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INTEGRATIVE MORPHO-PHYSIOLOGICAL PROFILING AND NODULATION EFFICIENCY ASSESSMENT IN ELITE CHICKPEA (*Cicer arietinum* L.) LINES

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ABSTRACT

Chickpea (*Cicer arietinum* L.) is an important self-pollinated pulse crop valued for its high nutritional content and role in sustainable agriculture. In the present investigation, 48 chickpea lines were evaluated for morphological, physiological, micronutrient content, and nodulation traits. Morphological characterization based on DUS descriptors revealed considerable variability among genotypes. Physiological evaluation showed significant variation in traits such as leaf area index (LAI), leaf area duration (LAD), relative growth rate (RGR), net assimilation rate (NAR), and chlorophyll content index (CCI). Certain genotypes demonstrated superior photosynthetic efficiency and growth performance, indicating their potential for higher biomass production and yield. Micronutrient analysis revealed substantial variation in iron, zinc, manganese, and copper content among genotypes. Nodulation studies conducted at 30, 45, and 60 days after sowing indicated progressive increases in total and effective nodules, along with root growth parameters. Genotypes with superior nodulation and root development were identified, suggesting enhanced biological nitrogen fixation capacity. Overall, the study identified promising genotypes combining desirable traits such as improved physiological efficiency, superior nodulation, and higher micronutrient content. These genotypes can be effectively utilized in breeding programs aimed at developing high-yielding, resilient, and nutritionally enriched chickpea varieties
Keywords **:** Integrative Morpho-Physiological Profiling, Nodulation Efficiency, Chickpea, RGR, NAR, LAI, LAD

Introduction

Chickpea (*Cicer arietinum* L.) is a self-pollinating, diploid (2n=2x=16) pulse crop with a 738Mbp genome (Varshney *et al*., 2013). Chickpea (*Cicer arietinum* L.) is a very important member of legumes. Also known as Bengal Gram or Garbanzo, it is ranked third in number after dry beans and peas worldwide (Yegrem, 2021). Chickpeas are a great source of nutrition (Singh *et al*, 2025) particularly that are essential for healthy brain and body development. A worldwide issue is the deficiency of specific micronutrients. Chickpeas are one crop that shows promise in the battle against nutritional deficiencies. Chickpeas also serve as an excellent source of essential minerals like selenium (Se), zinc (Zn), and iron (Fe). In addition to providing dietary fiber, vitamins, and minerals, they are naturally cholesterol-free. By promoting the development of micronutrient rich cultivars that increase the availability and consumption of high-quality chickpeas which are crucial to reducing hidden hunger and selecting genetic material that enriches micronutrients and the ideal growing environment, food solutions can be developed. Assessing various chickpea genotypes for yield, growth and root nodule characteristics might offer important information about whether genotypes have the desired qualities for increased crop productivity. The natural variance in nodulation and associated characteristics in genotypes of chickpeas without external rhizobium inoculation was evaluated at various post-sowing days. By analysing root nodule measures, which can reveal information about the genotypes' nodulation potential and nitrogen-fixing efficiency, grain output and soil health can be enhanced.

Materials and Methods

Morphological traits (As per DUS guideline on chickpea)

As per the DUS guideline, which focuses on 20 distinct morphological features, 48 lines of chickpea were studied and rated according to the PPV & FRA (2007) requirements. These traits consist of stem anthocyanin coloration, stem height at initiation of first flower, time of flowering (50% of the plants with at least one open flower), plant growth habit, plant color of foliage, leaflet size, leaf pattern, flower number per peduncle, flower color, flower stripes on standard, peduncle length, plant height, pod: size (length), pod number of seeds, seed color, seed size, seed shape, seed testa texture, seed ribbing and seed type.

