Indian Journal of Agroforestry 27(3): 73-80 (2025)

Evaluation of turmeric varieties under neem-based agroforestry system in the semi-arid region of Bundelkhand

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ABSTRACT: *This study evaluated the performance of five turmeric (Curcuma longa L.) varieties (C1–C5) under a neem-based agroforestry system in the semi-arid region of Bundelkhand across two growing seasons (2023–24 and 2024–25). The experiment compared two growing conditions, G1 (neem-based agroforestry) and G2 (open field) to assess their influence on growth, leaf area, and yield attributes. Results revealed that G1 consistently outperformed G2 in all measured parameters, likely due to a more favourable microclimate under neem shade. Variety C3 emerged as the top performer, recording the highest plant height, leaf area per plant (LAP), and rhizome yield per hectare (RYPH). In 2024–25, C3 under G1 achieved a maximum plant height of 174.50 cm at 170 DAS, LAP of 4958.60 cm², and RYPH of 15.272 t/ha, significantly surpassing other combinations. Statistical analysis confirmed highly significant differences among varieties and growing conditions for most traits. The study highlights strong genotype × environment interactions, with partial shade enhancing vegetative growth and rhizome productivity. These findings underscore the potential of integrating high-performing turmeric varieties like C3 with neem-based agroforestry systems as a sustainable approach to improve turmeric yield and quality in semi-arid regions.*

Research Article

ARTICLE INFO

Received: 02.04.2025

Accepted: 18.08.2025

Keywords:
*Neem based agroforestry,
Turmeric,
Intercropping,
Yield*

1. INTRODUCTION

The region of Bundelkhand is a treasure trove of traditional knowledge based on trees. It is situated in the country's heartland and has tremendous potential that can be realised through an all-encompassing planning approach. The area, which consists of 14 districts in Uttar Pradesh (seven) and Madhya Pradesh (seven), is rich in tree species, with many farmers, local tribes and landless labourers relying on them for their livelihood. Approximately 17.62% of the region's total geographic area, or 1.24 million hectares, is covered by forest. 6.72% of the total geographic area in the UP region of Bundelkhand and 25.41% in the MP region is covered by forest (Chavan *et al.*, 2016). Poor people in Bundelkhand have relied heavily on the forest for their daily sustenance.Despite its ecological wealth, Bundelkhand remains one of India's most underdeveloped and economically fragile regions. The area is characterized by erratic rainfall, poor irrigation infrastructure, highly eroded and low fertility soils, and a rugged topography. These challenges result in frequent droughts and recurring crop failures, making agriculture an unreliable livelihood source for the majority of the population (Gupta *et al.*, 2014; Sharma, 2023).

To enhance resilience and income diversification, agroforestry has emerged as a sustainable landuse strategy in Bundelkhand. The Central Agroforestry Research Institute (CAFRI), Jhansi, has developed multiple agroforestry models tailored to this region, such as bamboo-based agri-silviculture, shisham-based silvi-pastoral systems, and aonla-based agri-horticultural combinations. However, a key limitation of these models is the decline in crop yields as tree canopies mature and cast increasing shade after 4–5 years.One promising solution is the introduction of shade-tolerant, high-value crops like turmeric (*Curcuma longa* L.), which can thrive under moderate canopy conditions and offer improved economic returns to farmers. Turmeric, a member of the Zingiberaceae family, is an industrially important crop with rising global demand owing to its multifaceted applications in the food, cosmetic, dye, and pharmaceutical sectors (Singh *et al.*, 2012). The primary bioactive compound, curcumin, is renowned for its antioxidant, anti-inflammatory, antitumor, and antimicrobial properties (Deogade and Ghate, 2015). However, curcumin is sensitive to light and degrades

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under direct sunlight, which may reduce its quality during open-field cultivation (Priyadarsini, 2009).

Intercropping turmeric with shade providing species has been found to be beneficial in various agroecological zones. In some studies, intercropped turmeric produced higher fresh rhizome yield than monocropping due to moderated microclimate and reduced light stress, although contradictory results have also been reported depending on species and canopy density (Kittur *et al.*, 2016). These findings underline the need to study specific tree-crop interactions to identify the most compatible systems. Neem (*Azadirachta indica* A. Juss), a fast-growing, multipurpose species from the Meliaceae family, offers immense potential as an agroforestry tree in semi-arid regions. Known for its medicinal, pesticidal, and industrial uses, neem thrives in low-rainfall areas and has been an integral part of Indian agricultural systems since the Vedic era. The current demand for neem-based products especially neem oil for urea coating has positioned the industry at a value of nearly US$ 50 million in India, with a requirement of approximately 23 million mature neem trees annually (Chatterjee *et al.*, 2023). Despite its widespread use, limited scientific attention has been given to the performance of intercrops like turmeric under neem-based agroforestry systems.

