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# Identification of photothermo-insensitive with climate-smart early-maturing chickpea genotypes

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**Abstract**

Chickpea is a cool season, photothermal-sensitive crop, that is adversely affected by high temperatures (>35°C) and whose flowering is promoted by long-day conditions (>12 h). This prevents horizontal crop spread under a variety of agro-climatic conditions and the development of insensitive genotypes that perform well in all seasons. Therefore, a study was conducted to identify genotypes that are mature early, insensitive to photoperiod, high temperature and tolerant to drought stress. A set of 74 genotypes was evaluated under rainfed conditions in *Kharif* 2021 (off-season) to select eight promising early-maturing genotypes with high-yielding capacity. Then further investigations were conducted in five different seasons *Late Kharif* 2021, rabi 2021, summer 2022, early *Kharif* 2022 and *Kharif* 2022 to identify the genotypes with photothermo-insensitivity among the selected eight genotypes. With the exception of rabi 2021, each of these seasons were distinct from the chickpea's typical growing season. Among these eight, the stable genotypes which are performed better in all the seasons, especially in summer were considered, such as IPC 06-11, MNK-1, JG-14 and ICE 15654-A as a photothermo-insensitive, were able to flower and set pods with higher seed yield and, resulting in early maturity in a temperature range of 41.4/9.3°C with photoperiods of 13.1/10.9 h to reach in all seasons throughout the year. The heritability was more than 60%. Hence, these genotypes can be used as donor aids in the development of early maturing, drought stress tolerant and photothermo-insensitive chickpea.

## Introduction

Chickpea (*Cicer arietinum* L.) is the second most important legume after the common bean (Varshney *et al*., 2013b) and is an economically beneficial crop grown in India, Australia and the Mediterranean region. It is a photoperiod-sensitive (Daba *et al*., 2015) and thermo-sensitive plant (Kaushal *et al*., 2011). Chickpea is classified as a quantitative long-day plant (Verghis *et al*., 1999; Carberry *et al*., 2001), it requires more than 12 h of sunlight to initiate flowering. Therefore, temperature and photoperiod are the two most important factors affecting chickpea productivity (Summerfield *et al*., 1980).

Its physiological maturity varies from 80 to 180 days depending on genotype, high and low temperatures, photoperiod length, soil moisture, altitude and latitude (Gaur *et al*., 2008). Due to their indeterminate growth form, chickpea has a very low harvest index (HI), are photothermo-sensitive and are characterized by poor photosynthetic portioning (Yadav *et al*., 2006). HI is the ratio of grain to total shoot dry matter and is a measure of reproductive efficiency. PTI makes the crop invulnerable to photoperiod and temperature fluctuations, particularly in hot arid regions. Photosynthate partitioning is the deferential distribution of photosynthates to plant tissues.

Phenology (the timing of flowering, pod formation and maturity) is an important part of a plant growth model as it can be used to find the ideal rate and timeframe for plant growth. Predicting plant growth under field conditions has gained popularity in recent years. The sequence of each growth stage determines the plant's response to internal and external factors, as well as dry matter accumulation and partitioning into different organs (Sethi *et al*., 2018) and is more important for the adaptation of chickpea cultivars to different environmental conditions (Berger *et al*., 2006). Phenology that minimizes exposure to stressors and maximizes production is an important adaptive trait for the short growing season (Berger *et al*., 2006; Gaur *et al*., 2008).

The two main environmental factors that influence how long it takes for plants to flower and how quickly they develop are temperature and photoperiod (Daba *et al.*, 2016). However, the PTI behaviour of chickpea cultivars limits their cultivation across seasons and locations due to fluctuations in photoperiod and temperature. The potential yield is significantly reduced due to their susceptibility to changes in temperature and photoperiod when they lack photo-thermo insensitivity in *Vigna* species (Pratap *et al.*, 2014). It was found that cowpea genotypes varied greatly in terms of phenological and yield characteristics across different environments. Some of them flower and set pods at 10°C and as high as 46°C (Verma *et al.*, 2023)

Limited research on PTI characteristics in other crop species was conducted earlier. There hasn't been any research performed on chickpea that are stressed by drought and have early maturity traits. In this regard, the first step towards this goal is to identify trait/s (early flowering, early maturing and higher yield) of chickpea donor genotypes to improve adaptation and grain yield under drought stress. However, breeding for photothermal insensitivity requires donors for these traits. Thus, the identification of these traits helps breeders in developing insensitive genotypes that can be well adapted to all seasons or drought stress conditions would enable bridging the yield gap in chickpea. Therefore, the objective of this study was to evaluate chickpea genotypes under field conditions for 2 years to identify early maturing, drought-stress tolerant, PTI genotypes.