Table 1: Traits under study as per DUS Guideline of chickpea

S.No	Trait	Description / Stage of Observation	Status	Scale
1	**Stem: Anthocyanin colouration**	Before flowering; pigmentation on stem or leaves	Absent	1
			Present	9
2	**Stem: Height at initiation of first flower**	Height measured from ground at initial flowering	Low (<8 nodes)	3
			Medium (8–15 nodes)	5
			High (>15 nodes)	7
3	**Time of flowering (50% plants with at least one open flower)**	First flowering stage	Extra early (<40 days)	1
			Early (40–60 days)	3
			Medium (61–80 days)	5
			Late (>80 days)	7
4	**Plant: Growth habit**	At 50% flowering	Erect (0–15°)	3
			Semi-erect (16–60°)	5
			Spreading (61–80°)	7
5	**Plant: Color of foliage**	At 50% flowering	Light green	1
			Medium green	2
			Dark green	3
			Greenish purple	4
6	**Leaflet: Size (length)**	Middle leaflet at 50% flowering	Small (<10 mm)	3
			Medium (10–15 mm)	5
			Large (>15 mm)	7
7	**Leaf: Pattern**	At 50% flowering	Simple	1
			Compound	2
			Pinnate	3
8	**Flower: Number per peduncle**	At 50% flowering	Single	1
			Twin	3
9	**Flower: Colour**	At 50% flowering	White	1
			Pink	2
			Blue	3
10	**Flower: Stripes on standard**	At 50% flowering	Absent	1
			Present	9
11	**Peduncle: Length**	During pod development	Short (<5 mm)	3
			Medium (5–10 mm)	5
			Long (>10 mm)	7
12	**Plant: Height**	At completely formed green pod stage	Short (<45 cm)	3
			Medium (45–65 cm)	5
			Tall (>65 cm)	7
13	**Pod: Size (length)**	At harvest maturity	Small (<15 mm)	3
			Medium (15–20 mm)	5
			Large (>20 mm)	7
14	**Pod: Number of seeds**	At harvest maturity	One	1
			> One	3
15	**Seed: Colour**	30 days after harvesting	Beige	1
			Creamy beige	2
			Green	3

			Yellow	4
			Orange	5
			Brown	6
			Dark brown	7
			Grey	8
			Black	9
16	**Seed: Size (100-seed weight at 10% MC)**	30 days after harvesting	Very small (13–15 g)	1
			Small (16–20 g)	2
			Medium (21–25 g)	3
			Medium-Large (26–30 g)	4
			Large (31–35 g)	5
17	**Seed: Shape**	30 days after harvest	Pea-shaped	1
			Owl's head	2
			Angular	3
18	**Seed: Testa texture**	30 days after harvest	Rough	1
			Smooth	2
			Tuberculated	3
19	**Seed: Ribbing**	30 days after harvest	Absent	1
			Present	9
20	**Seed: Type**	30 days after harvest	Desi	1
			Kabuli	3

Physiological traits

Leaf Area Index

LAI expresses the ratio of leaf surface (One side only) to the ground area occupied by the plant, or a crop stand worked out as per the specifications of Gardner *et al*. (1985).

$$LAI = \frac{\text{Total leaf area}}{\text{Land area}}$$

$$LAI = \frac{(LA_1 + LA_2)}{2P}$$

Where, LA_1 and LA_2 represent leaf area during two consecutive intervals and 'P' ground area.

Leaf Area Duration

Leaf area duration expresses the magnitude and persistence of leaf area or leafiness during crop growth. It reflects the extent of seasonal integral of light interaction and correlated with yield. LAD was computed as per the formula suggested by (Watson, 1952).

$$LAD = \frac{(LA_1 + LA_2)}{2} x\,(t_2 - t_1)(cm^2 days)$$

Where, LA_1 and LA_2 represent the leaf area at two successive time intervals (t_1 and t_2).

