhizome Yield per plant (g)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Main plot									
S ₁	747.07	749.19	748.13	442.24	435.06	432.73	280.62	307.49	294.05
S ₂	689.44	691.90	690.67	437.88	439.53	438.70	259.89	277.67	268.78
S ₃	757.16	739.91	748.53	489.04	484.34	486.69	276.45	302.33	289.39
SEM	14.00	12.75	11.98	12.53	13.13	12.35	5.13	5.79	9.88
CD@5%	54.97	50.06	46.94	49.20	51.57	48.49	20.13	22.72	38.79
Sub plot									
N ₁	752.11	673.20	715.13	601.38	591.92	585.54	134.11	156.01	145.06
N ₂	687.21	662.58	674.89	490.09	486.00	488.04	197.12	229.88	256.52
N ₃	728.51	800.77	776.44	345.45	339.73	345.81	423.32	437.31	430.32
N ₄	757.06	771.45	749.98	388.62	394.26	391.44	334.73	360.10	347.42
SEM	20.70	15.19	15.02	19.31	20.62	19.44	7.22	10.18	11.95
CD@5%	61.50	45.14	44.62	57.36	61.26	57.75	21.45	30.25	35.49
Interaction S X N									
S ₁ N ₁	739.94	685.19	761.26	622.57	592.23	574.07	150.07	171.69	160.88
S ₁ N ₂	651.95	657.21	654.57	439.68	436.16	437.92	212.26	258.82	235.54

S ₁ N ₃	759.07	812.10	776.02	281.51	282.91	291.88	441.76	458.44	450.10
S ₁ N ₄	837.32	842.28	839.80	425.20	428.95	427.07	318.39	341.01	329.70
S ₂ N ₁	722.00	658.18	673.23	563.25	568.96	566.10	125.03	130.12	128.25
S ₂ N ₂	633.62	640.13	636.87	446.69	446.28	446.48	186.93	225.43	206.18
S ₂ N ₃	713.87	747.07	734.53	353.32	349.30	351.31	402.00	411.26	406.63
S ₂ N ₄	688.28	722.21	718.04	388.25	393.57	390.91	325.62	348.95	337.29
S ₃ N ₁	794.39	676.25	710.91	618.33	614.58	616.45	127.25	171.33	149.29
S ₃ N ₂	776.07	690.40	733.23	583.90	575.55	579.73	192.17	205.41	327.85
S ₃ N ₃	712.60	843.16	818.78	401.54	386.98	394.26	426.19	442.24	434.21
S ₃ N ₄	745.58	749.85	731.22	352.41	360.25	356.33	360.19	390.33	375.26
Total	8774.75	8724.05	8749.3	5476.7	5435.7	5432.5	3267.8	3549.9	3538.0
Mean	731.22	727.00	729.11	456.39	452.98	452.71	272.32	295.83	294.83
SEM	34.06	26.11	25.50	31.55	33.60	31.66	11.98	16.33	20.46
CD@5%	101.20	77.59	75.77	93.75	99.84	94.07	35.60	48.52	60.79
CV (%)	8.49	6.27	6.18	12.69	13.66	12.88	7.95	10.32	12.15

The treatment combination S₃ N₁ was found significantly superior over rest of the treatment combinations and recorded the highest root tubers per plant (618.33g; 614.58g and 616.45g respectively), and least was recorded in S₁ N₃ (281.51g; 282.91g and 291.88g respectively). In this we can

clearly infer that by providing optimum spacing (45 cmX30 cm) and nutrients (25t FYM +100% NPK (150:125:250kg/ha)) the production root tubers can be significantly reduce and improves the rhizome yield per plant.

Table 4: Effect of different spacing and nutrient level on rhizome yield per plot and per hectare of black turmeric.

