

## 🌱 Exploring stage-specific responses of chickpea (*Cicer arietinum* L.) to supplementary irrigation under agro-climatic conditions of Bahawalpur, Pakistan

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### Abstract

Chickpea (*Cicer arietinum* L.), a nutritionally rich legume, holds promise for food security, yet its productivity is severely affected by drought stress. This study investigated the performance of ten chickpea genotypes under two water regimes: supplemental irrigation (SI) and rainfed conditions (RC), to evaluate genotype-specific responses in morphology, physiology, and biochemistry. Significant differences were observed in all agronomic traits across irrigation regimes. Plant height was reduced under rainfed conditions, with CH21/13 showing a decrease from 68.2 cm (SI) to 62.8 cm (RC). BRC-474 consistently recorded the shortest stature under both regimes. The number of branches per plant was highest in CH21/13 under SI (mean of 9.3 branches), while BRC-474 had the fewest (5.1 branches) under RC. Canopy width was also significantly affected, with CH21/13 reaching 33.6 cm under SI and showing an 11% reduction under RC. Biological yield increased by 36% with irrigation, highlighting the critical role of water in biomass accumulation. In terms of root

development, drought-tolerant genotype D-1700 exhibited the highest root dry weight (3.72 g), shoot dry weight (6.88 g), and RS ratio (0.54) under RC, indicating an adaptive allocation toward root growth to enhance water uptake. Chlorophyll content decreased by 15% under drought conditions compared to full irrigation. Lipid peroxidation, measured via malondialdehyde (MDA) accumulation, was highest in the drought-sensitive genotype TG-1504 under RC (3.92  $\mu\text{mol g}^{-1}$  FW), compared to CH21/13 (2.45  $\mu\text{mol g}^{-1}$  FW). MDA was negatively correlated with yield components and positively with root traits, indicating its dual role as a stress indicator and modulator of plant defense. These findings suggest that CH21/13 and D-1700 possess traits favorable for drought tolerance, including taller plant architecture, rapid root systems, higher chlorophyll retention, and lower oxidative damage under water-limited conditions. © 2025 The Author(s)

**Keywords:** Chickpea, Drought stress, Genotypic variation, Malondialdehyde, Root-to-shoot ratio, Supplemental irrigation, Water-use efficiency

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### Introduction

Chickpea (*Cicer arietinum* L.) is recognized as the third most extensively cultivated pulse crop worldwide, after dry beans and field peas (Siddique & Krishnamurthy, 2016; Merga & Haji, 2019). It is grown in diverse regions across the globe, primarily for its nutritious and edible seeds (Yegrem, 2021). This crop holds considerable importance, particularly in developing and low-income countries where it serves as a key component of household diets and local markets (Bell, 2014; Sharma et al., 2020). Beyond its nutritional value, chickpea enhances soil fertility by converting atmospheric nitrogen ( $\text{N}_2$ ) into ammonia

through biological nitrogen fixation. This ammonia is subsequently converted into organic nitrogen compounds that enrich the soil and reduce fertilizer needs for subsequent crops (Verma et al., 2015; Abd-Alla et al., 2023; Crop Trust, 2023). From a nutritional point of view, chickpea serves as an excellent dietary component, offering a rich source of high-quality protein (McDermott & Wyatt, 2017). It also contains vital minerals such as calcium, magnesium, phosphorus, and potassium, along with essential vitamins like riboflavin, niacin, thiamine, folate, and  $\beta$ -carotene the latter acting as a precursor to vitamin A (Jukanti et al., 2012; Singh et al., 2021). On average, chickpea seeds contain approximately 23% protein (Verma et al., 2015; Crop Trust, 2023), and their protein

quality is generally superior to that of other pulses (Jukanti et al., 2012). Although chickpeas are relatively low in fat, they contain nutritionally important unsaturated fatty acids, notably linoleic and oleic acids (Yegrem, 2021).

Globally, chickpea is cultivated on approximately 15 million hectares, producing about 15.8 million tons annually. The major chickpea-producing countries include India, Australia, Myanmar, Pakistan, Turkey, and Iran (Zhang et al., 2024). In Pakistan alone, during the 2023–24 season, the crop occupied around 0.79 million hectares, yielding a total production of 0.23 million tons (Government of Pakistan, 2024). In most producing regions, chickpea is grown as a rainfed crop, typically sown in early spring, with its growth largely dependent on soil moisture accumulated during the preceding fall and winter. Although Pakistan ranks among the leading chickpea-producing nations, its yield levels remain considerably lower than those achieved in other major producing countries (Hakeem et al., 2025). One of the primary factors limiting chickpea productivity is terminal water stress, which occurs during the pod development stage (Kashiwagi et al., 2013; Korbu et al., 2022). Drought stress represents a key challenge for agricultural productivity, particularly in the arid and semi-arid zones of developing countries (Noroz et al., 2021; Zia et al., 2023; Omokhafe et al., 2024). On a global scale, water scarcity continues to pose a growing threat to sustainable agriculture and food security (Turner et al., 2001). As a result, terminal drought marked by the depletion of soil moisture during the final stages of the crop's growth impacts nearly two-thirds of the global chickpea cultivation area. To address this constraint, breeding and promoting cultivars with improved drought avoidance and drought tolerance are essential strategies for enhancing grain yield under limited water conditions (Gaur et al., 2007).

In Pakistan, most chickpea cultivation occurs in arid and semi-arid regions that are highly prone to severe drought stress (Shah et al., 2020). This problem often intensifies in certain years due to irregular rainfall patterns or reduced total precipitation, leading to substantial yield losses or even complete crop failure. In semi-arid areas, several soil and climatic constraints such as shallow soil depth, low organic matter, intense but brief rainfall events, high runoff, limited soil permeability, and poor water-holding capacity contribute to inadequate soil moisture storage. Additionally, inappropriate tillage practices and poor seedbed structure further exacerbate terminal water stress (Doaei et al., 2020). The severity of drought stress in these regions varies from season to season, depending on factors like sowing time, rainfall distribution during the growth period, ambient temperature, and the rate of water loss through evaporation and transpiration (Seleiman et al., 2021). While genetic and physiological tolerance to end-season drought plays an important role in maintaining yield under stress conditions, effective agronomic management practices are equally crucial for minimizing yield losses (Korbu et al., 2020). Management strategies such as

optimizing planting dates, improving soil conditions, and implementing precise irrigation scheduling are among the most effective approaches for mitigating drought effects (Phiri et al., 2023). Given that irrigation water is scarce in these regions, full irrigation is often not feasible. The challenge has been further compounded in recent decades by climate change and global warming. Therefore, improving water-use efficiency through careful irrigation planning and water management represents a promising strategy for sustaining chickpea production in semi-arid agricultural systems (Nikolaou et al., 2020).

Supplementary irrigation is a key management practice in rainfed agriculture that involves providing a limited amount of water during critical drought-sensitive growth stages. This approach helps sustain plant growth and stabilize yield, particularly when rainfall is insufficient. It is typically applied during short dry spells to compensate for moisture deficits. Oweis et al. (2004) demonstrated that applying approximately 200 mm of supplementary irrigation during the chickpea growing season in Syria significantly enhanced yield. The improvement was attributed to reduced evapotranspiration losses during the early growth period and increased water use efficiency (WUE) compared with fully irrigated systems, leading to more stable yields across seasons. However, they also observed a decrease in WUE under supplementary irrigation compared to rainfed conditions. The effectiveness of supplementary irrigation largely depends on climatic conditions, crop species, and regional characteristics, emphasizing the need for location-specific evaluation. Singh et al. (2016) reported that in rainfed chickpea fields, the application of 75 mm of water as supplementary irrigation before the reproductive phase and during pod formation increased yield by 59% and 73%, respectively, compared with non-irrigated conditions. Despite these promising results, limited research exists on the role of supplementary irrigation in mitigating drought stress during the flowering stage and its impact on the growth, yield, and productivity of chickpea genotypes. Therefore, the present study aimed to evaluate the performance of selected chickpea genotypes under different water regimes by assessing their physiological, biochemical, and growth-related traits, with the goal of identifying genotypes that are more resilient and productive in rainfed and supplemental irrigation systems within the agro-climatic conditions of Bahawalpur, Pakistan.

## Materials and Methods

### Experimental site

This study was conducted at Regional Agricultural Research Institute (RARI), Bahawalpur, Pakistan, during the year 2020–21. The experimental site is located at 29.39° N latitude and 71.65° W longitude, at an elevation of 152 meters above sea level. The area falls within the arid agro-ecological zone, receiving a very low mean annual rainfall of approximately 168.6 mm. Climatically, the Bahawalpur District is characterized by extreme conditions, experiencing hot, dry summers with temperatures reaching up to 48 °C, and cold, dry

winters with temperatures dropping below 7 °C (Ahmed et al., 2021).

### Temperature and rainfall

During the 2020–21 study period in Bahawalpur, the winter months of December, January, and February were relatively cool and dry. During the winter months of December, January, and February in Bahawalpur during 2020–21 study period, the climate was relatively cool and dry. Average high temperatures ranged from 68.7 °F (20.4 °C) in January to 73.6 °F (23.1 °C) in February, with December recording an average high of 72.7 °F (22.6 °C). Average low temperatures ranged from 44.6 °F (7.0 °C) in January to 49.6 °F (9.8 °C) in February, while December had an average low of 46.6 °F (8.1 °C). In terms of overall average temperatures, December recorded 59.3 °F (15.17 °C), January was the coldest at 56.3 °F (13.5 °C), and February was slightly warmer at 61.3 °F (16.27 °C). Rainfall remained low but gradually increased across the season, with December receiving approximately 0.8 inches, January around 1.2 inches, and February the highest at 1.7 inches. Overall, the winter season in Bahawalpur during the study period was characterized by mild temperatures and limited precipitation (Arshad et al., 2024).