Net Assimilation Rate

The term NAR was used by Williams (1946). NAR is defined as dry matter increment per unit leaf area or per unit leaf dry weight per unit of time. The NAR is a measure of the average photosynthetic efficiency of leaves in a crop community.

$$NAR = \frac{(W_2 - W_1)}{(t_2 - t_1)} x \frac{(LogL_2 - LogL_1)}{(L_2 - L_1)} (g\ cm^{-2} day^{-1})$$

Where, W_1 and W_2 is dry weight of whole plant at time t_1 and t_2 respectively L_1 and L_2 are leaf weights or leaf area at t_1 and t_2 respectively (t_2-t_1) are time interval in days.

Relative Growth Rate

The Relative growth rate expresses the dry weight increase in the time interval about initial weight. In practical situations, the mean relative growth rate is calculated from measurements at t_1 and t_2. It was calculated as per the formula given by Watson, (1952).

$$RGR = \frac{LnW_2 - LnW_1}{t_2 - t_1} (g\ g^{-1} day^{-1})$$

Ln represents a natural log

W_1= dry weight per unit area at t_1 interval

W_2 = dry weight per unit area at t_2 interval

t_1= days to first sampling

t_2= days to second sampling

Chlorophyll Content Index (CCI)

A non-destructive method using an optical device called a chlorophyll meter (SPAD-502 Plus) was used to measure the chlorophyll content in five plants from each plot.

Quality analysis

Micronutrient analysis

One gram of seed should be added to a 100 ml conical flask in order to digest the seed samples. A colorless solution was obtained by digesting the entire bulk on a hot plate after adding 10.0 ml of a mixture of nitric acid (HNO_3) and perchloric acid ($HCIO_4$) (9:4) into each flask and transferring it to a hot plate. The machine was then run for 60 minutes on the first cycle and 90 minutes on the second. Using Whatman filter paper (Grade No. 1), filter the sample after digestion. Then, transfer it to a volumetric flask and make sure the volume is up to 15 ml with ultra-pure water. Use a standard solution for the blank reading and then Zinc (Zn), Iron (Fe) , Manganese (Mn) and Copper (Cu) content in seed was determined by AAS (Atomic Absorption Spectrophotometer) (Jackson, 1965).

Nodulation studies

An evaluation of root nodulation was conducted on 48 genotypes of chickpeas with varying genetic backgrounds. Chickpea genotypes without external rhizobium inoculation were evaluated for natural variation in nodulation at 30, 45, and 60 days. Five plants were selected at random from each genotype in each replication on each post-sowing day as part of the evaluation process. These plants were carefully uprooted, and in order to prevent harm, extra care was taken to lift and clean the root systems. Observations are number of effective nodules; number of total nodules, length of primary roots and length of secondary roots were recorded.

Results and Discussion

Morphological Characterization

A morphological analysis of 48 genotypes of chickpeas (*Cicer arietinum* L.) using the Distinctness, Uniformity, and Stability (DUS) criteria showed significant phenotypic heterogeneity across a number of diagnostic and agronomic parameters (Table 2). Only two of the 48 genotypes evaluated lacked anthocyanin pigmentation, whereas 46 genotypes of them included it. Twelve genotypes in the current study had a high node count, thirty genotypes had a medium count, and six genotypes had a low count. The forty-three genotypes that showed a medium flowering duration, five showed early flowering.

It was discovered that 47 genotypes showed semi-erect, while just 1genotype showed a spreading habit. Breeding strategies that aim to improve compatibility with mechanical harvesting often favour upright to semi-erect growth forms because of their consistent stand structure and lower lodging tendency.

The majority thirty-eight genotypes had medium-green leaves, whereas eight genotypes had dark-green leaves, which may be a sign of increased chlorophyll content and improved photosynthetic efficiency. Light green foliage was seen in only two genotypes. Nine of the genotypes had little leaflets, thirty-two genotypes had medium-sized leaflets, and seven genotypes had large leaflets. The distribution of flower colours showed that only two genotypes produced white flowers, whereas 46 genotypes produced a preponderance of pink flowers. Interestingly, no genotype had blue flowers.

The genotypes were divided into three groups based on plant height assessment: tall (three genotypes), medium (twenty-nine genotypes), and short (sixteen genotypes). Because of their higher first fruiting node, tall or semi-erect growth habits are beneficial from a breeding perspective for automated harvesting.