Treatments	Rhizome Yield per plot (kg)			Rhizome Yield per hectare (t)			Duration (Days)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Main plot									
S ₁	4.66	4.94	4.80	8.09	8.57	8.33	-	-	-
S ₂	3.07	3.74	3.41	5.34	6.52	5.92	-	-	-
S ₃	4.28	4.88	4.58	7.42	8.73	8.07	-	-	-
SEM	0.14	0.07	0.10	0.24	0.22	0.23	-	-	-
CD@5%	0.55	0.26	0.39	0.96	0.85	0.90	-	-	-
Sub plot									
N ₁	2.01	2.57	2.29	3.49	4.49	3.98	-	-	-
N ₂	3.71	3.97	3.84	6.44	7.24	6.84	-	-	-
N ₃	5.40	5.94	5.67	9.37	10.32	9.84	-	-	-
N ₄	4.89	5.60	5.25	8.49	9.72	9.10	-	-	-
SEM	0.10	0.12	0.09	0.17	0.26	0.17	-	-	-
CD@5%	0.29	0.36	0.27	0.50	0.76	0.51	-	-	-
Interaction S X N									
S ₁ N ₁	2.33	2.61	2.47	4.04	4.54	4.29	255	255	255
S ₁ N ₂	4.01	4.23	4.12	6.97	7.34	7.15	265	265	265
S ₁ N ₃	6.14	6.59	6.37	10.66	11.43	11.05	265	265	265
S ₁ N ₄	6.15	6.33	6.24	10.67	10.99	10.83	265	265	265
S ₂ N ₁	1.85	2.36	2.11	3.21	4.18	3.69	255	255	255
S ₂ N ₂	3.00	3.26	3.13	5.21	5.66	5.43	265	265	265
S ₂ N ₃	4.28	5.00	4.64	7.44	8.68	8.05	265	265	265
S ₂ N ₄	3.17	4.34	3.76	5.50	7.54	6.52	265	265	265
S ₃ N ₁	1.85	2.73	2.29	3.21	4.74	3.97	255	255	255
S ₃ N ₂	4.12	4.44	4.28	7.16	8.72	7.94	265	265	265
S ₃ N ₃	5.77	6.24	6.00	10.01	10.83	10.42	265	265	265
S ₃ N ₄	5.36	6.12	5.74	9.30	10.63	9.96	265	265	265
Total	48.06	54.29	51.20	83.42	95.33	89.34	-	-	-
Mean	4.00	4.52	4.26	6.95	7.94	7.44	-	-	-
SEM	0.20	0.19	0.17	0.35	0.44	0.35	-	-	-
CD@5%	0.60	0.58	0.50	1.05	1.32	1.03	-	-	-
CV (%)	7.29	8.12	6.43	7.29	9.72	6.97	-	-	-

There is a significant difference among the treatments for rhizome yield of black turmeric at different spacing and nutrients levels (Table 4). The spacing S₁ has highest rhizome yield per plot (4.66kg; 4.94kg & 4.80kg at 2023, 2024 & pooled respectively) and per hectare (8.09 t; 8.57 t & 8.33 t at 2023, 2024 & pooled respectively) followed by S₃. At different nutrient levels N₃ had maximum rhizome yield per plot (5.40 kg; 5.94 kg and 5.67 kg respectively) and lowest was recorded in N₁ level. N₃: 25t FYM +100% NPK (150:125:250kg/ha) has influence on the rhizome yield production, the treatment combination S₁ N₃ was found

significantly superior over rest of the treatment combinations and recorded the highest rhizome yield per pot (6.14 kg; 6.59 kg and 6.37 kg respectively) and yield per hectare (10.66 t; 11.43 t and 11.05 t respectively), and least was recorded in S₂ N₁ (1.85 kg, 2.36 kg and 2.11 kg per plot and 3.21 t; 4.18t & 3.69 t per ha respectively). Spacing is an important factor in crop production as it affects plant photosynthetic activities and competition for light and water and eventual plant performance (Pratap and Singh, 2007). At low nutrient level yield declines, neither wider spacing nor closer spacing supported high yield, optimum spacing

favours the production. Present study is evident that closer spacing is not suitable (30x30 cm) as recorded low yield, however yield decline after 45x30 cm spacing, similar trend is also observed with the nutrients level also. This indicated that increase in nutrient levels does not necessarily translate to higher yield, as higher nutrient rates can lead to reduction in crop performance due to toxification of soil and luxury consumptions by plants (Futules and Bagale, 2008).

The duration of the crop is not having any significant differences; crop is completed by 265 days duration (Table 4), irrespective of the spacing harvesting is done at 265 days after sowing. With respect to nutrient levels, N1 level crop is completed within 255 days due to non availability of sufficient nutrients to the crop growth, which is compromised at growth and rhizome yield levels.

The rhizome characters like number and weight of mother rhizome, primary rhizome and secondary rhizomes were analyzed for different spacing and nutrient requirements. The results clearly show that there is a significant difference among the different level of spacing and nutrient applications on rhizomes characters (Table 5a).

The trend on higher number of mother rhizome, primary rhizomes and secondary rhizomes was recorded in wider spacing (S_1 and S_3). With respect to nutrients levels N3 and N4 had recorded more number of rhizomes in both the season.