## Materials and methods

### Experimental site

The present experiments were conducted from *rabi* 2020–21 to *Kharif* 2022 (seven seasons in which five are different) at ICAR-National Institute of Abiotic Stress Management, Pune, India 18°09′ N latitude and 74°30′ E longitude with an elevation of 550 mean sea level.

### Planting materials and experimental details

The experiment consisted of eight chickpea genotypes. They were selected by screening a set of 74 chickpea genotypes in two seasons i.e. during rabi 2020–21 and *Kharif* 2021. Seventy-four chickpea genotypes include 54 dominating varieties cultivated across India and 20 advanced breeding lines. These were sown and harvested on 15 November 2020 to 11 March 2021 and 19 June to 30 August 2021, under normal (winter *rabi* 2020–21) and off-season (I-*Kharif 2021*), respectively. The crop was grown under drought conditions at the pod filling stage during rabi 2020–21 whereas under rainfed conditions in *Kharif* 2021, and only one irrigation was performed during pre-flowering, and the rainfall was negligible after flowering. The entire genotypes were grouped based on the physiological maturity and yield parameter by factoextra multivariate cluster analysis (Kassambara and Mundt, 2020) for selecting a set of eight genotypes with early maturation and high yield such as MNK-1, ICE 15654-A, IPC 06-11, JG-11, JG-14, JG-16, Vishal and Vijay (cluster 4 in Fig. 1). The salient characteristics and biological status of the experimental materials of normal *rabi* season are presented in online Supplementary Table S2.

Seeds from eight chickpea genotypes were planted in a factorial randomized block design with two replications in each season. All eight genotypes were planted in different seasons in 2021 and 2022. In 2021 (two seasons), these genotypes were sown and harvested on 30 August to 21 November (II-Late *Kharif*) and 17 November 2021 to 12 February 2022 (III-rabi); respectively. In 2022, three different sowings and harvests were carried out e.g. on 19 February to 26 April (IV-summer), 26 April to 17 June (V-early *Kharif*) and 23 June to 7 September (VI-*Kharif*); respectively.

### Crop management

The recommended fertilizer dose of $N:P_2O_5:K_2O$ 25:50:20 (kg/ha) was applied in the form of diammonium phosphate, urea and muriate of potash at the time of sowing. Sowing was carried out by hand dibbling the seeds into furrows at a distance of 30 cm between rows and 10 cm between plants. One to two seeds were dibbled per hill. Light irrigation was provided from date of sowing to the flowering stage. Twenty-five days after sowing (DAS), hand weeding and intermediate cultivation were performed at 45 DAS to remove weeds. Pests and diseases during the growth phase of the plants were controlled with the greatest care. The crop was harvested after genotypes achieved physiological maturity.

### Observations

#### Phenological parameters

Several reproductive or phenological traits such as days to first flower, days to 50% flower, days to first pod, days to 50% pod and days to physiological maturity were recorded.

*Days to first flowering and pod*: Number of days from sowing to until the first flower or pod appears on the net plot area.

*Days to 50% flowering and pod*: Number of days from sowing to 50% plants on the net plot area had flowered and poded.

*Days to physiological maturity*: Number of days from sowing to maturity when 80% of the pods in the net plot area were matured.

#### Yield parameters

At the physiological maturity, five plants from each replication were randomly hand harvested and processed to record yield components.

*Number of filled pods per plant*: The total number of filled pods from five plants from each plot was counted and the average of filled pods per plant was recorded.

*Total seeds per plant*: The total number of seeds per plant was recorded from randomly selected five plants from each plot and the average was calculated.