Given this background, the present investigation was designed to evaluate the growth and yield performance of different turmeric varieties under neem-based agroforestry system in the semi-arid region of Bundelkhand. The study also aims to assess the interaction between microclimatic changes induced by neem canopy and varietal response in turmeric.

2. MATERIALS AND METHODS

The study was conducted during two years 2023-2024 and 2024–2025 seasons at the Department of Silviculture & Agroforestry, Rani Lakshmi Bai Central Agricultural University, Jhansi, India, located in the semi-arid region of Bundelkhand, India. The region falls under a hot semi-arid climate characterized by extreme temperature fluctuations and erratic rainfall. The site is located at 25.31°N latitude, 78.33°E longitude, and 285 m above mean sea level, with a sandy loam soil texture, variation in weather parameters during 2 years of study has been described in figure 1a and 1b. The region is primarily defined by two dominant soil types, red soil and black soil. The average annual rainfall of the region ranges between 800–1000 mm, mostly received during the monsoon months (June to September). The soil type of the experimental field was sandy loam with low organic carbon, medium phosphorus, and low nitrogen status, typical of Bundelkhand's degraded lands.

The experiment was laid in split plot design with 10 combination treatment and 3 replications. The main plot was assigned for the growing condition (G1: turmeric intercrops with 4 year old neem tree, G2: sole turmeric crop) and sub plot assigned to varieties (C1:NDH-3, C2: Pratibha, C3: NDH 98, C4: BSR202-1, C5:Azad haldi-1). Layout of an experimental field has been detailed in figure 2.

Turmeric was used for the intercropping trial under 4-year-old neem plantation. This is a tropical herb grown on different types of soil under irrigated and rainfed conditions. It is a shade tolerant crop with shallow roots suitable for intercropping where low to medium shade is available. In the present experiment five varieties of turmeric are planted under the block plantation of neem and in the adjacent open field to evaluate the performance of different turmeric varieties under neem and in open condition and to recommend the suitable varieties for the cultivation with the neem-based agroforestry in the Bundelkhand region. The field has been well prepared by performing ploughing after giving the irrigation.

All the required cultural practices have been performed during both years *i.e.* weeding, irrigation, application of recommended doses of fertilizers. planting of the turmeric has been done by following

A. Variation in weathers parameters during crop period (2023-24)

B. Variation in weathers parameters during crop period (2024-25)

Figure 1: Monthly trends in temperature, rainfall, and relative humidity during the experimental years

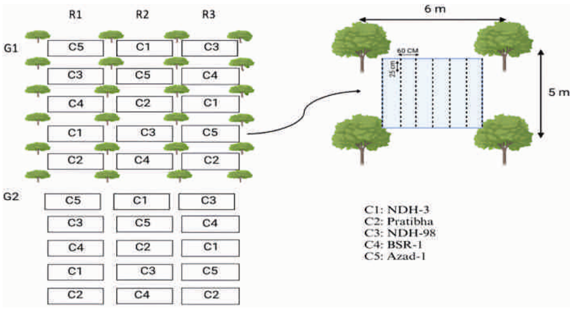

Figure 2: Layout of the experimental field

the ridge and furrow method of planting with spacing between the ridge in 60cm and plant to plant spacing in the line is 25 cm.

Standard agronomic practices were followed for all treatments. Land preparation involved deep ploughing, harrowing, and levelling. Well-decomposed FYM @ 25 t/ha was incorporated before sowing. Healthy, disease-free rhizomes were used for planting. Irrigation and weed management were done as per crop requirement. In neem-based agroforestry plots, care was taken to avoid root interference of neem trees with turmeric rows.