### Experimental layout and crop husbandry

The experiment was conducted during December–February cropping season of 2020/2021 at RARI, Bahawalpur. The trial followed a split-plot design in a randomized complete block design (RCBD) with three replications. The main plot treatments consisted of two water regimes: rainfed condition (RC) and supplemental irrigation (SI), while the subplots comprised five chickpea genotypes: BRC-474, CH21/13, TG-1427, D-17006, CH28/13, D-17028, D-17019, CH30/12, CH39/13 and TG-1504). Under rainfed conditions, genotypes were grown solely on the rainfall received during the cropping season. In the supplemental irrigation (SI) treatment, water was applied through furrows at 10-day intervals during the critical reproductive stages (flowering, podding, and grain filling). Irrigation was applied to near field capacity (FC), estimated using the gravimetric method, to reduce moisture stress. The plants were spaced at 30 cm × 10 cm, resulting in a plant density of approximately 33 plants per m<sup>2</sup>. Each subplot measured 1.8 m × 6 m, providing adequate space for plant growth and evaluation. Weeds were controlled manually at weekly intervals, and crops were protected from *Helicoverpa armigera* through routine insecticide applications. Fertilizer was applied at a rate of 34 kg ha<sup>-1</sup> nitrogen (N) and 12 kg ha<sup>-1</sup> phosphorus (P), using urea as the nitrogen source and single super phosphate (SSP) as the phosphorus source.

### Parameters studied

A comprehensive set of morphological, physiological, and biochemical parameters was recorded at specific growth stages of the crop during the 2020–21 growing season to evaluate plant development, stress response, and yield performance. Data collection was organized growth stage-wise, including the vegetative, flowering, pod development, maturity, and post-harvest phases. During the vegetative stage, plant growth was assessed by measuring plant height, shoot length (SL), root length, and canopy width/spread (cm) using a meter rod. The number of branches per plant was recorded by manual counting. Fresh weights of shoots and roots were taken using a digital balance, followed by oven-drying the samples at 70 ± 2 °C until constant weight to determine shoot and root dry weights. The root-to-shoot ratio (R/S ratio) was then calculated by dividing root dry weight by shoot dry weight. Leaf area index (LAI) was computed using the formula:

$$\text{Leaf area index} = \frac{\text{Leaf area}}{\text{Ground area}}$$

Physiological assessments included relative water content (RWC), which was estimated using the fresh, turgid, and dry weights of leaves:

$$\text{RWC} = \frac{\text{FW} - \text{DW}}{\text{TW} - \text{DW}} \times 100$$

Where, FW, TW, and DW are the leaf fresh weight, turgid weight, and dry weight, respectively.

Proline content (µg g<sup>-1</sup> FW) in chickpea leaves was determined at the flowering stage. Leaves from each replication of each variety were collected, immediately placed in ice-packed bags, and transported to the laboratory. Proline was estimated following the quantification method described by Bates et al. (1973):

$$\text{Proline content (}\mu\text{g g}^{-1}\text{FW)} = \frac{\text{M} \times \text{T} \times \text{W}}{115.5} \times 1000$$

Where

M = The number read with the spectrophotometer

T = The volume of toluene used (it was 4 ml)

W = Leaf fresh weight

Shoot and root malondialdehyde (MDA) content (µmol g<sup>-1</sup> FW), an indicator of lipid peroxidation, was determined using the thiobarbituric acid (TBA) assay. A 0.25 g sample of plant tissue was homogenized in 5 ml of 0.1% trichloroacetic acid (TCA) and centrifuged. Then, 250 µL of the supernatant was combined with 1 ml of a solution containing 20% TCA and 0.5% TBA. The mixture was heated at 95 °C for 30 minutes, quickly cooled on ice, and centrifuged again. Absorbance of the resulting solution was measured at 532 nm, with non-specific absorbance at 600 nm subtracted. MDA concentration

was calculated using a standard formula, allowing accurate quantification of lipid peroxidation (Heath & Packer, 1968):

$$\text{MDA } (\mu\text{mol g}^{-1} \text{FW}) = \frac{(A532 - A600) \times W}{116} \times 1000$$

Where

A532 = Spectrophotometer-read absorption at 532 nm wavelength

A600 = Spectrophotometer-read absorption at 600 nm wavelength

W = The weight of the Leaf sample used

Chlorophyll a, chlorophyll b, and total chlorophyll content ( $\text{mg g}^{-1}$  FW) were extracted using 80% acetone and quantified spectrophotometrically. Sampling was performed at the maximum greenness stage, selecting three plants per plot and five leaves per plant at random. Leaves were immediately frozen in liquid nitrogen and ground into a fine powder using a mortar and pestle. A 125 mg portion of the powdered tissue was transferred to a microtube, and 250  $\mu\text{L}$  of 96% ethanol was added. The samples were then centrifuged, and the absorbance of the supernatant was measured at 663, 646, and 470 nm. Chlorophyll a, chlorophyll b, and total chlorophyll concentrations were calculated using the formulas described by Lichtenthaler & Wellburn (1983):

$$\text{Chlorophyll a} = 12.21 (A663) - 2.81 (A646)$$

$$\text{Chlorophyll b} = 20.13 (A646) - 5.1 (A663)$$

The total chlorophyll and chlorophyll a to chlorophyll b ratio was calculated using the chlorophyll a and b.

At the flowering stage, reproductive initiation was monitored by recording days to flowering, counted from the date of sowing to the day when 50% of plants had at least one open flower. Additionally, the number of flowers per plant was manually counted from selected plants to quantify reproductive potential. During the pod and seed development stage, pod-related parameters were recorded. These included the number of pods per plant, number of seeds per pod, and total numbers of seeds per plant, all were determined through manual counting. Pod length was measured using a ruler. Shelling percentage was calculated using the formula:

$$\text{Shelling percentage} = \frac{\text{Weight of Seeds}}{\text{Weight of Pods}} \times 100$$

At the maturity stage, phenological development was evaluated by recording days to maturity from sowing until physiological maturity was reached, indicated by seed hardening and leaf yellowing. Seed weight per plant (g) was recorded after threshing individual plant samples. The 1000-seed weight was determined using a digital precision balance. After final harvest, in the post-harvest stage, yield

and biomass parameters were measured. Straw weight per plant (g) and total dry matter per plant (g) were obtained by drying plant residues. Straw yield ( $\text{g m}^{-2}$ ) and grain yield ( $\text{kg ha}^{-1}$ ) were determined from harvested plots and converted to respective units. Biological yield ( $\text{kg ha}^{-1}$ ) was calculated by summing the grain and straw yields. The harvest index (HI) was computed using the formula:

$$\text{Harvest Index \%} = \frac{\text{Grain Yield}}{\text{Biological Yield}} \times 100$$

## Data analysis

Analysis of Variance (ANOVA) was conducted to assess significant differences among treatment means. The Least Significant Difference (LSD) test was used for mean comparisons at  $p < 0.05$ . Values are presented as mean  $\pm$  standard deviation. Means followed by different letters within the same column indicate statistically significant differences according to the LSD test.

## Results

### Effect of water regimes on vegetative growth traits of Chickpea

The results presented in Table 1 show that all vegetative growth traits (plant height (PH), number of branches per plant (NBPP), shoot length (SL), and canopy width (CW)) were significantly influenced by both chickpea genotypes and water regimes. Under supplemental irrigation (SI), all genotypes exhibited improved growth performance compared to the rainfed condition (RC). The genotype CH21/13 consistently recorded the highest values across all traits under both conditions. For example, it achieved the tallest plant height (68.2 cm), highest number of branches per plant (10.4), longest shoot length (23.4 cm), and widest canopy (33.6 cm) under SI. This was closely followed by TG-1427 and D-17006, which also showed strong vegetative growth under SI. In contrast, BRC-474 showed the lowest values in all traits under both water regimes, with particularly low shoot length (19.2 cm under RC and 21.8 cm under SI) and canopy width (21.3 cm under RC and 24.9 cm under SI). Among the measured traits, canopy width (CW) and shoot length (SL) demonstrated more pronounced responses to supplemental irrigation. For instance, CH39/13 showed a notable increase in shoot length from 26.3 cm (RC) to 29.0 cm (SI), while CH30/12 exhibited a similar trend with canopy width increasing from 25.2 cm to 28.7 cm.

### Effect of water regimes on biomass accumulation traits of Chickpea

The biomass accumulation traits of chickpea genotypes were significantly influenced by water regimes. Across all genotypes, supplemental irrigation led to increases in total dry matter per plant, straw weight per plant, straw yield per square meter, and biological yield per hectare (Table 2). Among the

genotypes, CH21/13 recorded the highest values for all biomass traits under both rainfed and supplemental irrigation conditions. Its total dry matter per plant increased from 18.9 g to 22.7 g, straw weight per plant from 41.6 g to 48.2 g, straw yield per square meter from 91.8 g to 105.6 g, and biological yield per hectare from 7463 kg to 8350 kg. Genotypes TG-1427 and D-17006 followed closely, also showing strong performance under

both water regimes. In contrast, BRC-474 exhibited the lowest biomass accumulation across all traits, with total dry matter per plant ranging from 12.6 to 15.4 g and biological yield per hectare from 4285 to 4805 kg. The consistent improvement in biomass traits under supplemental irrigation indicates that increased water availability enhances dry matter production and overall productivity in chickpea, although the degree of response varied among the genotypes.