To classify pod size variation, it was found that eleven genotypes generated little pods, thirty-three genotypes medium-sized pods, and four produced giant pods. This characteristic is still a significant factor in determining prospective yield because pod size frequently correlates with both seed number and seed size.

Only four genotypes generated a single seed per pod, whereas 44 genotypes included more than one seeds per pod, which is a trait that is advantageous for increasing production. The majority of the seeds (40 genotypes) were brown, followed by beige (2 genotypes), yellow (3 genotypes), and dark brown (3 genotypes).Based on the 100-seed weight the five groups were very small (4 genotypes), small (5 genotypes), medium (15 genotypes), medium-large (19 genotypes), and large (5 genotypes). There were only two genotypes that had the owl's head shape that is typical of *kabuli* types, but the bulk of genotypes (46) displayed the distinctive angular shape.

There were 32 genotypes of smooth testa and 16 genotypes of rough testa.

The majority of genotypes (46) had seed ribbing, whereas only in two genotypes seed ribbing is absent. In case of seed type 46 genotypes are *desi* type, while 2 genotypes are *kabuli* type.

All 48 genotypes could be reliably distinguished through the integration of numerous phenotypic features, even in cases when individual qualities overlapped. The findings are consistent with those of Behera *et al* (2023), Asati *et al.* (2023), Thakur *et al.* (2021), Upadhyaya *et al.* (2002) and Shakaya (2017).

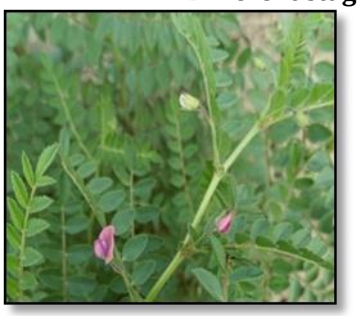
Table 2: Frequency distribution of morphological characters of elite lines of chickpea

S. No.	Characters	Pattern	Score	Genotypic frequency	Frequency (%)
1	Stem anthocyanin colouration	Absent	1	2	4.16
		Present	9	46	95.83
2	Stem height at initiation of first flower	Low (<8 nodes)	3	6	12.5
		Medium (8-15 nodes)	5	30	62.5
		High (>15 nodes)	7	12	25
3	Time of flowering (50% of the plants with at least one open flower)	Extra early (<40 days)	1	0	0
		Early (40-60 days)	3	5	10.41
		Medium (61-80 days)	5	43	89.58
		Late (> 80 days)	7	0	0
4	Plant growth habit	Erect (0-15 From vertical)	3	0	0
		Semi-erect (16-60 From vertical	5	47	97.91
		Spreading (61-80 From vertical	7	1	2.08
5	Plant color of foliage	Light green	1	2	4.16
		Medium green	2	38	79.16
		Dark green	3	8	16.66
		Greenish purple	4	0	0
6	Leaflet size (length) (middle of the plant and middle of the leaf)	Small (<10mm)	3	9	18.75
		Medium (10-15mm)	5	32	66.66
		Large (>15mm)	7	7	14.58
7	Leaf pattern	Simple	1	0	0
		Compound	2	0	0
		Pinnate	3	48	100
8	Flower number per peduncle	Single	1	48	100
		Twin	3	0	0
9	Flower colour	White	1	2	4.16
		Pink	2	46	95.83
		Blue	3	0	0
10	Flower stripes on standard	Absent	1	0	0
		Present	9	48	100
11	Peduncle length	Short (<5mm)	3	0	0
		Medium (5-10mm)	5	0	0
		Long (>10mm)	7	48	100
12	Plant height	Short (<45 cm)	3	16	33.33
		Medium (45-65 cm)	5	29	60.41
		Tall (>65 cm)	7	3	6.25
13	Pod size (length)	Small (<15mm)	3	11	22.91
		Medium (15-20mm)	5	33	68.75
		Large (>20mm)	7	4	8.33
14	Pod number of seeds	One	1	4	8.33
		More than one	3	44	91.66
15	Seed colour	Beige	1	2	4.16
		Creamy beige	2	0	0
		Green	3	0	0
		Yellow	4	3	6.25
		Orange	5	0	0
		Brown	6	40	83.33
		Dark brown	7	3	6.25
		Grey	8	0	0
		Black	9	0	0
16	Seed size (weight of 100 seeds at 10 % moisture content)	Very small (13-15g)	1	4	8.33
		Small (16-20g)	2	5	10.41
		Medium (21-25g)	3	15	31.25
		Medium-Large (26-30g)	4	19	39.58
		Large (31-35g)	5	5	10.41