Major growth parameters of turmeric were measured to evaluate the performance of the turmeric varieties *i.e.* plant height, leaf area per plant, wight of mother rhizome per plant, weight of primary rhizome per plant, and rhizome yield per hectare. Plant height and leaf area per plant was taken at the interval of 45, 105, 170 days after planting. Plant height of turmeric was measured by measuring tape from base to the highest leaf tip of 10 randomly selected plants. Leaf area has been measured by the leaf area meter by plucking the leaf from the 3rd leaf from the base from 5 randomly selected plants. The other yield related parameters were collected after harvesting and thoroughly cleaning the rhizomes.

The collected data were subjected to analysis of variance (ANOVA) using appropriate statistical software by adopting split plot design as suggested by Panse and Sukhatme (1978). The significance of the treatments was tested through 'F' test at 5 per cent level of significance. The critical difference CD was calculated to assess the significance of difference among the different treatments. To test the significance of treatment, the calculated value of "F" was compared with tabular value of "F" at 5% level of probability against error degree of freedom.

3. RESULTS AND DISCUSSION

The plant height of turmeric was measured at three growth stages*i.e*45, 105, and 170 days after sowing (DAS)across two successive seasons, 2023–24 and 2024–25, under two different growing conditions (G1 and G2). The data showed that growing condition G1 consistently produced significantly taller plants than G2 at all stages and in both years. In 2023–24, plant height under G1 was 67.96 cm at 45 DAS, 114.62 cm at 105 DAS, and 135.24 cm at 170 DAS, compared to 45.65 cm, 78.30 cm, and 92.97 cm, respectively, under G2. Similar trends were observed in the following season, with G1 plants reaching 63.25 cm at 45 DAS, 130.34 cm at 105 DAS, and 148.42 cm at 170 DAS, which were all significantly higher than G2 heights of 49.12 cm, 108.59 cm, and 125.55 cm, respectively.Among the five turmeric varieties tested (C1, C2, C3, C4, and C5), variety C3 consistently exhibited superior plant height across all growth stages and seasons. In 2023–24, C3 attained 69.65 cm at 45 DAS, 112.80 cm at 105 DAS, and 131.34 cm at 170 DAS, noticeably taller than other varieties. By 2024–25, its height advantage became even more marked, with C3 reaching 76.73 cm at 45 DAS, 154.01 cm at 105 DAS, and a remarkable 173.86 cm at 170 DAS. Other varieties such as C1 and C5 showed consistently lower heights throughout the study period; for example, C1 reached only 47.78 cm at 45 DAS and 126.35 cm at 170 DAS in 2024–25, while C5 reached 53.19 cm and 120.87 cm at the corresponding stages as mentioned in table 2. The increment in hight growth (Figure 3) has been reported highest in C2 (Pratibha) during both the years, whereas, highest overall growth has been reported in C3 (NDH 98).

The interaction between growing condition and variety revealed that C3 under G1 achieved the greatest height at all stages. In 2023–24, G1 C3 plants were 79.75 cm at 45 DAS, 129.43 cm at 105 DAS, and 148.75 cm at 170 DAS. The following season showed an even stronger performance with G1 C3 plants reaching 87.35 cm, 159.84 cm, and 174.50 cm at the respective stages. While G2 C3 plants also performed well, they were slightly shorter—attaining 66.12 cm at 45 DAS and 173.23 cm at 170 DAS in 2024–25—demonstrating the inherent vigor of this variety as mentioned in table 3. Lesser-performing combinations, such as G2 C5 and G2 C1, consistently had the lowest plant heights at all stages.This aligns with research indicating that improved growth environments, such as greenhouse or shaded conditions, enhance leaf area, nutrient uptake, photosynthetic efficiency, and overall vegetative growth in turmeric, whereas stressors like radiation can impede growth and yield (Aydınşakir *et al.*, 2025)

This underscores the influence of genetic variation in turmeric, where genotype plays a critical role in determining growth attributes such as plant height, leaf area, and yield potential (Sagor *et al.*, 2021). The prominent performance of C3 under G1—with the highest heights recorded—emphasizes the importance of growing condition × genotype interactions. Such interactions are known to significantly modulate turmeric growth, confirming that optimal environmental conditions amplify the genetic potential of high-performing varieties (Madina *et al.*, 2024)

Leaf Area Per Plant (LAP)