**Table 1** Effect of water regimes on vegetative growth traits of selected chickpea (*Cicer arietinum* L.) genotypes during 2020/2021 crop season

Genotypes	PH		NBPP		SL		CW	
	RC	SI	RC	SI	RC	SI	RC	SI
BRC-474	52.8 <sup>g</sup> ±1.3	56.9 <sup>f</sup> ±1.2	7.5 <sup>f</sup> ±0.23	7.1 <sup>f</sup> ±0.25	19.2 <sup>h</sup> ±0.24	21.8 <sup>i</sup> ±0.26	21.3 <sup>h</sup> ±1.16	24.9 <sup>h</sup> ±1.08
CH21/13	62.8 <sup>a</sup> ±1.5	68.2 <sup>a</sup> ±1.3	11.1 <sup>a</sup> ±0.25	10.4 <sup>a</sup> ±0.30	20.6 <sup>i</sup> ±0.23	23.4 <sup>i</sup> ±0.25	30.2 <sup>a</sup> ±1.25	33.6 <sup>a</sup> ±1.10
TG-1427	61.2 <sup>ab</sup> ±1.2	66.7 <sup>ab</sup> ±1.6	10.6 <sup>ab</sup> ±0.28	9.9 <sup>ab</sup> ±0.27	21.3 <sup>h</sup> ±0.25	24.1 <sup>h</sup> ±0.27	29.4 <sup>b</sup> ±1.30	32.8 <sup>b</sup> ±1.05
D-17006	60.1 <sup>bc</sup> ±1.4	65.4 <sup>b</sup> ±1.5	10.2 <sup>b</sup> ±0.30	9.6 <sup>b</sup> ±0.26	22.2 <sup>g</sup> ±0.26	25.0 <sup>g</sup> ±0.29	28.6 <sup>c</sup> ±1.22	31.9 <sup>c</sup> ±1.15
CH28/13	59.4 <sup>bc</sup> ±1.3	64.8 <sup>bc</sup> ±1.7	9.7 <sup>bc</sup> ±0.27	9.2 <sup>bc</sup> ±0.29	23.0 <sup>f</sup> ±0.27	25.9 <sup>f</sup> ±0.26	27.9 <sup>d</sup> ±1.18	30.8 <sup>d</sup> ±1.20
D-17028	58.9 <sup>cd</sup> ±1.7	63.6 <sup>cd</sup> ±1.4	9.3 <sup>cd</sup> ±0.29	8.8 <sup>cd</sup> ±0.24	23.8 <sup>e</sup> ±0.25	26.5 <sup>e</sup> ±0.24	26.8 <sup>e</sup> ±1.14	30.1 <sup>e</sup> ±1.13
D-17019	58.1 <sup>cd</sup> ±1.2	62.9 <sup>cd</sup> ±1.3	9.0 <sup>cd</sup> ±0.26	8.4 <sup>cd</sup> ±0.22	24.7 <sup>d</sup> ±0.28	27.3 <sup>d</sup> ±0.25	26.0 <sup>f</sup> ±1.17	29.5 <sup>f</sup> ±1.18
CH30/12	56.7 <sup>de</sup> ±1.6	61.2 <sup>de</sup> ±1.5	8.6 <sup>de</sup> ±0.25	8.1 <sup>de</sup> ±0.20	25.6 <sup>b</sup> ±0.26	28.2 <sup>b</sup> ±0.27	25.2 <sup>g</sup> ±1.15	28.7 <sup>g</sup> ±1.12
CH39/13	55.3 <sup>ef</sup> ±1.4	59.7 <sup>e</sup> ±1.6	8.3 <sup>de</sup> ±0.24	7.9 <sup>de</sup> ±0.21	26.3 <sup>a</sup> ±0.24	29.0 <sup>a</sup> ±0.23	24.6 <sup>h</sup> ±1.20	28.0 <sup>h</sup> ±1.10
TG-1504	54.1 <sup>f</sup> ±1.5	58.3 <sup>ef</sup> ±1.4	8.0 <sup>e</sup> ±0.22	7.6 <sup>e</sup> ±0.23	20.1 <sup>i</sup> ±0.22	22.6 <sup>i</sup> ±0.24	23.1 <sup>h</sup> ±1.10	26.2 <sup>i</sup> ±1.09

PH = Plant height (cm); NBPP = Number of branches per plant; SL = Shoot length (cm); CW = Canopy width (cm); RC = Rainfed condition; SI = Supplemental irrigation; Values following ± sign represent the standard deviation; Means followed by different letters within columns are significantly different at  $p < 0.05$  according to LSD test.

**Table 2** Effect of water regimes on biomass accumulation traits of selected chickpea (*Cicer arietinum* L.) genotypes during 2020/2021 crop season

Genotype	TDMPP		SWPP		SY		BY	
	RC	SI	RC	SI	RC	SI	RC	SI
BRC-474	12.6 <sup>g</sup> ±0.27	15.4 <sup>f</sup> ±0.25	24.3 <sup>h</sup> ±0.25	29.5 <sup>h</sup> ±0.27	54.1 <sup>h</sup> ±1.7	61.0 <sup>h</sup> ±1.8	4285 <sup>h</sup> ±61.8	4805 <sup>h</sup> ±66.0
CH21/13	18.9 <sup>a</sup> ±0.28	22.7 <sup>a</sup> ±0.30	41.6 <sup>a</sup> ±0.30	48.2 <sup>a</sup> ±0.32	91.8 <sup>a</sup> ±2.4	105.6 <sup>a</sup> ±3.1	7463 <sup>a</sup> ±85.3	8350 <sup>a</sup> ±90.5
TG-1427	18.1 <sup>b</sup> ±0.30	21.8 <sup>b</sup> ±0.28	39.5 <sup>b</sup> ±0.28	46.0 <sup>b</sup> ±0.31	87.9 <sup>b</sup> ±2.6	100.2 <sup>b</sup> ±2.9	7080 <sup>b</sup> ±82.7	7915 <sup>b</sup> ±87.2
D-17006	17.3 <sup>c</sup> ±0.27	20.9 <sup>c</sup> ±0.29	37.2 <sup>c</sup> ±0.29	43.5 <sup>c</sup> ±0.30	83.5 <sup>c</sup> ±2.5	94.5 <sup>c</sup> ±2.7	6725 <sup>c</sup> ±80.4	7510 <sup>c</sup> ±84.1
CH28/13	16.8 <sup>d</sup> ±0.26	20.1 <sup>d</sup> ±0.27	35.8 <sup>d</sup> ±0.27	41.1 <sup>d</sup> ±0.28	79.2 <sup>d</sup> ±2.3	89.3 <sup>d</sup> ±2.5	6380 <sup>d</sup> ±77.6	7120 <sup>d</sup> ±82.3
D-17028	16.2 <sup>e</sup> ±0.25	19.5 <sup>e</sup> ±0.26	33.9 <sup>e</sup> ±0.28	39.6 <sup>e</sup> ±0.27	75.0 <sup>e</sup> ±2.2	85.2 <sup>e</sup> ±2.3	6020 <sup>e</sup> ±75.1	6755 <sup>e</sup> ±80.2
D-17019	15.6 <sup>f</sup> ±0.29	18.8 <sup>f</sup> ±0.25	32.1 <sup>f</sup> ±0.25	37.8 <sup>f</sup> ±0.26	71.4 <sup>f</sup> ±2.0	81.3 <sup>f</sup> ±2.1	5685 <sup>f</sup> ±72.7	6380 <sup>f</sup> ±77.9
CH30/12	14.9 <sup>g</sup> ±0.30	18.0 <sup>g</sup> ±0.28	30.5 <sup>g</sup> ±0.26	36.0 <sup>g</sup> ±0.25	67.5 <sup>g</sup> ±1.9	77.0 <sup>g</sup> ±2.0	5310 <sup>g</sup> ±69.9	5950 <sup>g</sup> ±74.3
CH39/13	14.3 <sup>h</sup> ±0.24	17.2 <sup>h</sup> ±0.26	28.8 <sup>h</sup> ±0.24	33.7 <sup>h</sup> ±0.24	63.1 <sup>h</sup> ±1.8	71.6 <sup>h</sup> ±1.9	4975 <sup>h</sup> ±67.2	5560 <sup>h</sup> ±71.6
TG-1504	13.4 <sup>i</sup> ±0.26	16.3 <sup>i</sup> ±0.27	26.9 <sup>i</sup> ±0.27	31.8 <sup>i</sup> ±0.26	58.7 <sup>i</sup> ±1.9	66.3 <sup>i</sup> ±1.8	4630 <sup>i</sup> ±64.4	5190 <sup>i</sup> ±69.1

TDMPP = Total dry matter per plant (g); SWPP = Straw weight per plant (g); SY = Straw yield ( $\text{g m}^{-2}$ ); BY = Biological yield ( $\text{kg ha}^{-1}$ ); RC = Rainfed condition; SI = Supplemental irrigation; Values following ± sign represent the standard deviation; Means followed by different letters within columns are significantly different at  $p < 0.05$  according to LSD test.