S. No.	Characters	Pattern	Score	Genotypic frequency	Frequency (%)
17	Seed shape	Pea-shaped	1	0	0
		Owl's head	2	2	4.16
		Angular	3	46	95.83
18	Seed testa texture	Rough	1	16	33.33
		Smooth	2	32	66.66
		Tuberculated	3	0	0
19	Seed ribbing	Absent	1	2	4.16
		Present	9	46	95.83
20	Seed type	*Desi*	1	46	95.83
		Kabuli	3	2	4.16

Different stages of flower

Variation in leaf size

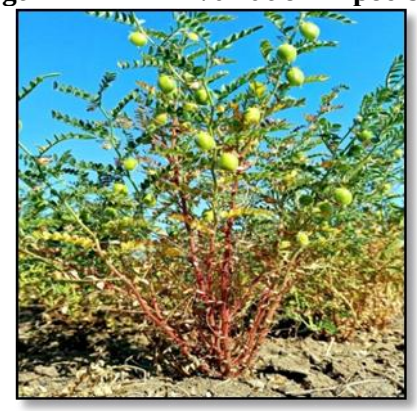


Single flower per peduncle

Peduncle length

Variation in pod size

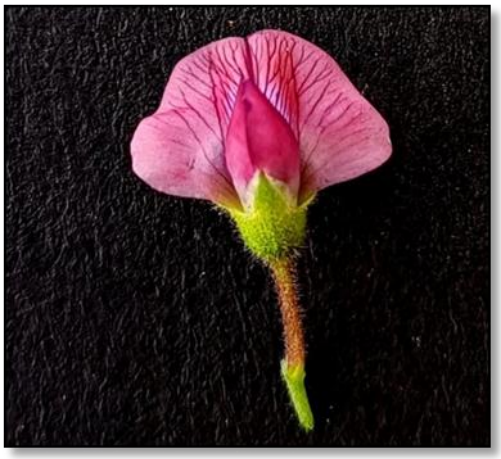
Absent

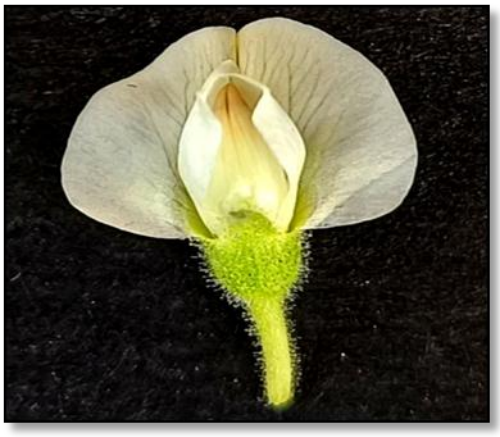


Present

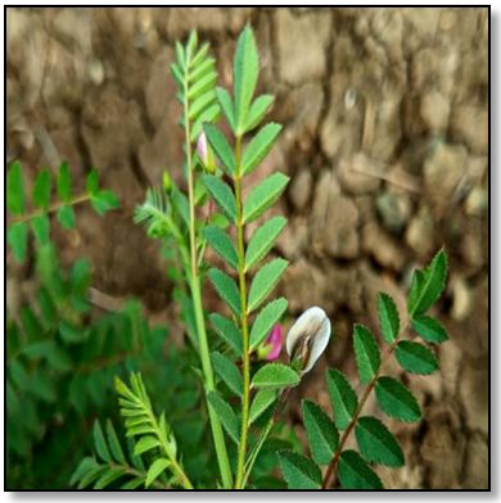
Anthcyanin pigmentation

Morphological characterization





Variation in flower colour



Pinnate leaf pattern

Plant height

Semi erect growth habit

Assessment of Physiological Traits

The estimation of various physiological traits was taken, involving LAI, LAD, RGR, NAR and CCI. The results are shown in Table 3.

Leaf area index – I at 90 DAS

The LAI – I values ranged from 0.786 to 1.594 with an average of 1.306. The high value was observed in the genotypes ICCV 241110 (1.594), followed by ICCV 241206 (1.554), JG 2022-8 (1.551), JG-36(ch) (1.539), ICCV 241104 (1.527), ICCV 241118 (1.508)

and ICCV 241114 (1.504).The minimum value was observed in the genotypes NC 12 (0.786) followed by BG 4066 (0.924) and RKGP 24-2 (0.955).

Leaf area index – II at 105 DAS

The LAI – II ranged from 0.698 to 1.360 with a mean value of 1.144. The maximum value was recorded in the genotypes ICCV 241110 (1.360) followed by ICCV 241206 (1.349), JG-36(ch) (1.331), ICCV 241118 (1.327), ICCV 241114 (1.322) and JG 2022-8 (1.317). The minimum value was observed in the genotypes NC 12 (0.698) followed by BG 4066 (0.819), RKGP 24-2 (0.856) and ICCV 241107 (0.895).