The leaf area per plant (LAP) of turmeric showed significant variation among varieties and growing conditions across the two seasons studied. Generally, the LAP was higher under the G1 growing condition. In the 2023–24 season, LAP for G1 was recorded at 1319.81 cm^2, 5071.65 cm^2, and 3571.42 cm^2 at 45, 105, and 170 days after sowing (DAS), respectively, whereas under G2 these values were lower at 943.68 cm^2, 3735.61 cm^2, and 2841.01 cm^2 at the same stages. The 2024–25 season followed a similar pattern, with G1 recording LAP of 1489.06 cm^2, 5455.83 cm^2, and 4336.47 cm^2 at 45, 105, and 170 DAS respectively, again outperforming G2 (1316.43 cm^2, 3743.32 cm^2, and 4176.59 cm^2). This is strongly supported by recent research demonstrating that shaded or greenhouse conditions enhance turmeric's leaf area by improving nutrient uptake and photosynthetic efficiency while mitigating heat and radiation stress (Aydınşakir *et al.*, 2025), study of Sharangi (2022) indicates that turmeric performs best under partial shade (around 50%), which promotes optimal leaf area development and biomass accumulation.

Among the turmeric varieties, C3 exhibited the highest leaf area per plant consistently. In 2023–24, C3 reached a peak LAP of 1596.91 cm^2 at 45 DAS and 5291.03 cm^2 at 105 DAS, which remained relatively high at 3819.71 cm^2 at 170 DAS. In the following season, C3 again maintained the highest LAP with 1873.61 cm^2 at 45 DAS, 5304.84 cm^2 at 105 DAS, and 4958.60 cm^2 at 170 DAS as shown in table 4. Other varieties showed comparatively lower LAP values throughout the experiment, with C1 and C5 generally recording the lowest. The highest leaf area increment (Figure 4) has been recorded in C2 (Pratibha).The

Table 1: Effect of growing conditions and cultivar on plant height (cm) of turmeric plant.

	Plant height 2023-24			Plant height 2024-25		
Growing condition	**45 DAS**	**105 DAS**	**170 DAS**	**45 DAS**	**105 DAS**	**170 DAS**
G1	67.96[a]	114.62[a]	135.24[a]	63.25[a]	130.34[a]	148.42[a]
G2	45.65[b]	78.30[b]	92.97[b]	49.12[b]	108.59[b]	125.55[b]
CD 5%	6.46	5.31	11.44	4.97	7.17	2.86
Variety						
C1	51.22[c]	86.92[d]	102.95[d]	47.78[c]	105.92[b]	126.35[c]
C2	49.76[c]	93.29[c]	111.39[c]	48.9[c]	113.61[b]	128.90[c]
C3	69.65[a]	112.80[a]	131.34[a]	76.73[a]	154.01[a]	173.86[a]
C4	61.17[b]	100.84[b]	119.19[b]	54.32[b]	114.41[b]	134.94[b]
C5	52.22[c]	88.46[cd]	105.65[cd]	53.19[b]	109.37[b]	120.87[d]
CD 5%	5.50	6.15	6.88	2.40	10.38	4.44

Table 2: Interaction effect of growing conditions and cultivar on plant height (cm) of turmeric plant.

	Plant height 2023-24			Plant height 2024-25		
GC x Variety	**45 DAS**	**105 DAS**	**170 DAS**	**45 DAS**	**105 DAS**	**170 DAS**
G1 C1	59.08	102.08	119.32[cd]	53.13[d]	118.84	140.18[c]
G1 C2	63.03	113.39	134.19[b]	50.18[de]	119.02	138.77[c]
G1 C3	79.75	129.43	148.75[a]	87.35[a]	159.84	174.50[a]
G1 C4	75.32	124.27	148.96[a]	64.31[bc]	129.91	151.60[b]
G1 C5	59.55	103.92	124.95[bc]	61.28[c]	124.06	137.04[c]
G2 C1	43.37	71.75	86.57[e]	42.44[g]	93.00	112.51[e]
G2 C2	36.48	73.19	88.58[e]	47.62[ef]	108.20	119.04[d]
G2 C3	62.62	96.16	113.92[d]	66.12[b]	148.18	173.23[a]
G2 C4	47.02	77.39	89.42[e]	44.33[fg]	98.91	118.29[de]
G2 C5	41.83	72.98	86.33[e]	45.11[fg]	94.67	104.70[f]
CD 5%	NS	NS	13.42	4.69	NS	8.67