*Seed yield*: The total seed yield from the net plot area was measured and calculated using the following formula suggested by Norman *et al.* (1995) converted into kg/ha:

$$\text{Grain yield (kg/ha)} = \frac{\text{Sample yield per plot (kg)} \times 10{,}000}{\text{Number of sub-samples} \times \text{segment length (m)} \times \text{row spacing (m)}}$$

### Agro-meteorological data

The weekly standard data on agro-meteorological parameters namely maximum and minimum temperature ($T_{max}$ and $T_{min}$, °C), relative humidity (RH, %), rainfall (mm), photoperiod (h) and sunshine (h) during the experiments were recorded by the Agro-metrological Observatory of the School of Atmospheric

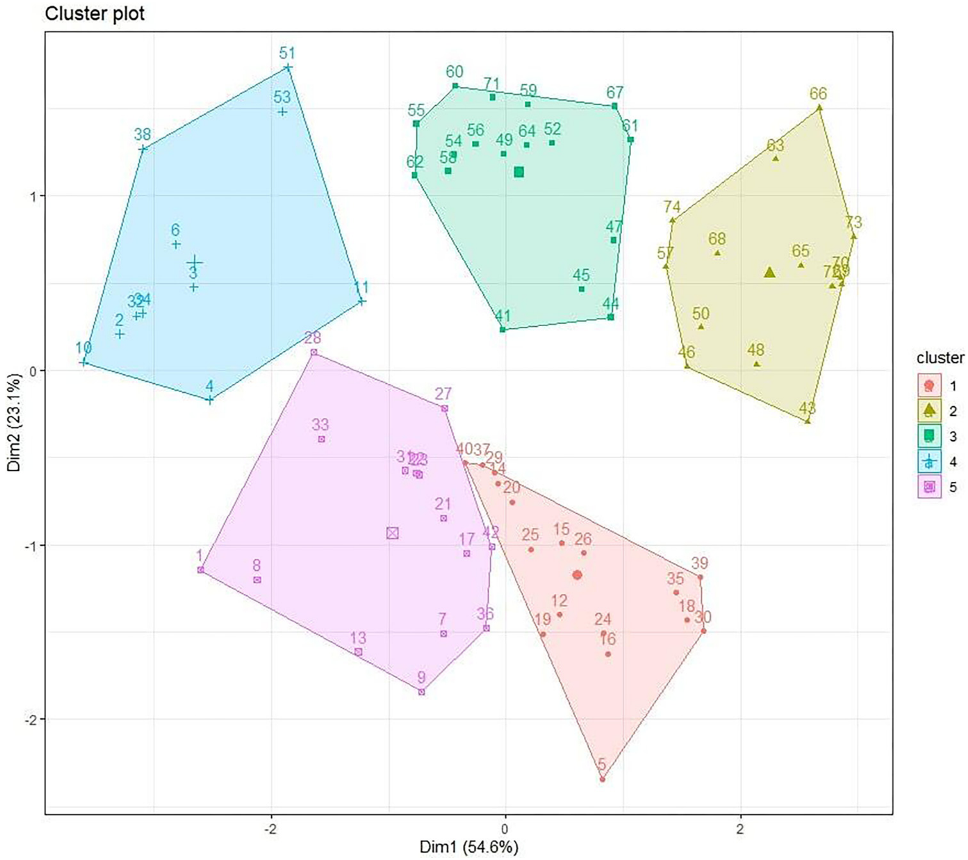


**Figure 1.** Clustering of chickpea genotypes considering physiological maturity and yield parameters of *rabi* 2020–21 and *Kharif* 2021 under drought stress conditions.

Stress Management, ICAR-National Institute of Abiotic Stress Management, Pune (refer to the online Supplementary data).

### *Statistical analysis*

Data obtained from experiments were subjected to statistical analysis using one-way analysis of variance with level of significance (least significant difference, $P \leq 0.05$), the data were interpreted according to Gomez and Gomez (1984) and the Duncan multiple range tests were performed. The grouping of 74 genotypes was done based on a hierarchical cluster analysis and the principal component analysis (PCA) was performed considering the phenological and yield parameters using the 'ggdendro' and 'ggplot2' packages of R 3.6.1 (Vries and Ripley, 2022).