Leaf area duration at 90-105 DAS

The LAD varied from 11.138 to 22.164 with an overall mean of 18.388. The maximum value was observed in the genotypes ICCV 241110 (22.164) followed by ICCV 241206 (21.779), JG-36(ch) (21.534), JG 2022-8 (21.513) and ICCV 241118 (21.264). In contrast, the minimum value was noted in the genotypes NC 12 (11.138) followed by BG 4066 (13.077), RKGP 24-2 (13.592), RKGP 24-1 (14.412) and ICCV 241107 (14.439).

Relative growth rate at 90-105 DAS

The RGR had a mean value of 0.019113 and varied from 0.013115 to 0.024326. The maximum value was observed in the genotypes BG 4065 (0.024326) followed by ICCV 241117 (0.023416), ICCV 241112 (0.023238), ICCV 241104 (0.022999), IPC 23-220 (0.022387) and JG-36(ch) (0.022043). The minimum value was observed in the genotypes ICCV 241202 (0.013115) followed by ICCV 241116 (0.014463), Phule Vikram (0.015601), ICCV 241207 (0.015612), ICCV 241101 (0.015684) and ICCV 241118 (0.015935).

Net assimilation rate at 90-105 DAS

The NAR ranged from 0.000217 to 0.000371 with an average of 0.000285. The maximum value was observed in the genotypes ICCV 241117 (0.000371) followed by BG 4065 (0.000358), MABC-WR-SA10 (0.000340), MABC-WR-SA2 (0.000329), ICCV 241201 (0.000328), ICCV 241113 (0.000325) and ICCV 241112 (0.000322). The minimum value was observed in the genotypes ICCV 241202 (0.000217) followed by ICCV 241116 (0.000219), ICCV 241106 (0.000240) and RKGP 24-2 (0.000241).

Chlorophyll content index at 75 DAS

The CCI had a mean value of 47.33 and ranged from 44.73 to 49.36. The genotypes JG 2023-109 (49.36) and ICCV 241206 (49.30), MABC-WR-SA2 (49.30), ICCV 241201 (49.26), and Phule Vikram (49.26) had the highest values. The genotypes with the lowest value were ICCV 241111 (44.73), IPC 2005-62(ch) (44.86), and RKGP 24-2 (44.90).