The S_3 spacing had highest number of mother rhizomes per plant (4.59) and secondary rhizomes per plant (3.41). S_1 had more number of Primary rhizomes per plant (4.73). Lower spacing S_2 had minimum number of mother and primary rhizomes per plant (3.87 and 4.18 respectively).

Table 5a: Effect of different spacing and nutrient level on rhizome characters of black turmeric.

Treatments	Number of mother rhizome per plant			Number of primary rhizome per plant			Number of secondary rhizome per plant		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Main plot									
S ₁	4.24	4.23	4.24	4.73	4.71	4.73	2.71	2.65	2.68
S ₂	3.86	3.88	3.87	4.15	4.22	4.18	2.99	3.06	3.02
S ₃	4.59	4.59	4.59	4.48	4.54	4.51	3.37	3.45	3.41
SEM	0.15	0.15	0.15	0.14	0.11	0.13	0.08	0.08	0.08
CD@5%	0.59	0.61	0.60	0.55	0.45	0.50	0.31	0.33	0.31
Sub plot									
N1	2.79	2.84	2.82	2.33	2.39	2.36	1.91	2.00	1.95
N2	3.71	3.71	3.71	4.01	4.03	4.02	2.63	2.66	2.65
N3	5.35	5.32	5.34	5.65	5.71	5.69	3.97	3.96	3.97
N4	5.06	5.07	5.07	5.82	5.84	5.83	3.57	3.60	3.59
SEM	0.12	0.12	0.12	0.11	0.13	0.12	0.11	0.10	0.10
CD@5%	0.36	0.36	0.36	0.34	0.38	0.36	0.32	0.29	0.30
Interaction S X N									
S ₁ N1	2.81	2.86	2.84	2.46	2.48	2.47	1.89	1.92	1.91
S ₁ N2	3.51	3.48	3.50	4.30	4.21	4.26	2.30	2.26	2.29
S ₁ N3	5.60	5.60	5.60	6.20	6.53	6.22	3.75	3.51	3.63
S ₁ N4	5.03	5.00	5.01	5.97	5.99	5.98	2.89	2.91	2.91
S ₂ N1	2.52	2.55	2.53	2.40	2.51	2.46	1.82	1.96	1.89
S ₂ N2	3.17	3.25	3.21	3.45	3.55	3.50	2.60	2.67	2.63
S ₂ N3	5.09	5.08	5.08	4.82	4.90	4.86	4.08	4.14	4.44
S ₂ N4	4.66	4.66	4.66	5.92	5.90	5.91	3.46	3.46	3.46
S ₃ N1	3.05	3.12	3.08	2.11	2.19	2.15	2.02	2.11	2.07
S ₃ N2	4.45	4.40	4.42	4.30	4.33	4.32	3.00	3.05	3.02
S ₃ N3	5.38	5.30	5.34	5.95	6.01	5.98	4.10	4.21	4.16
S ₃ N4	5.50	5.55	5.53	5.57	5.65	5.61	4.37	4.43	4.40
Total	50.81	50.87	50.85	53.48	53.99	53.76	36.30	36.69	36.52
Mean	4.23	4.24	4.23	4.46	4.49	4.48	3.02	3.05	3.04
SEM	0.23	0.24	0.24	0.22	0.22	0.22	0.18	0.17	0.17
CD@5%	0.70	0.71	0.70	0.65	0.66	0.65	0.54	0.50	0.51
CV (%)	8.50	8.61	8.48	7.61	8.49	8.02	10.77	9.61	9.87

The treatment combination S₁ N3 was found significantly superior over rest of the treatment combinations and recorded the highest number of mother rhizome per plant (5.60) and primary rhizome per plant (6.22). Whereas the minimum was observed in S₂ N1 (2.53; 2.46 and 1.89 respectively).

Table 5b clearly gives an insight that spacing and nutrient management is more important for rhizome characters like mother rhizome weight, primary rhizome weight and weight of the secondary rhizomes. There is a significant difference among the treatments for different spacing and nutrients levels.

Table 5b: Effect of different spacing and nutrient level on rhizome characters of black turmeric.