**Effect of water regimes on root and shoot development traits of Chickpea**

Root and shoot development traits of chickpea genotypes were significantly affected by water regimes. Root length was consistently higher under rainfed conditions across all genotypes, with the longest roots recorded in TG-1427 (25.55 cm) and CH21/13 (24.42 cm) (Table 3). Under supplemental irrigation, root length decreased in all genotypes, though TG-1427 and CH21/13 still maintained relatively longer roots, with 17.37 and 16.22 cm, respectively. Shoot fresh weight and root fresh weight also showed reductions under irrigation but remained highest in the same two genotypes. TG-1427 exhibited the highest shoot fresh weight with 6.03 g under rainfed and 5.52 g

under irrigated conditions, followed by CH21/13 with 5.60 and 5.10 g, respectively. A similar trend was observed in root fresh weight, where TG-1427 and CH21/13 again led in both water regimes. In contrast, BRC-474 recorded the lowest values for root and shoot biomass, regardless of water availability. Canopy spread, however, increased under supplemental irrigation for all genotypes. TG-1427 exhibited the widest canopy, expanding from 52.4 cm under rainfed conditions to 60.3 cm under irrigation, followed closely by CH21/13. The smallest canopy spread was observed in BRC-474, TG-1504, and CH39/13. These findings highlight that while root traits tend to diminish with irrigation, shoot development and canopy expansion benefit from improved water availability, with considerable genotypic variation in response.

**Effect of water regimes on dry matter partitioning traits of Chickpea**

Dry matter partitioning traits of chickpea genotypes responded significantly to different water regimes. Across all genotypes, supplemental irrigation resulted in increased shoot dry weight, root dry weight, and leaf area index. The highest shoot dry weight was observed in genotype D-17006, increasing from 2.78 g under rainfed conditions to 3.02 g with supplemental irrigation, followed closely by CH21/13 and TG-1427 (Table 4). These three genotypes also showed the highest root dry weight values, with D-17006 reaching up to 2.02 g under irrigation. The root to shoot ratio, however, showed minimal variation between

water regimes, remaining relatively stable across genotypes. Interestingly, genotypes with higher shoot and root dry weights tended to have lower root to shoot ratios, suggesting a balanced growth pattern between above-ground and below-ground biomass. The leaf area index improved under supplemental irrigation for all genotypes, with D-17006 again recording the highest value (1.20), followed by CH21/13 and TG-1427. In contrast, BRC-474 consistently recorded the lowest values for all traits, including shoot dry weight, root dry weight, and leaf area index, regardless of water availability. These results indicate that supplemental irrigation enhances dry matter accumulation and canopy development, particularly in high-performing genotypes, without significantly altering the proportional allocation between shoot and root biomass.

**Table 3** Effect of water regimes on root and shoot development traits of selected chickpea (*Cicer arietinum* L.) genotypes during 2020/2021 crop season

Genotype	RL		SFW		RFW		CS	
	RC	SI	RC	SI	RC	SI	RC	SI
BRC-474	11.62±0.25	10.91±0.24	1.05 ± 0.06 <sup>j</sup>	0.90 ± 0.05 <sup>j</sup>	1.05±0.06	0.90±0.05	32.8±0.9	37.7±0.9
TG-1427	25.55±0.42	17.37±0.38	6.03±0.18	5.52±0.16	5.15±0.14	4.62±0.13	52.4±1.3	60.3±1.4
CH21/13	24.42±0.40	16.22±0.36	5.60±0.17	5.10±0.15	4.73±0.13	4.28±0.12	50.1±1.2	57.6±1.3
D-17006	23.22±0.37	15.30±0.33	5.00±0.15	4.52±0.14	4.25±0.12	3.84±0.11	47.8±1.2	55.0±1.3
CH28/13	22.39±0.35	14.15±0.32	4.40±0.14	3.90±0.12	3.78±0.11	3.36±0.10	45.6±1.1	52.2±1.2
D-17028	18.22±0.33	14.94±0.31	3.85±0.12	3.30±0.11	3.30±0.10	2.95±0.09	43.1±1.1	49.6±1.2
D-17019	17.22±0.31	13.71±0.30	3.10±0.11	2.65±0.09	2.85±0.09	2.52±0.08	41.0±1.0	47.1±1.1
CH30/12	16.25±0.30	13.64±0.29	2.45±0.10	2.10±0.08	2.30±0.08	2.00±0.07	38.4±1.0	44.8±1.1
CH39/13	15.30±0.28	13.10±0.28	1.90±0.08	1.55±0.07	1.75±0.07	1.45±0.06	36.1±0.9	41.7±1.0
TG-1504	14.15±0.27	12.32±0.26	1.35±0.07	1.15±0.06	1.25±0.06	1.05±0.05	34.0±0.9	39.1±1.0

RL = Root length (cm); SFW = Shoot fresh weight (g); RFW = Root fresh weight (g); CS = Canopy spread (cm); RC = Rainfed condition; Values following ± sign represent the standard deviation; SI = Supplemental irrigation; Means followed by different letters within columns are significantly different at p < 0.05 according to LSD test.

**Table 4** Effect of water regimes on dry matter partitioning traits of selected chickpea (*Cicer arietinum* L.) genotypes during 2020/2021 crop season

Genotype	SDW		RDW		R/S ratio		LAI	
	RC	SI	RC	SI	RC	SI	RC	SI
BRC-474	1.52±0.06	1.65±0.05	1.22±0.04	1.35±0.04	0.80±0.03	0.82±0.03	0.56±0.02	0.64±0.02
D-17006	2.78±0.09	3.02±0.10	1.88±0.05	2.02±0.06	0.68±0.02	0.67±0.02	1.12±0.04	1.20±0.05
CH21/13	2.65±0.07	2.89±0.08	1.80±0.06	1.95±0.05	0.68±0.02	0.67±0.02	1.05±0.03	1.12±0.04
TG-1427	2.53±0.06	2.78±0.07	1.72±0.05	1.86±0.06	0.68±0.02	0.67±0.02	0.96±0.04	1.05±0.05
CH28/13	2.42±0.08	2.66±0.07	1.65±0.04	1.79±0.05	0.68±0.02	0.67±0.02	0.88±0.05	0.97±0.04
D-17028	2.30±0.07	2.54±0.08	1.59±0.05	1.72±0.05	0.69±0.02	0.68±0.02	0.82±0.04	0.92±0.04
D-17019	2.18±0.05	2.39±0.06	1.52±0.04	1.65±0.04	0.70±0.02	0.69±0.02	0.76±0.03	0.86±0.04
CH30/12	2.05±0.06	2.24±0.06	1.45±0.05	1.58±0.05	0.71±0.02	0.70±0.02	0.71±0.03	0.81±0.03
CH39/13	1.94±0.05	2.15±0.07	1.38±0.04	1.52±0.05	0.71±0.02	0.71±0.02	0.66±0.03	0.76±0.03
TG-1504	1.82±0.04	2.01±0.05	1.30±0.05	1.44±0.04	0.72±0.02	0.72±0.02	0.61±0.02	0.70±0.03

SDW = Shoot dry weight (g); RDW = Root dry weight (g); R/S ratio = Root to shoot ratio; LAI = Leaf area index; RC = Rainfed condition; SI = Supplemental irrigation; Values following ± sign represent the standard deviation; Means followed by different letters within columns are significantly different at p < 0.05 according to LSD test.

**Table 5** Effect of water regimes on nutrient and water use efficiency traits of selected chickpea (*Cicer arietinum* L.) genotypes during 2020/2021 crop season

Genotype	SP		DF		DM		HI	
	RC	SI	RC	SI	RC	SI	RC	SI
BRC-474	48.0±0.5	50.0±0.5	106.3±0.5	104.5±0.6	117.5±0.6	115.8±0.6	22.5±0.5	24.6±0.5
CH21/13	63.0±0.6	65.0±0.5	91.2±0.5	89.5±0.6	104.2±0.6	102.5±0.5	38.6±0.6	40.0±0.5
D-17006	61.0±0.5	63.0±0.6	93.0±0.6	91.0±0.5	106.0±0.6	104.3±0.6	36.8±0.5	38.5±0.6
TG-1427	59.0±0.6	61.0±0.5	94.8±0.7	93.0±0.6	107.8±0.6	106.0±0.5	34.9±0.6	36.7±0.5
CH28/13	57.0±0.5	60.0±0.6	96.5±0.6	94.7±0.6	109.3±0.7	107.6±0.6	33.0±0.5	35.2±0.6
D-17028	56.0±0.4	59.0±0.5	98.0±0.5	96.3±0.7	110.7±0.6	109.0±0.6	31.7±0.6	33.9±0.5

D-17019	55.0 <sup>ef</sup> ±0.5	57.0 <sup>ef</sup> ±0.6	99.5 <sup>c</sup> ±0.6	97.7 <sup>c</sup> ±0.6	112.0 <sup>c</sup> ±0.5	110.2 <sup>c</sup> ±0.5	29.8 <sup>ef</sup> ±0.5	32.1 <sup>ef</sup> ±0.6
CH30/12	54.0 <sup>fg</sup> ±0.6	56.0 <sup>fg</sup> ±0.5	101.0 <sup>bc</sup> ±0.5	99.3 <sup>bc</sup> ±0.5	113.5 <sup>bc</sup> ±0.6	111.8 <sup>bc</sup> ±0.6	28.4 <sup>fg</sup> ±0.6	30.6 <sup>fg</sup> ±0.5
CH39/13	54.0 <sup>fg</sup> ±0.5	55.0 <sup>g</sup> ±0.6	102.7 <sup>b</sup> ±0.6	101.0 <sup>b</sup> ±0.6	114.7 <sup>b</sup> ±0.5	113.0 <sup>b</sup> ±0.5	27.2 <sup>g</sup> ±0.5	29.3 <sup>g</sup> ±0.6
TG-1504	53.0 <sup>g</sup> ±0.6	54.0 <sup>g</sup> ±0.5	104.5 <sup>ab</sup> ±0.6	102.8 <sup>ab</sup> ±0.5	116.0 <sup>ab</sup> ±0.6	114.2 <sup>ab</sup> ±0.5	25.6 <sup>h</sup> ±0.6	27.8 <sup>h</sup> ±0.5

SP = Shelling percentage; DF = Days to flowering; DM = Days to maturity; HI = Harvest index (%); RC = Rainfed condition; SI = Supplemental irrigation; Values following ± sign represent the standard deviation; Means followed by different letters within columns are significantly different at p < 0.05 according to LSD test.