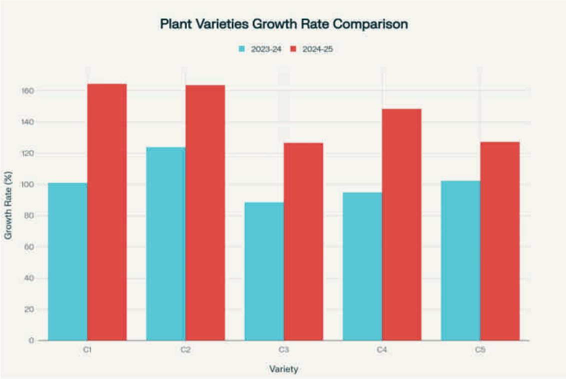

Figure 3: Growth rate of different turmeric varieties during 2023-24 and 2024-25

interaction effect of growing condition and variety further highlighted C3's superior performance, with G1 C3 achieving the largest leaf area values, for instance, 1900.16 cm² at 45 DAS and 5975.33 cm² at 105 DAS in 2023–24. These larger leaf areas indicate a greater photosynthetic surface, which is likely to contribute to better overall plant growth and higher yields. This underscores significant genotypic variation in leaf area traits. Supporting this, a genetic variability study found high genotypic coefficients of variation (GCV) as well as very high heritability (around 99%) for leaf area in turmeric, indicating strong genetic control (Sivakumar *et al.*, 2019)

Rhizome Yield

The data on turmeric rhizome weight and yield parameters were analyzed for two consecutive seasons, 2023 and 2024, focusing on the effects of growing conditions (GC) and variety on several quality traits: weight of mother rhizome (WMR), weight of primary rhizome (WPR), and rhizome yield per hectare (RYPH).

Under the two growing conditions tested, G1 consistently showed better performance than G2 across most parameters. Specifically, the weight of mother rhizome under G1 was 55.32 g in 2023 and increased to 65.68 g in 2024, showing an improvement over G2, which recorded 48.59 g and 61.33 g for the corresponding years as mentioned in table 6. Although the CD for mother rhizome weight was reported as

Table 3: Effect of growing conditions and cultivars on leaf area per plant (LAP) cm^2 of turmeric.

GC	LAP 2023-24			LAP 2024-25		
	45 DAS	105 DAS	170 DAS	45 DAS	105 DAS	170 DAS
G1	1319.81^{a}	5071.65^{a}	3571.42^{a}	1489.06	5455.83^{a}	4336.47
G2	943.68^{b}	3735.61^{b}	2841.01^{b}	1316.43	3743.32^{b}	4176.59
CD 5%	182.70	317.64	723.31	NS	282.17	NS
Variety						
C1	849.10^{c}	4422.30^{bc}	2330.68^{c}	1243.40^{c}	4343.11^{cd}	3337.38^{c}
C2	1101.02^{b}	3804.70^{d}	3669.84^{a}	1100.58^{d}	4576.10^{bc}	4706.86^{a}
C3	1596.91^{a}	5291.03^{a}	3819.71^{a}	1873.61^{a}	5304.84^{a}	4958.60^{a}
C4	1210.74^{b}	4558.04^{b}	3185.96^{b}	1489.91^{b}	5074.37^{ab}	3862.26^{bc}
C5	900.96^{c}	3942.09^{cd}	3024.90^{b}	1306.24^{c}	3699.48^{d}	4417.54^{ab}
CD 5%	119.66	512.42	427.19	80.67	696.33	655.32

Table 4: Interaction effect of growing conditions and cultivars on leaf area per plant (LAP) cm^2 of turmeric.

GC x Variety	LAP 2023-24			LAP 2024-25		
	45 DAS	105 DAS	170 DAS	45 DAS	105 DAS	170 DAS
G1 C1	917.38^{de}	4670.79	2656.36^{de}	1187.60^{ef}	4939.38	3700.85^{de}
G1 C2	1268.02^{c}	4537.71	4381.23^{a}	1100.61^{f}	5355.78	4973.05^{ab}
G1 C3	1900.16^{a}	5975.33	3616.42^{bc}	2045.56^{a}	6142.02	4486.64^{bcd}
G1 C4	1439.31^{b}	5298.85	4234.68^{a}	1828.78^{b}	6321.86	4694.65^{abc}
G1 C5	1074.18^{d}	4875.55	2968.43^{d}	1282.77^{de}	4520.13	3827.13^{cde}
G2 C1	780.82^{ef}	4173.80	2004.99^{f}	1299.19^{de}	3746.83	2973.91^{e}
G2 C2	934.01^{de}	3071.68	2958.46^{d}	1100.56^{f}	3796.41	4440.67^{bed}
G2 C3	1293.67^{bc}	4606.73	4023.00^{ab}	1701.67^{c}	4467.65	5430.56^{a}
G2 C4	982.17^{d}	3817.22	2137.25^{ef}	1151.03^{f}	3826.87	3029.86^{e}
G2 C5	727.75^{f}	3008.63	3081.37^{cd}	1329.71^{d}	2878.83	5007.94^{ab}
CD 5%	169.23	NS	604.14	114.09	NS	926.76