## Results

### *Selection of a set of eight promising genotypes under drought stress conditions*

The 74 chickpea genotypes were phenotypes for early flowering or maturity and yield related traits in *rabi* 2020–21 and *Kharif* 2021 under natural open-field conditions. Based on the screening, a selected set of the most promising and contrasting early-flowering and high-yielding genotypes were used for validation studies. Based on five variables (days to 50% flower, days to 50% pod, days to physiological maturity, total seeds per plant and yield) genotypes were grouped into five major sub-clusters using hierarchical cluster analysis: clusters 1–5 (Fig. 1). Cluster 1 contained 16 genotypes that showed the lowest yield with more days to physiological maturity, therefore this cluster was flagged as a long-duration genotype. Cluster 2 had 13 genotypes that showed moderate yield with longer duration to physiological maturity, so these genotypes could be recognized as moderately yielding genotypes with moderately late maturation. Cluster 3 included 18 genotypes with moderately yielding capacity, while cluster 4 included 11 genotypes with high-yielding capacity and lower days for physiological maturity, so these genotypes were grouped as high yielding with short duration. Finally, cluster 5 included 16 genotypes that produced the highest yield with the highest number of days to maturity; therefore, these genotypes were defined as late-maturing genotypes with high-yielding capacity.

PCA biplot was used to optimize the results of the hierarchical cluster analysis. Dim1 (principal component [PC]1) and Dim2 (PC2) explained about 54.6 and 23.1% of the data variations in the PCA biplot, respectively. PCA distinguished between early- and late-maturing genotypes based on yield capacity. Since Dim1 explains almost one-third of the data variability, we classified all genotypes based on PC1. In a PCA biplot, genotypes on the left side were considered the highest yielding with early-maturing genotypes, while genotypes on the right side were considered the lowest yielding with late-maturing genotypes, and genotypes in the centre were responded to all parameters (Fig. 1). Based on the hierarchical cluster and PCA analyses, eight early-maturing with high-yielding chickpea genotypes were selected.

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### *Phenological parameters of selected eight chickpea genotypes for PTI studies*

We observed significant variations in phenology and yield parameters in all crop seasons among the genotypes. Across six seasons, days to first flower ranged from 28 to 48 days, and the days to physiological maturity ranged from 49 to 86 days. From this, it can be determined that the reproductive phase varied between 16 and 43 days. We observed early flowering and pod formation in IV, V and VI seasons than in I, II and III seasons.

In our result, differences in genotypic responses to different photoperiod lengths and temperatures were observed. Substantial diversity in days to flowering was observed for different genotypes across different seasons, as genotypes with delayed flowering onset had delayed days to pod formation and large variations in the length of the reproductive phase. The temperature range and the duration of sunshine hours also affect the phenological parameters in different crop seasons. Among the seasons, the genotypes show early flowering in the VI season.

### *Yield parameters and heritability of selected eight chickpea genotypes for PTI studies*

Yield parameters differed significantly between chickpea genotypes in all crop seasons but except for some seasons, there is no significant difference between genotypes for the total number of filled pods per plant in the I and V seasons and also total seeds per plant in the V and VI seasons along with seed yield in the V season. Among the different seasons number of filled pods per plant was lower in the IV and V seasons and higher in the III season (which is the normal *rabi* season of chickpea cultivation). Among genotypes, Vishal, MNK-1, ICE 15654-A and JG-11 had more filled pods per plant in most of the crop seasons (Table 1). The number of filled pods is directly related to improved seed yield, hence the same genotypes showed the highest seeds per plant and highest seed yield. Compared to all crop seasons, the genotypes in the III and I seasons have the highest yield and in the V and IV seasons a very low yield. The VI season crop duration coincided with the I season. However, the yield was meager compared to the I season as the VI season crop was affected by continuous rainfall during pod filling, resulting in pod shedding and yield loss. Among the genotypes, Vishal, MNK-1, ICE 15654-A and JG-11 recorded maximum yield with a greater number of seeds per plant in most of the crop seasons. In the I season, total filled pods (29.60 per plant) and total seeds (33.50 and 30.20 per plant) were more in JG-16 and Vijay, respectively. In the II season, the genotype Vijay had the highest filled pod (34.4 per plant) and total seeds (44.42 per plant) while Vishal had the highest seed yield of 1029.3 kg/ha. JG-11 (1247 kg/ha) had the highest yield, followed by Vishal (1100 kg/ha) and MNK-1 (1046.50 kg/ha) and genotype Vijay showed more total filled pods (62.80 per plant) and seeds (61.50 per plant) in the III season. ICE 15654-A and IPC 06-11 produced the highest seed yield (601.40 and 581.49 kg/ha) with the highest filled pods (26.62 and 28.62 per plant) and seeds (29.75 and 26.37 per plant), respectively in the IV season. In the V season, yield and yield parameters showed no significant difference between genotypes with a very lower yield and ICE 15654-A recorded comparatively more yield (238.28 kg/ha) with more filled pods (35.10 per plant) and seeds (40.50 per plant) and in the VI season, the total number of seeds per plant had no significant difference between genotypes and genotype Vishal recorded the highest seed yield (477.60 kg/ha) but highest filled pods (53 per plant) and seeds (54.67 per plant) were recorded in the genotype Vijay (Table 2). The heritability percentage of I, II, III, IV, V and VI seasons were 69, 90, 86, 61, 37 and 85%, respectively. It was more than 60% of the heritability percentage in all the seasons except for the V (early *Kharif*) season because of the higher rainfall during the pod setting stage. Here, the environmental (G × E) influence was more and reduced the heritability percentage.