**Effect of water regimes on nutrient and water use efficiency traits of Chickpea**

Water regimes significantly influenced nutrient and water use efficiency traits across the tested chickpea genotypes. Shelling percentage was significantly higher under supplemental irrigation across all genotypes, with CH21/13 showed the highest values of 63% under rainfed conditions and increasing to 65% with supplemental irrigation (Table 5). This was followed closely by D-17006 and TG-1427. In contrast, BRC-474 recorded the lowest shelling percentage under both conditions. Regarding phenological development, days to flowering and days to maturity were reduced under supplemental irrigation for all genotypes, indicating an accelerated crop cycle in improved moisture conditions. CH21/13 reached flowering earliest, while BRC-474 was the latest flowering genotype. Similarly, BRC-474 also exhibited the longest duration to maturity, taking over 117 days under rainfed and 115 days with irrigation, whereas CH21/13 matured the earliest, in approximately 104 days. Harvest index, which reflects the proportion of economic yield to total biomass, improved under supplemental irrigation in all genotypes. CH21/13 again stood out with the highest harvest index values (38.6%) under rainfed and 40% under irrigated conditions followed by D-17006 and TG-1427. Conversely, BRC-474 had the lowest harvest index, increasing only slightly from 22.5% to 24.6% with supplemental watering.

**Effect of water regimes on floral and pod development traits of Chickpea**

Floral and pod development traits of chickpea genotypes were significantly influenced by water regimes. Across all genotypes, the number of flowers per plant increased under supplemental irrigation, with CH21/13 producing the highest number (82.4 flowers per plant) under rainfed conditions and increasing to 105.7 under supplemental irrigation (Table 6). This was followed closely by TG-1427 and D-17006. In contrast, BRC-474 consistently recorded the lowest flower production under both conditions. The number of pods per plant increased under supplemental irrigation for all genotypes. CH21/13 outperformed other genotypes with 55.6 pods per plant under irrigation, while BRC-474 remained at the lower end with only 41.3 pods. Pod length did not show significant variation among genotypes or between water regimes, remaining relatively stable at around 2.1 to 2.2 cm across treatments. However, the number of seeds per pod showed the modest improvement under supplemental irrigation. CH21/13 and TG-1427 produced the highest seed numbers per pod, reaching 1.72 and 1.70 seeds per pod, respectively, under irrigation. Conversely, BRC-474 had the lowest values in this trait. Overall, supplemental irrigation consistently enhanced floral and reproductive development traits, with CH21/13 and TG-1427 emerging as the most responsive and productive genotypes under improved moisture conditions.

**Table 6** Effect of water regimes on floral and pod development traits of selected chickpea (*Cicer arietinum* L.) genotypes during 2020/2021 crop season

Genotype	NFPP		NPPP		PL		NSPP	
	RC	SI	RC	SI	RC	SI	RC	SI
BRC-474	55.3 <sup>b</sup> ±5.2	78.6 <sup>ab</sup> ±6.4	38.7 <sup>d</sup> ±2.8	41.3 <sup>d</sup> ±2.5	2.1 <sup>a</sup> ±0.05	2.1 <sup>a</sup> ±0.04	1.47 <sup>c</sup> ±0.05	1.54 <sup>c</sup> ±0.04
CH21/13	82.4 <sup>a</sup> ±6.8	105.7 <sup>a</sup> ±5.3	52.8 <sup>a</sup> ±3.2	55.6 <sup>a</sup> ±2.9	2.2 <sup>a</sup> ±0.05	2.2 <sup>a</sup> ±0.06	1.60 <sup>abc</sup> ±0.05	1.72 <sup>a</sup> ±0.04
TG-1427	79.1 <sup>a</sup> ±7.1	101.8 <sup>a</sup> ±6.1	50.6 <sup>ab</sup> ±3.1	54.2 <sup>ab</sup> ±3.0	2.2 <sup>a</sup> ±0.04	2.2 <sup>a</sup> ±0.05	1.58 <sup>abc</sup> ±0.06	1.70 <sup>a</sup> ±0.05
D-17006	75.2 <sup>ab</sup> ±6.2	98.9 <sup>a</sup> ±5.9	48.9 <sup>abc</sup> ±2.8	52.3 <sup>abc</sup> ±2.6	2.2 <sup>a</sup> ±0.05	2.1 <sup>a</sup> ±0.05	1.56 <sup>bc</sup> ±0.05	1.67 <sup>ab</sup> ±0.04
CH28/13	71.3 <sup>ab</sup> ±5.7	95.6 <sup>a</sup> ±6.0	47.1 <sup>abc</sup> ±3.4	50.2 <sup>abc</sup> ±2.7	2.1 <sup>a</sup> ±0.05	2.2 <sup>a</sup> ±0.04	1.54 <sup>bc</sup> ±0.05	1.65 <sup>abc</sup> ±0.06
D-17028	68.4 <sup>ab</sup> ±5.5	91.3 <sup>ab</sup> ±5.4	45.8 <sup>abcd</sup> ±2.9	48.7 <sup>abcd</sup> ±2.5	2.1 <sup>a</sup> ±0.04	2.2 <sup>a</sup> ±0.05	1.53 <sup>bc</sup> ±0.06	1.63 <sup>abc</sup> ±0.05
D-17019	65.7 <sup>ab</sup> ±5.1	89.2 <sup>ab</sup> ±6.2	44.3 <sup>abcd</sup> ±3.0	47.6 <sup>abcd</sup> ±2.6	2.1 <sup>a</sup> ±0.05	2.1 <sup>a</sup> ±0.06	1.52 <sup>bc</sup> ±0.05	1.61 <sup>bc</sup> ±0.06
CH30/12	62.9 <sup>b</sup> ± 6.4	86.7 <sup>ab</sup> ±5.8	42.9 <sup>bcd</sup> ±2.7	46.1 <sup>bcd</sup> ±2.9	2.1 <sup>a</sup> ±0.06	2.1 <sup>a</sup> ±0.05	1.51 <sup>c</sup> ±0.05	1.60 <sup>bc</sup> ±0.05
CH39/13	60.2 <sup>b</sup> ±5.8	83.3 <sup>ab</sup> ±6.7	41.5 <sup>cd</sup> ±2.6	44.8 <sup>cd</sup> ±2.8	2.1 <sup>a</sup> ±0.05	2.1 <sup>a</sup> ±0.06	1.50 <sup>c</sup> ±0.05	1.58 <sup>c</sup> ±0.04
TG-1504	58.1 <sup>b</sup> ±4.9	81.2 <sup>ab</sup> ±5.6	40.2 <sup>cd</sup> ±2.9	43.5 <sup>cd</sup> ±3.1	2.1 <sup>a</sup> ±0.06	2.1 <sup>a</sup> ±0.05	1.49 <sup>c</sup> ±0.04	1.56 <sup>c</sup> ±0.05

NFPP = Number of flowers per plant; NPPP = Number of pods per plant; PL = Pod length (cm); NSPP = Number of seeds per pod; RC = Rainfed condition; SI = Supplemental irrigation; Values following ± sign represent the standard deviation; Means followed by different letters within columns are significantly different at p < 0.05 according to LSD test.

**Effect of water regimes on seed production and yield traits of Chickpea**

Chickpea genotypes showed significant changes in seed production and yield traits in response to varying water

regimes (Table 7). Supplemental irrigation consistently enhanced all measured parameters across the genotypes. The number of seeds per plant was higher under irrigation, with TG-1427 and CH21/13 showing the greatest seed production, 44.5 and 42.8 seeds per plant, respectively. In contrast, BRC-

474 and TG-1504 produced significantly fewer seeds, especially under rainfed conditions. Thousand-seed weight increased slightly under irrigation for all genotypes. TG-1427 and CH21/13 achieved the highest weights, exceeding 270 g, while BRC-474 had the lowest, weight (255 g) even with irrigation. Seed weight per plant followed a similar trend, with TG-1427 producing up to 38.2 g per plant under irrigation, indicating strong sink strength and efficient resource use. BRC-474 again lagged behind, with seed weights of only 19.8 g under rainfed and

24.9 g under irrigated conditions. Grain yield was significantly influenced by water availability. TG-1427 recorded the highest yield (12,606 kg ha<sup>-1</sup>) under supplemental irrigation, followed closely by CH21/13 and D-17006. The lowest yields were observed in BRC-474 and TG-1504 under both water regimes. These findings confirm that genotypes like TG-1427 and CH21/13 are particularly responsive to improved moisture conditions and are suitable candidates for cultivation under water-limited environments with supplemental irrigation.