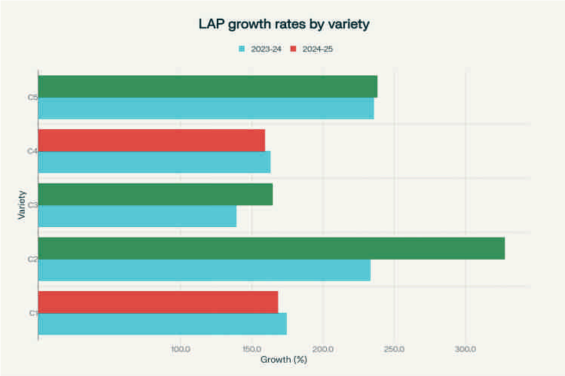

Figure 4: Leaf area increment in different varieties of turmeric

significant, the trend favors G1 for higher WMR values. For the weight of primary rhizome, G1 yielded 126.00 g in 2023 and 112.33 g in 2024, compared to lower values in G2 at 106.90 g and 108.32 g, respectively, again indicating that G1 conditions promote better growth of primary rhizomes, although the differences were statistically non-significant.

Rhizome yield per hectare (RYPH) showed a clearly significant difference influenced by growing condition, with G1 outperforming G2. The rhizome yield under G1 was 12.545 t/ha in 2023, slightly decreasing to 12.403 t/ha in 2024 but still higher compared to G2's yields of 11.543 t/ha and 11.606 t/ha for the respective years. The critical differences (CD) for RYPH (0.325 and 0.504) indicate that these differences are statistically significant at the 5% level, confirming that favourable growing conditions (G1) positively affect turmeric rhizome production.

When comparing varieties, a clear genotypic effect was observed across all traits measured. Variety C3 significantly outperformed others in terms of mother rhizome weight, recording 113.87 g in 2023 and a remarkable increase to 169.72 g in 2024, which was substantially higher than all other varieties. This superior performance of C3 for WMR was mirrored by its primary rhizome weight, where it registered considerable values of 111.13 g in 2023 and 128.35 g

Table 5: Effect of growing conditions and cultivar on rhizome yield of turmeric (t/ha).

GC	WMR 2023-24	WMR 2024-25	WPR 2023-24	WPR 2024-25	RYPH 2023-24	RYPH 2024-25
G1	55.32	65.68	126.00	112.33	12.545^{a}	12.856^{a}
G2	48.59	61.33	106.90	108.32	11.543^{b}	12.137^{b}
CD 5%	6.59	NS	8.69	NS	0.33	0.43
Variety						
C1	25.96^{c}	25.74^{d}	115.89^{b}	90.37^{b}	11.86^{bc}	11.07^{d}
C2	45.67^{b}	50.74^{b}	103.26^{d}	88.41^{b}	11.309^{bc}	11.463^{cd}
C3	113.87^{a}	169.72^{a}	111.13^{c}	128.35^{a}	13.886^{a}	15.272^{a}
C4	44.61^{b}	40.89^{c}	126.52^{a}	121.17^{a}	12.01^{b}	12.609^{b}
C5	29.65^{c}	30.44^{d}	125.44^{a}	123.33^{a}	11.156^{c}	12.064^{bc}
CD 5%	2.05	9.33	3.72	7.98	0.708	0.764

WMR: Weight of mother rhizome, **WPR:** Weight of primary rhizome, **RYPH:** Rhizome yield per hectare

Table 6: Interaction effect of growing conditions and cultivars on yield (t/ha) and yield contributing parameters of turmeric.