Chlorophyll content index at 95 DAS

The CCI ranged from 35.73 to 44.00 with a mean value of 38.86. The maximum value was observed in the genotypes ICCV 241209 (44.00) followed by ICCV 241203 (43.73), JG18 (43.70), ICCV 241201 (43.53) and MABC-WR-SA10 (43.23). The minimum value was observed in the genotypes BG 4065 (35.73) followed by ICCV 241111 (35.76), RG 2022-B-01# (35.83) and GL 21-18 (36.06).

Table 3: Physiological traits of chickpea genotypes

Traits	Range		Mean
	Minimum	Maximum	
LAI (90 DAS)	0.7867	1.5947	1.3069
LAI (105 DAS)	0.6984	1.3605	1.1448
LAD (90-105 DAS) (cm^2 days)	11.1385	22.1646	18.3886
RGR (90-105 DAS) (g g^{-1} day^{-1})	0.0131	0.0243	0.0191
NAR (90-105 DAS) (g cm^{-2} day^{-1})	0.00021	0.00037	0.00028
CCI (75 DAS)	44.7333	49.3666	47.3333
CCI (95 DAS)	35.7333	44.00	38.8687

Quality Analysis

Forty-eight genotypes of chickpea were analyzed for their micronutrient content. Micronutrients viz., zinc, manganese, copper and iron were estimated. The results are summarized in Table 4.

Iron (ppm)

The average iron content was recorded 30.17 with the range of 3.64 to 75.21. The maximum content was observed in the genotypes IPC 23-220 (75.21) followed by NBeG47 (73.20), MABC-WR-SA10 (70.20), JG-36(ch) (66.21) and RG 2022-B-01 (66.21). The minimum content was observed in the genotypes

ICCV 241117 (3.64) followed by ICCV 241106 (3.96), ICCV 241113 (5.79), ICCV 241111 (7.93) and ICCV 241116 (8.86).

Manganese (ppm)

The average manganese content was recorded 7.34 with the range of 4.38 to 19.36. The maximum content was observed in the genotypes MABC-WR-SA2 (19.36) followed by GL 21-18 (11.46), RG 2022-B-01# (11.17), ICCV 241110 (9.70), IPC 23-220 (9.54) and ICCV 241114 (9.31). The minimum content was observed in the genotypes ICCV 241116 (4.38) followed by RG 2022-B-08 (4.39), ICCV 241102 (4.86), ICCV 241108 (4.92) and ICCV 241113 (4.95).

Copper (ppm)

The average copper content was recorded 8.26 with the range of 4.03 to 14.29. The maximum content was observed in the genotypes ICCV 241208 (14.29) followed by ICCV 241110 (13.89), IPC 23-220 (12.22), ICCV 241103 (12.12) and ICCV 241101 (11.05). The minimum content was observed in the genotypes ICCV 241113 (4.03) followed by ICCV 241102 (4.09), ICCV 241108 (4.14), ICCV 241106 (5.25) and ICCV 241111 (5.50).

Zinc (ppm)

The average zinc content was recorded 16.63 with the range of 4.08 to 29.75. The maximum content was observed in the genotypes ICCV 241110 (29.75) followed by JG 2023-109 (25.82), IPC 23-220 (25.48), RKGP 24-1 (25.35), ICCV 241208 (25.26) and GL 21-18 (24.75). The minimum content was observed in the genotypes ICCV 241106 (4.08) followed by ICCV 241201 (4.41), ICCV 241108 (7.33), ICCV 241113 (7.44) and RG 2022-B-08 (7.88).

Table 4: Quality traits of chickpea genotypes

Traits	Range (ppm)		Mean (ppm)
	Minimum	Maximum	
Iron (Fe)	3.64	75.21	30.17
Manganese (Mn)	4.38	19.36	7.34
Copper (Cu)	4.03	14.29	8.26
Zinc (Zn)	4.08	29.75	16.63

Nodulation Studies

Forty-eight genotypes of chickpea were evaluated to assess natural variation in nodulation at 30, 45 and 60 days after sowing (DAS).Observations recorded included the number of total nodules, number of effective nodules, length of primary roots and length of secondary roots.