Treatments	Weight of mother rhizome (g/pl)			Weight of primary rhizome (g/pl)			Weight of secondary rhizome (g/pl)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
Main plot									
S ₁	131.39	137.85	134.61	128.72	143.41	136.09	20.55	24.59	22.57
S ₂	121.14	124.49	122.81	120.33	131.04	125.68	18.42	21.85	20.13
S ₃	131.52	139.03	135.27	124.36	133.37	128.86	20.56	23.09	21.82
SEM	2.52	2.95	2.36	1.99	1.85	1.53	0.86	1.51	0.73
CD@5%	9.88	11.57	9.25	7.82	7.28	6.00	3.39	5.95	2.88
Sub plot									
N1	64.04	66.02	65.03	59.48	66.33	62.91	10.58	11.34	10.96
N2	92.53	95.30	93.91	89.71	109.45	99.58	14.93	22.24	18.58
N3	199.04	210.41	204.72	193.09	198.98	196.07	31.17	29.29	30.23
N4	156.45	163.43	159.94	155.59	168.99	162.29	22.69	29.84	26.26
SEM	3.60	4.40	3.81	3.29	4.52	3.32	1.07	1.42	1.10
CD@5%	10.70	13.07	11.33	9.77	13.43	9.88	3.17	4.21	3.26
Interaction S X N									
S ₁ N1	70.86	75.66	73.26	67.72	77.53	72.62	11.47	10.68	11.07
S ₁ N2	100.09	105.15	102.62	97.43	124.58	111.00	14.90	21.26	19.58
S ₁ N3	208.29	223.50	215.89	199.93	206.05	203.09	33.54	32.22	32.88
S ₁ N4	146.31	147.08	146.69	149.80	165.47	157.64	22.28	31.22	26.75
S ₂ N1	57.13	52.18	54.65	56.42	59.35	57.89	11.47	12.16	11.81
S ₂ N2	86.52	87.83	87.17	86.65	110.65	98.65	13.75	20.92	17.33
S ₂ N3	188.54	203.80	196.17	188.09	187.87	187.98	25.37	26.80	26.08

S ₂ N ₄	152.37	154.15	153.25	150.15	166.29	158.22	23.09	27.53	25.31
S ₃ N ₁	64.13	70.22	67.17	54.31	62.12	58.22	8.80	11.19	9.99
S ₃ N ₂	90.98	92.91	91.94	85.05	93.11	89.08	16.14	21.54	18.83
S ₃ N ₃	200.30	203.92	202.11	191.26	203.03	197.14	34.62	28.86	31.74
S ₃ N ₄	170.67	189.08	179.87	166.81	175.21	171.01	22.70	30.78	26.74
Total	1536.22	1605.51	1570.85	1493.68	1631.31	1562.58	238.16	278.18	258.14
Mean	128.01	133.79	130.90	124.47	135.94	130.21	19.85	23.18	21.51
SEM	5.96	7.23	6.19	5.32	7.03	5.21	1.82	2.61	1.80
CD@5%	17.71	21.47	18.38	15.80	20.88	15.49	5.41	7.76	5.36
CV (%)	8.44	9.87	8.74	7.93	9.97	7.66	16.14	18.34	15.32

The data reveals that the spacing of 45 cmX30 cm is ideal for rhizome characters, as maximum weight of mother rhizomes (134.61g), primary rhizome (136.09g) and secondary rhizome (22.57g) was observed at S₁ level, which is followed by S₃. The data clearly denotes that as the nutrient level increases the yield/weight of the mother, primary and secondary rhizomes also improves in both the season. It indicates the nutrient responsiveness of the crop and possibilities of improving the yield levels. Still N₃ levels considered as best for as it recorded highest mother rhizome (204.72g), primary rhizome (196.07g) and secondary rhizome (30.23g) weight per plant. Least was observed in N₁ levels at both the season.

The treatment combination S₁ N₃ was found significantly superior over rest of the treatment combinations and recorded the highest weight of mother rhizome per plant

(215.89 g), primary rhizome (203.09 g) and secondary rhizome (32.88 g) weight. Whereas the minimum was observed in S₂ N₁ (54.65g and 57.89g at mother and primary rhizome weight per plant) and S₃ N₁ had very low secondary rhizome yield per plant (9.99g). this clearly shows the nutrient responsiveness of the crop.

The rhizomes mainly contains Epicurzerone, Curcumenol, 4,5 Epoxi germacrone and Zederone. The effect of different spacing and nutrient level on bio chemical profiling of black turmeric was studied (Table 6), shows that there is no much differences on the chemical constituent of the rhizomes. Wider spacing with high nutrient level (S₃N₃) favoured the Epicurzerone content (30.14%), the Curcumenol is high in S₁N₃ (21.73%) & S₂N₃ (23.23%), 4,5 Epoxygmacrone and Zederone are higher in S₁N₃ (31.24% & 9.86% respectively).