**Table 7** Effect of water regimes on seed production and yield traits of selected chickpea (*Cicer arietinum* L.) genotypes during 2020/2021 crop season

Genotype	NSPP		1000-SW		SWPP		GY	
	RC	SI	RC	SI	RC	SI	RC	SI
BRC-474	26.1 <sup>d</sup> ±2.3	30.9 <sup>d</sup> ±2.1	235.3 <sup>d</sup> ±6.9	252.6 <sup>d</sup> ±6.8	19.8 <sup>d</sup> ±1.3	24.9 <sup>d</sup> ±1.4	6,534 <sup>d</sup> ±429	8,217 <sup>d</sup> ±462
TG-1427	39.8 <sup>a</sup> ±2.1	44.5 <sup>a</sup> ±2.3	259.2 <sup>ab</sup> ±6.8	275.5 <sup>a</sup> ±7.2	31.6 <sup>a</sup> ±1.4	38.2 <sup>a</sup> ±1.6	10,428 <sup>a</sup> ±461	12,606 <sup>a</sup> ±529
CH21/13	38.5 <sup>a</sup> ±2.0	42.8 <sup>a</sup> ±2.2	258.1 <sup>ab</sup> ±7.0	273.3 <sup>a</sup> ±6.7	30.2 <sup>a</sup> ±1.3	36.7 <sup>a</sup> ±1.5	9,966 <sup>a</sup> ±429	12,111 <sup>a</sup> ±495
D-17006	36.9 <sup>ab</sup> ±2.2	41.2 <sup>a</sup> ±2.1	254.6 <sup>ab</sup> ±7.1	270.2 <sup>ab</sup> ±6.8	28.6 <sup>ab</sup> ±1.5	35.2 <sup>ab</sup> ±1.4	9,438 <sup>ab</sup> ±495	11,616 <sup>ab</sup> ±461
CH28/13	34.6 <sup>abc</sup> ±2.1	39.5 <sup>ab</sup> ±2.3	250.8 <sup>ab</sup> ±6.6	266.4 <sup>ab</sup> ±6.9	27.1 <sup>b</sup> ±1.4	33.6 <sup>b</sup> ±1.5	8,943 <sup>b</sup> ±462	11,088 <sup>b</sup> ±495
D-17028	33.1 <sup>abc</sup> ±2.3	38.2 <sup>abc</sup> ±2	248.3 <sup>b</sup> ±6.9	264.9 <sup>ab</sup> ±7.1	25.9 <sup>bc</sup> ±1.5	32.5 <sup>b</sup> ±1.6	8,547 <sup>b</sup> ±495	10,725 <sup>b</sup> ±528
D-17019	31.7 <sup>bc</sup> ±2.0	36.9 <sup>bc</sup> ±2.2	246.2 <sup>bc</sup> ±7.0	263.1 <sup>bc</sup> ±6.7	24.6 <sup>bc</sup> ±1.3	30.9 <sup>bc</sup> ±1.5	8,118 <sup>bc</sup> ±429	10,197 <sup>bc</sup> ±495
CH30/12	30.2 <sup>c</sup> ±2.2	35.7 <sup>c</sup> ±2.1	243.7 <sup>bc</sup> ±6.5	260.8 <sup>bc</sup> ±7.0	23.4 <sup>c</sup> ±1.4	29.6 <sup>c</sup> ±1.4	7,722 <sup>c</sup> ±462	9,768 <sup>c</sup> ±462
CH39/13	28.9 <sup>c</sup> ±2.0	34.1 <sup>c</sup> ±2.0	240.9 <sup>c</sup> ±6.8	258.7 <sup>c</sup> ±7.2	22.1 <sup>cd</sup> ±1.5	27.8 <sup>cd</sup> ±1.3	7,293 <sup>cd</sup> ±495	9,174 <sup>cd</sup> ±429
TG-1504	27.6 <sup>cd</sup> ±2.1	32.5 <sup>cd</sup> ±2.3	237.6 <sup>cd</sup> ±6.7	255.4 <sup>cd</sup> ±6.9	20.9 <sup>d</sup> ±1.4	26.3 <sup>d</sup> ±1.5	6,897 <sup>d</sup> ±462	8,679 <sup>d</sup> ±495

NSPP = Number of seeds per plant; 1000-SW = 1000-seed weight (g); SWPP = Seed weight per plant (g); GY = Grain yield (kg ha<sup>-1</sup>); RC = Rainfed condition; SI = Supplemental irrigation; Values following ± sign represent the standard deviation; Means followed by different letters within columns are significantly different at p < 0.05 according to LSD test.

**Effect of water regimes on drought stress physiology traits of Chickpea**

The drought stress physiology traits of selected chickpea genotypes showed significant variation in response to different water regimes during the 2020/2021 crop season (Table 8). Shoot and root malondialdehyde levels, which indicate lipid peroxidation and oxidative stress were consistently higher under rainfed conditions across all genotypes. The genotype TG-1504 exhibited the highest shoot malondialdehyde (0.48 μmol g<sup>-1</sup> FW) and root malondialdehyde (0.52 μmol g<sup>-1</sup> FW) under rainfed conditions, followed closely by CH39/13 and CH30/12. In contrast, CH21/13 and TG-1427 recorded significantly lower malondialdehyde contents under both rainfed and supplemental irrigation conditions, suggesting better oxidative stress management. Under supplemental irrigation, malondialdehyde levels significantly decreased in all genotypes, with CH21/13 showing the lowest shoot malondialdehyde (0.17 μmol g<sup>-1</sup> FW) and root malondialdehyde (0.18 μmol g<sup>-1</sup> FW). Leaf relative water content was significantly influenced by both water regime and genotype. Under rainfed conditions, CH21/13 (54.1%) and TG-1427 (52.4%) maintained the highest leaf relative water contents, suggesting a greater ability to retain water under drought stress. These two genotypes also retained high relative water content under supplemental irrigation (59.3% and 58%, respectively). In contrast, BRC-474 recorded the lowest relative water content (38.6%) under rainfed conditions. Leaf proline accumulation, which

reflects the plant's osmotic adjustment under drought, showed significant differences among genotypes. Under rainfed conditions, CH21/13 (272.5 μg g<sup>-1</sup> FW), TG-1427 (268.3 μg g<sup>-1</sup> FW), and D-17006 (260.2 μg g<sup>-1</sup> FW) showed the highest proline contents. These values remained high under supplemental irrigation, with CH21/13 maintaining the highest level (209.4 μg g<sup>-1</sup> FW), indicating its superior drought adaptation. On the other hand, BRC-474 exhibited the lowest leaf proline content under both rainfed (209.3 μg g<sup>-1</sup> FW) and supplemental irrigation conditions (149.4 μg g<sup>-1</sup> FW).

**Effect of water regimes on photosynthetic pigments traits of Chickpea**

The water regimes had a significant effect on photosynthetic pigment traits namely chlorophyll a content, chlorophyll b content, total chlorophyll content, and the chlorophyll a to chlorophyll b ratio (Table 9). Genotypes CH21/13, TG-1427, and D-17006 recorded the highest chlorophyll a contents under both conditions, with CH21/13 reaching 0.68 mg/g fresh weight under rainfed condition and 0.78 mg/g fresh weight under supplemental irrigation. In contrast, BRC-474 and TG-1504 had the lowest chlorophyll a content, particularly under rainfed condition (0.38 mg/g and 0.42 ± 0.06 mg/g fresh weight, respectively). A similar trend was observed in chlorophyll b content. The genotypes CH21/13, TG-1427, and D-17006 also exhibited significantly higher chlorophyll b levels under both water regimes, with CH21/13 achieving 0.25 ± 0.02 mg/g under rainfed condition and 0.27 ± 0.02 mg/g under supplemental irrigation. In contrast, TG-1504 and BRC-

474 had the lowest chlorophyll b contents under both regimes. Total chlorophyll content (sum of chlorophyll a and b) was highest in CH21/13 (0.93 mg/g under rainfed; 1.05 mg/g under supplemental irrigation), followed closely by TG-1427 and D-17006. Genotypes such as BRC-474 and TG-1504 recorded significantly lower total chlorophyll levels, particularly under rainfed condition (0.50 mg/g and 0.55 mg/g, respectively). The chlorophyll a to chlorophyll

b ratio differed significantly across genotypes but was generally less affected by the water regime. Higher ratios were found in BRC-474 (3.17 under rainfed), and TG-1504 (3.23), while CH21/13, TG-1427, and other high-performing genotypes had significantly lower ratios (approximately 2.71–2.74 under rainfed), indicating a more balanced pigment composition.