Nodulation Studies at 30 Days after Sowing (DAS)

At 30 days after sowing total nodule counts ranged from 6.66 to 16.00 per plant with a mean of 11.10, with genotype ICCV 241203 exhibiting the maximum total nodule (16 nodules). Number of effective nodules showed a similar pattern, with ICCV 241207 and ICCV 241209 having the largest number (14.33 nodules) and it ranged from 5.66 to 14.33 with a mean of 10.35. Different genotypes had different root development at the beginning of growth, as evidenced by the average primary root length ranging from 5.96 cm to 10.10 cm with a mean of 8.15 cm. The highest length of primary root was recorded for the genotype RKGP 24-1. The average secondary root length had range of 5.50 cm to 9.03 cm with a mean of 7.04 cm. The highest length of secondary root was recorded for the genotype BG 4066 (Table 05).

Table 5: Nodulation traits at 30 DAS

Traits	Range		Mean
	Minimum	Maximum	
Number of total nodules	6.66	16.00	11.10
Number of effective nodules	5.66	14.33	10.35
Length of primary roots (cm)	5.96	10.10	8.15
Length of secondary roots (cm)	5.50	9.03	7.04

Nodulation Studies at 45 Days after Sowing (DAS)

Nodulation clearly increased at 45 DAS, The average number of total nodules was observed 17.15, with values ranging from a minimum of 11.66 to a maximum of 21.00, with genotype ICCV 241209 exhibiting the maximum total nodule. Number of effective nodules was observed a mean 15.95, with a range from a minimum of 10.66 to a maximum of 20.66. The highest number of effective nodules was observed in the genotype ICCV 241203. The average length of primary root was observed 9.90, ranging from a minimum of 8.03 to a maximum of 11.86. The

highest length of primary root was recorded for the genotype ICCV 241112. The average length of secondary root was found 9.40, ranging from a minimum of 7.46 to a maximum of 11.43. The highest length of secondary root was recorded for the genotype RKGP 24-1.This indicating that nodule and root growth were coordinated to enhance nitrogen fixation capability in mid-growth stages (Table 06).

Table 06: Nodulation traits at 45 DAS

Traits	Range		Mean
	Minimum	Maximum	
Number of total nodules	11.66	21.00	17.15
Number of effective nodules	10.66	20.66	15.95
Length of primary roots (cm)	8.03	11.86	9.90
Length of secondary roots (cm)	7.46	11.43	9.40

Nodulation Studies at 60 Days after Sowing (DAS)

Nodulation rose even further by 60 DAS. The average number of total nodules was observed 22.22, with values ranging from a minimum of 16.66 to a maximum of 27.00. The highest number of total nodules was observed in the genotype JG 2023-109. The average number of effective nodules was observed 20.56, with a range from a minimum of 15.66 to a maximum of 25.00. The highest number of effective nodules was observed in the genotype ICCV 241203, while the average length of primary root was observed 13.03, ranging from a minimum of 10.66 to a maximum of 15.56. The highest length of primary root was recorded for the genotype JG18 and the average length of secondary root was found 12.81, ranging from a minimum of 9.86 to a maximum of 15.03. The highest length of secondary root was recorded for the genotype RG 2022-B-01. These similar findings are indicated by Kumari *et al* (2024).

This study emphasizes the significance of choosing genotypes with robust root architecture and good nodulation performance in order to optimize BNF and chickpea productivity.

Table 07: Nodulation traits at 60 DAS

Traits	Range		Mean
	Minimum	Maximum	
Number of total nodules	16.66	27.00	22.22
Number of effective nodules	15.66	25.00	20.56
Length of primary roots (cm)	10.66	15.56	13.03
Length of secondary roots (cm)	9.86	15.03	12.81

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