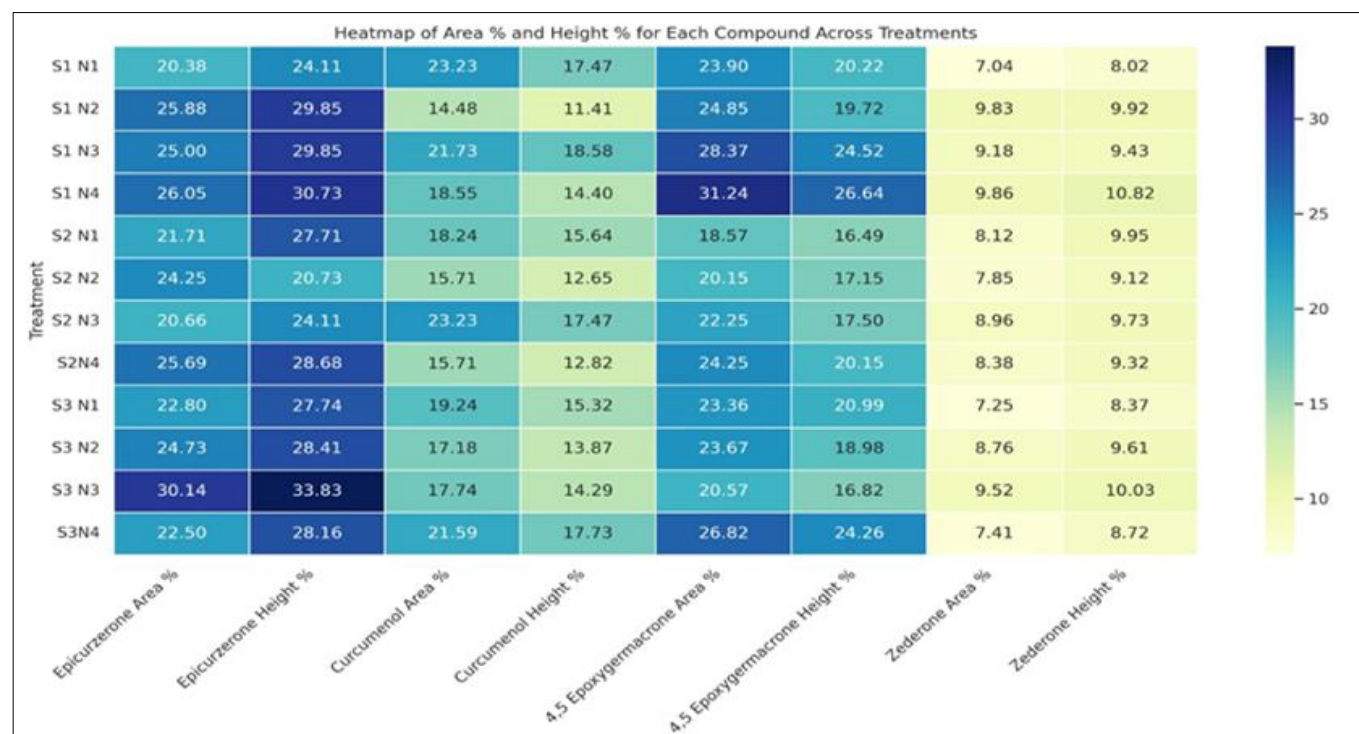


Fig 2: Heat map Area % and Height % for Each compound across Treatments

This clearly shows that the spacing of 45 cm X 30 cm and at 25t FYM +100% NPK(150:125:250kg/ha) nutrient level not only it gives higher yield but also the qualitative aspects of the rhizomes are at optimum level.

Conclusion

The present study demonstrated that crop geometry and nutrient management play a decisive role in enhancing the growth, yield, and rhizome quality of black turmeric (*Curcuma caesia* Roxb.). Among the tested treatments, a spacing of 45 cm × 30 cm combined with the application of

25 t FYM and 100% NPK (150:125:250 kg ha⁻¹) (S₁N₃) was found to be the most effective, producing superior rhizome yield and quality traits. While higher nutrient levels further promoted vegetative growth, they did not significantly enhance yield beyond the optimum level. The findings suggest that integrated nutrient management and appropriate plant spacing not only optimize productivity but also support the sustainable cultivation and conservation of this threatened medicinal species. Future research should focus on long-term soil health impacts, post-harvest quality, and

biochemical standardization of black turmeric under different agro-ecological conditions.

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