**Table 8** Effect of water regimes on drought stress physiology traits of selected chickpea (*Cicer arietinum* L.) genotypes during 2020/2021 crop season

Genotype	SMDA		RMDA		RWC		PC	
	RC	SI	RC	SI	RC	SI	RC	SI
BRC-474	0.42 <sup>ab</sup> ±0.04	0.25 <sup>b</sup> ±0.02	0.46 <sup>ab</sup> ±0.04	0.16 <sup>d</sup> ±0.02	38.6 <sup>d</sup> ±2.1	45.2 <sup>d</sup> ±2.1	209.3 <sup>d</sup> ±6.7	149.4 <sup>d</sup> ±5.6
CH21/13	0.29 <sup>c</sup> ±0.03	0.17 <sup>d</sup> ±0.02	0.33 <sup>c</sup> ±0.03	0.18 <sup>d</sup> ±0.02	54.1 <sup>a</sup> ±2.2	59.3 <sup>a</sup> ±2.0	272.5 <sup>a</sup> ±8.2	209.4 <sup>a</sup> ±7.6
TG-1427	0.32 <sup>c</sup> ±0.04	0.18 <sup>d</sup> ±0.02	0.35 <sup>c</sup> ±0.04	0.19 <sup>cd</sup> ±0.02	52.4 <sup>ab</sup> ±2.1	58.0 <sup>a</sup> ±2.1	268.3 <sup>a</sup> ±8.4	203.6 <sup>a</sup> ±7.3
D-17006	0.34 <sup>bc</sup> ±0.03	0.20 <sup>cd</sup> ±0.02	0.37 <sup>bc</sup> ±0.03	0.21 <sup>c</sup> ±0.02	50.6 <sup>ab</sup> ±2.2	56.5 <sup>ab</sup> ±2.0	260.2 <sup>ab</sup> ±8.1	198.7 <sup>ab</sup> ±6.9
CH28/13	0.37 <sup>b</sup> ±0.03	0.22 <sup>c</sup> ±0.02	0.40 <sup>b</sup> ±0.04	0.22 <sup>c</sup> ±0.02	48.7 <sup>b</sup> ±2.3	54.9 <sup>b</sup> ±2.1	254.7 <sup>b</sup> ±7.8	191.5 <sup>b</sup> ±6.8
D-17028	0.39 <sup>b</sup> ±0.04	0.24 <sup>c</sup> ±0.03	0.42 <sup>b</sup> ±0.03	0.24 <sup>bc</sup> ±0.03	47.2 <sup>bc</sup> ±2.0	53.3 <sup>bc</sup> ±2.0	247.9 <sup>bc</sup> ±7.9	186.3 <sup>bc</sup> ±6.5
D-17019	0.41 <sup>ab</sup> ±0.04	0.26 <sup>b</sup> ±0.02	0.45 <sup>ab</sup> ±0.04	0.26 <sup>bc</sup> ±0.02	45.5 <sup>bc</sup> ±2.1	51.6 <sup>bc</sup> ±2.2	239.6 <sup>bc</sup> ±7.6	179.4 <sup>bc</sup> ±6.3
CH30/12	0.43 <sup>ab</sup> ±0.03	0.27 <sup>b</sup> ±0.02	0.47 <sup>ab</sup> ±0.03	0.28 <sup>b</sup> ±0.02	43.7 <sup>c</sup> ±2.0	50.3 <sup>c</sup> ±2.0	231.8 <sup>cd</sup> ±7.3	171.8 <sup>cd</sup> ±6.0
CH39/13	0.46 <sup>a</sup> ±0.04	0.28 <sup>b</sup> ±0.03	0.49 <sup>a</sup> ±0.04	0.29 <sup>b</sup> ±0.02	41.9 <sup>cd</sup> ±2.1	48.7 <sup>cd</sup> ±2.1	226.5 <sup>cd</sup> ±7.1	165.2 <sup>cd</sup> ±5.9
TG-1504	0.48 <sup>a</sup> ±0.03	0.30 <sup>b</sup> ±0.02	0.52 <sup>a</sup> ±0.03	0.31 <sup>b</sup> ±0.02	40.3 <sup>cd</sup> ±2.2	47.0 <sup>d</sup> ±2.0	218.1 <sup>d</sup> ±6.9	158.7 <sup>d</sup> ±5.7

SMDA = Shoot malondialdehyde (µmol g<sup>-1</sup> FW); RMDA = Root malondialdehyde (µmol g<sup>-1</sup> FW); RWC = Leaf relative water contents (%); PC = Proline contents (µg g<sup>-1</sup> FW); RC = Rainfed condition; SI = Supplemental irrigation; Values following ± sign represent the standard deviation; Means followed by different letters within columns are significantly different at p < 0.05 according to LSD test.

**Table 9** Effect of water regimes on photosynthetic pigments traits of selected chickpea (*Cicer arietinum* L.) genotypes during 2020/2021 crop season

Genotype	Chl a		Chl b		Total Chl		Chl a/b	
	RC	SI	RC	SI	RC	SI	RC	SI
BRC-474	0.38 <sup>c</sup> ±0.05	0.45 <sup>c</sup> ±0.04	0.12 <sup>c</sup> ±0.02	0.14 <sup>c</sup> ±0.02	0.50 <sup>d</sup> ±0.07	0.59 <sup>d</sup> ±0.05	3.17 <sup>c</sup> ±0.15	3.21 <sup>c</sup> ±0.12
CH21/13	0.68 <sup>a</sup> ±0.04	0.78 <sup>a</sup> ±0.05	0.25 <sup>a</sup> ±0.02	0.27 <sup>a</sup> ±0.02	0.93 <sup>a</sup> ±0.05	1.05 <sup>a</sup> ±0.06	2.72 <sup>d</sup> ±0.07	2.89 <sup>d</sup> ±0.08
TG-1427	0.65 <sup>a</sup> ±0.04	0.75 <sup>a</sup> ±0.05	0.24 <sup>a</sup> ±0.02	0.26 <sup>a</sup> ±0.02	0.89 <sup>ab</sup> ±0.06	1.01 <sup>ab</sup> ±0.06	2.71 <sup>d</sup> ±0.08	2.88 <sup>d</sup> ±0.09
D-17006	0.63 <sup>a</sup> ±0.05	0.72 <sup>a</sup> ±0.05	0.23 <sup>a</sup> ±0.02	0.25 <sup>a</sup> ±0.02	0.86 <sup>ab</sup> ±0.06	0.97 <sup>ab</sup> ±0.06	2.74 <sup>d</sup> ±0.09	2.88 <sup>d</sup> ±0.10
CH28/13	0.60 <sup>ab</sup> ±0.05	0.68 <sup>ab</sup> ±0.05	0.22 <sup>ab</sup> ±0.02	0.24 <sup>ab</sup> ±0.02	0.82 <sup>b</sup> ±0.06	0.92 <sup>b</sup> ±0.06	2.73 <sup>d</sup> ±0.10	2.83 <sup>d</sup> ±0.09
D-17028	0.55 <sup>ab</sup> ±0.05	0.63 <sup>ab</sup> ±0.05	0.20 <sup>ab</sup> ±0.02	0.22 <sup>ab</sup> ±0.02	0.75 <sup>bc</sup> ±0.06	0.85 <sup>bc</sup> ±0.06	2.75 <sup>d</sup> ±0.11	2.86 <sup>d</sup> ±0.10
D-17019	0.50 <sup>b</sup> ±0.06	0.58 <sup>b</sup> ±0.05	0.18 <sup>b</sup> ±0.02	0.20 <sup>b</sup> ±0.02	0.68 <sup>c</sup> ±0.07	0.78 <sup>c</sup> ±0.06	2.78 <sup>d</sup> ±0.13	2.90 <sup>d</sup> ±0.11
CH30/12	0.48 <sup>b</sup> ±0.05	0.55 <sup>b</sup> ±0.05	0.17 <sup>b</sup> ±0.02	0.19 <sup>b</sup> ±0.02	0.65 <sup>c</sup> ±0.06	0.74 <sup>c</sup> ±0.06	2.82 <sup>d</sup> ±0.12	2.89 <sup>d</sup> ±0.10
CH39/13	0.46 <sup>b</sup> ±0.04	0.52 <sup>b</sup> ±0.04	0.16 <sup>b</sup> ±0.02	0.18 <sup>b</sup> ±0.02	0.62 <sup>c</sup> ±0.06	0.70 <sup>c</sup> ±0.05	2.88 <sup>d</sup> ±0.10	2.89 <sup>d</sup> ±0.09
TG-1504	0.42 <sup>c</sup> ±0.06	0.50 <sup>c</sup> ±0.05	0.13 <sup>c</sup> ±0.02	0.15 <sup>c</sup> ±0.02	0.55 <sup>d</sup> ±0.08	0.65 <sup>d</sup> ±0.06	3.23 <sup>c</sup> ±0.14	3.33 <sup>c</sup> ±0.11

Chl a = Chlorophyll a content (mg g<sup>-1</sup> FW); Chl b = Chlorophyll b content (mg g<sup>-1</sup> FW); Total Chl = Total chlorophyll content (mg g<sup>-1</sup> FW); Chl a/b = Chlorophyll a/b ratio; RC = Rainfed condition; SI = Supplemental irrigation; Values following ± sign represent the standard deviation; Means followed by different letters within columns are significantly different at p < 0.05 according to LSD test.

## Discussion

In recent years, there has been growing attention on the need to diversify global food sources due to increasing population pressures and the ongoing depletion of arable land (FAO, 2017; Iqbal et al., 2018; Abbas & Shafique, 2019; Alamgeer et al., 2022; Dinsa & Balcha, 2024). Meeting the rising food demand will require a 60% increase in agricultural productivity by 2050. However, climate change, especially water scarcity poses significant challenges to achieving sustainable crop production (Bourgault et al., 2020). In this context, legumes have emerged as important crops for enhancing food security, improving nutrition, and contributing to climate change mitigation (Calles et al., 2019; Iannetta et al., 2021).

Despite their potential, water stress negatively impacts multiple stages of chickpea growth, including germination and final yield (Yücel et al., 2010; Azimi et al., 2015). A thorough understanding of genotypic variation in drought resilience is therefore essential to guide breeding programs and improve chickpea productivity under water-limited conditions.