GC × Variety	WMR 2023-24	WMR 2024-25	WPR 2023-24	WPR 2024-25	RYPH 2023-24	RYPH 2024*25
G1C1	25.04	25.63	130.33	87.81	12.131^{bcd}	11.99^{cd}
G1C2	50.41	46.67	104.89	86.37	11.537^{cde}	11.154^{de}
G1C3	119.33	191.04	120.67	134.19	15.142^{a}	14.976^{ab}
G1C4	49.56	38.52	137.33	123.07	12.496^{bc}	14.303^{b}
G1C5	32.26	26.56	136.78	130.22	11.42^{de}	11.858^{cd}
G2C1	26.89	25.85	101.44	92.93	11.589^{cde}	10.157^{e}
G2C2	40.93	54.82	101.63	90.44	11.08^{e}	11.773^{cd}
G2C3	108.41	148.41	101.59	122.52	12.63^{b}	15.568^{a}
G2C4	39.67	43.26	115.70	119.26	11.523^{cde}	10.915^{de}
G2C5	27.04	34.33	114.11	116.44	10.892^{e}	12.271^{e}
CD 5%	2.90	13.19	5.26	NS	1.001	1.08

Note: GC- Growing conditions, **G1-** Under neem, **G2-** Sole crop, **WMR-** Weight of mother rhizome (gm plant^{-1}), **WPR-** Weight of primary rhizome (gm plant^{-1}), **RYPH-** Rhizome yield per hectare (tonne) in 2024, second only to C4 and C5, which also showed high WPR but not matching C3's overall consistency.Regarding rhizome yield per hectare, C3 again proved dominant, delivering the highest yields of 13.886 t/ha in 2023 and 15.272 t/ha in 2024, substantially surpassing other varieties. Particularly noteworthy is the performance jump for C3 in 2024, reflecting both its genetic potential and favourable environmental or management conditions that year. Other varieties, such as C4 and C5, also recorded relatively high yields (around 12 t/ha), but varieties C1 and C2 lagged behind, with yields close to or below 11.5 t/ha. Numerous studies further establish that leaf morphological traits—such as leaf length, width, and LAP—are positively correlated with yield attributes in turmeric. For example, research from North-Eastern India demonstrated significant positive associations between leaf area parameters and rhizome yield, underscoring the agronomic importance of enhanced leaf area (Luiram *et al.*, 2018), In a study conducted in Sri Lanka, growth and yield of turmeric were significantly improved under 50% shade, which was deemed optimal for cultivation. Lower shade levels supported higher dry matter, leaf area index, and assimilative rates (Shende *et al.*, 2025).

Statistical significance tests reveal that the variety effect on all parameters WMR, WPR, and RYPH is highly significant, supported by low CD values (e.g., 1.70 and 2.18 for WMR, 3.72 and 7.98 for WPR, and 0.708 and 0.833 for RYPH across the two years), indicating that the genetic differences among varieties robustly influence growth and yield outcomes.

In the interaction study (Table 7) the interaction of growing conditions and varieties have been found non-significant for weight of mother rhizome per plant and weight of primary rhizome per plant. Singh et al., (2020) also reported significant genotype x environment interaction for weight of mother rhizome and weight of primary rhizome in turmeric which suggests differential response of these traits to changing environment conditions. Ali *et al.*, (2018) in their study on the mango turmeric agroforestry system has reported significant interaction effect for two growing conditions, which has been inline with our study in which growing condition and variety has reported significant interaction effect on rhizome yield per hectare.

4. CONCLUSION

The study clearly highlights the advantage of cultivating turmeric under a neem-based agroforestry system (G1) over open-field conditions (G2) in the semi-arid region of Bundelkhand. The partial shade provided by neem trees contributed to improved microclimatic conditions, enhancing plant growth, leaf area per plant, rhizome development, and overall yield. Among the five varieties evaluated, NDH 98 (C3) consistently outperformed others across both years, recording the highest rhizome yield and showing excellent adaptability to shaded environments. This integrated approach not only boosts turmeric productivity but also supports soil moisture conservation, climate resilience, and long-term sustainability. Thus, the combination of neem-based agroforestry (G1) with variety NDH 98 (C3) offers a promising and farmer-friendly strategy to enhance income and resource-use efficiency in dryland agriculture.

Acknowledgments

The authors are sincerely thankful to Rani Lakshmi Bai Central Agricultural University, Jhansi (U.P.), for providing the necessary facilities, academic support, and research environment required to carry out this study.

CONFLICT OF INTEREST DECLARATION

The authors declare that they have no known competing financial interest.

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