Plant height was significantly influenced by both chickpea variety and water regime. Reduced plant height has been commonly observed in chickpeas grown under rainfed conditions (Hussain et al., 2015). Consistent with the present study, El-Warakly and Koliey (2000) reported that irrigation applied during branching, flowering, and pod development stages resulted in taller plants. Among the varieties tested, CH21/13 produced the tallest plants, whereas BRC-474 showed the shortest stature. Across all genotypes, plants under rainfed conditions exhibited consistently lower heights

compared to those receiving supplemental irrigation. For instance, CH21/13 decreased from 68.2 cm under irrigation to 62.8 cm under rainfed conditions, highlighting the negative impact of limited water on vegetative growth. Under water-limited conditions, plant growth is generally inhibited due to reduced transpiration as stomata close to conserve water. Additionally, apoplastic barriers restrict the movement of water and solutes into plant tissues, leading to lower biomass accumulation (Basu et al., 2016; Feng et al., 2016). Plant height is also regulated by hormonal interactions, particularly auxin, which drives cell elongation. Water deficit limits cell expansion, and drought stress may reduce auxin biosynthesis, further contributing to decreased plant height under rainfed conditions (Pandey & Shukla, 2016).

Supplemental irrigation had a significant effect on the number of branches per plant, with a notable interaction between irrigation regime and variety. In contrast to the findings of El-Waraky and Koley (2000), who reported increased branches and seeds per plant when irrigation was applied at branching, flowering, and pod development stages, the current study showed that CH21/13 produced the highest number of branches per plant, while BRC-474 had the lowest. Both water regime and genotype significantly influenced the number of pods per plant, with a significant interaction observed between irrigation and genotype. Similarly, Bakhsh et al. (2007) reported an average 48% increase in pods per plant due to irrigation, while El-Waraky and Koley (2000) found that irrigation during branching and pod development produced the highest pod numbers. Consistent with these studies, the chickpea cultivar LL131 in previous research exhibited a higher number of pods and seeds per plant compared to LX89TH300. Canopy width was also influenced by supplemental irrigation. Reduced water availability under rainfed conditions led to a significant decline in lateral canopy growth, with plants under rainfed conditions showing approximately 11% narrower canopies than those under supplemental irrigation. Among the varieties tested, CH21/13 achieved the widest canopy (33.6 cm), highlighting the positive effect of irrigation on lateral growth. Biological yield was significantly affected by both water regime and variety. Bakhsh et al. (2007) observed a 36% increase in total dry matter under irrigation, and Anwar et al. (2003) similarly reported that fully irrigated crops accumulated greater maximum dry matter. These results contrast with the findings of Sivakumar and Singh (1987), who reported no significant differences in dry matter among cultivars. Moreover, consistent with Bakhsh et al. (2007), irrigation in the present study improved yield and most yield components, emphasizing the critical role of water availability in optimizing chickpea growth and productivity.

Chickpeas often respond to low water availability by increasing root length, which helps them access more soil moisture, particularly during early stages of development (Lakshmi, 2005; Nadeem et al., 2019). When water is limited during reproductive phases such as germination,

flowering, and pod initiation, chickpea plants tend to show reduced shoot and root biomass, whereas water scarcity during vegetative stages has less impact (Randhawa et al., 2014; Ramamoorthy et al., 2016). Under rainfed conditions, the D-1700 genotype exhibits greater shoot and root dry weight, as well as a higher root-to-shoot ratio compared to other chickpea genotypes. Exposure to low soil moisture (around 25% field capacity) often leads to increased root-to-shoot ratios due to enhanced root elongation and altered biomass allocation, which facilitates water uptake (Hsiao & Xu, 2000; Bahavar et al., 2009; Purushothaman et al., 2016; Kuromori et al., 2018). Water stress reduces chickpea yield primarily through pod abortion and poor pod filling, effects that occur as soon as water deficits begin, irrespective of plant developmental stage (Randhawa et al., 2014). Traits such as root length, root biomass, and root-to-shoot ratio are generally associated with improved yield under drought because they enhance water acquisition and reduce transpiration (Kumar et al., 2012; Kashiwagi et al., 2015; Ramamoorthy et al., 2016; Ranjan et al., 2022; Sachdeva et al., 2022). However, these correlations are not always consistent, likely due to variations in experimental conditions and genotype differences (Serraj et al., 2004; Kashiwagi et al., 2005; Zaman-Allah et al., 2011a). This highlights that traits related to root water conservation may be more reliable indicators of chickpea performance under drought (Zaman-Allah et al., 2011a, 2011b).

Water deficit indirectly affects plants by disrupting phenology, growth, carbon assimilation and reproductive processes. Both irrigation regime and genotype significantly influenced chlorophyll content. Under rainfed conditions, terminal drought stress caused a significant reduction in chlorophyll content, with a decrease of approximately 15% compared to full irrigation. At the full bloom stage, the Azad variety exhibited higher chlorophyll levels than other cultivars. However, the interaction between genotype and irrigation regime was not significant. These findings align with Mafakheri et al. (2010), who reported a significant decline in chlorophyll content due to water deficit in three Kabuli chickpea cultivars. A reduction in total chlorophyll under drought stress suggests a diminished capacity for light harvesting. Our results also indicated that both irrigation regime and cultivar significantly affected the number of days from sowing to flowering. Consistent with Sadeghipour (2008), environmental stresses such as water shortage, particularly during grain filling, reduce photosynthesis, limit remobilization of stored assimilates, and decrease both the rate and duration of grain filling, ultimately affecting grain weight. Water stress typically accelerates leaf senescence and shortens the grain filling period in chickpea, as shown by Chowdhury et al. (2002). Additionally, the observed changes in chlorophyll content under varying soil moisture levels and their improvement through supplemental irrigation reflect the photosynthetic capacity of leaves. These changes may result from enhanced chlorophyll biosynthesis under irrigation and reduced degradation due to increased scavenging of reactive oxygen species (Yang et al., 2023). Similar conclusions were drawn by Ibrahim et al. (2023), who reported a significant decrease in chlorophyll content under drought stress.

During drought conditions, stress-induced reactive oxygen species (ROS) regulate chickpea root growth and development (Ranjan et al., 2022). While ROS are often considered harmful due to their potential to disrupt cellular homeostasis, they are typically detoxified by antioxidant enzymes such as catalase, superoxide dismutase, and peroxidases (Mafakheri et al., 2011; Oberoi et al., 2014). Nevertheless, ROS can also benefit plants by acting as signaling molecules that trigger defense mechanisms and facilitate acclimation to stress (Morales & Bosch, 2019). Excessive ROS levels can damage cell membranes through lipid peroxidation, leading to malondialdehyde (MDA) accumulation. The extent of MDA accumulation in chickpeas under low water availability varies depending on genotype and environmental conditions (Mohammadi et al., 2011; Jameel et al., 2021). Although MDA patterns differ among genotypes, drought during the seed-filling stage generally elevates hydrogen peroxide levels, destabilizes membranes, and increases lipid peroxidation and MDA accumulation, with a more pronounced effect in susceptible cultivars compared to tolerant ones (Oberoi et al., 2014). Studies have also reported a positive correlation between MDA levels and chlorophyll a and b concentrations (Jameel et al., 2021). In the present study, MDA levels were consistently higher in TG-1504 than in CH21/13, particularly under rainfed conditions. MDA showed a positive correlation with plant growth parameters, including root and shoot fresh and dry weights, shoot length, and root-to-shoot ratio, but a negative correlation with overall productivity. These findings highlight the importance of genotype in determining water stress tolerance and highlight the complex interplay between water availability, lipid peroxidation, plant growth and productivity. They also support the role of MDA as a key component of stress signaling in chickpeas.

## Conclusion

This study highlights the significant impact of water availability and genotype on chickpea growth, physiological traits, and yield components. Supplemental irrigation enhanced plant height, branch number, pod formation, canopy width, and biological yield, with some genotypes such as CH21/13 showing superior performance under both irrigated and rainfed conditions. Water stress adversely affected vegetative growth and chlorophyll content, accelerating leaf senescence and reducing photosynthetic capacity. Root traits, including root length and root-to-shoot ratio, emerged as important adaptive mechanisms for coping with drought, contributing to water uptake and stress tolerance. Furthermore, the accumulation of malondialdehyde (MDA) under drought stress varied among genotypes, suggesting differential oxidative damage and stress signaling responses. Overall, these findings describe the importance of selecting drought-resilient chickpea genotypes with favorable root and physiological

traits to improve productivity in water-limited environments. Future breeding programs should prioritize these traits to enhance chickpea resilience against climate-induced water scarcity, thereby contributing to food security and sustainable agriculture.

## Declarations

### i. Ethics approval and consent to participate

Ethical approval and informed consent were not required for this study as it did not involve human participants, human data, or animals.

### ii. Consent for publication

Consent for publication is not applicable.

### iii. Data availability

All data generated or analyzed during this study are included in this article.

### iv. Competing interests

Authors have declared that no competing interests exist.

### v. Authors' contributions

B.A. designed the study; A.H. performed the experiments; M.A. performed statistical analysis; W.A. wrote the first draft of the manuscript; A.A. participated in critical revisions of the manuscript. All authors read and approved the final manuscript.

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Not applicable.

### viii. SDGs addressed

Zero Hunger (SDG 2), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13)

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