### *Mean performance and stability of selected eight chickpea genotypes based on G.G.E. biplot*

The stability mean analysis was performed for genotypes under different seasons using G.G.E. biplot software to further validate the results mentioned above. The PC1 and PC2 explained 52.54 and 31.07% of the total yield variation across the seasons (Fig. 2).

The eight chickpea genotypes were ranked through the average tester axis with a line indicating a greater value based on their mean performance across all six seasons. This ranking was based on the mean performance and stability view of the G.G.E. biplot of yield for the genotypes. The projections of their markings on the average tester axis approximate the average yield of the genotypes (Apraku *et al.*, 2011). The genotypes projection onto the double arrow line 'y' serves as an indication of the stability of the genotypes. A genotype is less stable the longer its projection is in terms of distance (Yan *et al.*, 2000; Yan, 2001). The complete field experiment during six seasons to screen the stable genotypes is depicted diagrammatically (Fig. 3). This illustrates the initial screening during off-season in season I. Then eight chickpea genotypes were screened in five different seasons under natural open-field conditions. All five seasons were different from the normal growing season of the chickpea crop except season III. This result reveals that the genotypes JG-14, ICE 15654-A, IPC 06-11 and MNK-1 show the highest yield and most stable.

## Discussion

### *Phenological parameters of selected eight chickpea genotypes for PTI studies*

The genotypes JG-14, ICE 15654-A, IPC 06-11 and MNK-1 showed early maturity and the highest yield and were most stable in all the seasons studied. Early vigour and flowering is an adaptive criterion that minimizes exposure to climatic stress conditions and maximizes productivity (Berger *et al.*, 2011). Early phenology is a key trait for chickpea adaptation to short-season environments.

Due to the higher maximum temperature (IV, V and VI seasons), flowering was predominantly early (Daba *et al.*, 2015) thereby the reproductive phase was completed early and maturity was early (Devasirvatham *et al.*, 2013). The higher temperature than the optimum during the plant development fastens maturity duration. Growing degree days and cardinal temperature play a role in plant development (Pessotto *et al.*, 2023). In chickpea, flowering time is a major component of crop duration and is regulated by genotype, temperature, photoperiod and their interactions (Roberts *et al.*, 1985; Rebetzke and Lawn, 2006).

In IV and V seasons due to higher maximum temperature with sunshine from 10 to 10.8 h, genotypes evincing early flowering and pod formation due to high temperatures (>35°C), resulted in the shortened vegetative period by 10–15 days compared to the optimum temperature (28°C) (ICRISAT, 2011) and eventually

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**Table 1.** Days to physiological maturity and total number of filled pods per plant of chickpea genotypes in all six seasons

| Season | I. *Kharif* 2021 (19 June to 30 August) | | II. Late *Kharif* 2021 (August 30 to November 22) | | III. Rabi 2021-22 (November 17 to February 12) | | IV. Summer 2022 (19 February to 26 April) | | V. Early *Kharif* 2022 (26 April to 17 June) | | VI. *Kharif* 2022 (23 June to 07 September) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°C) | 34.5/19.7 | | 33.6/11.4 | | 32.9/9.3 | | 40.3/12.8 | | 41.4/18.9 | | 34.2/19.6 | |
| Photoperiod (h) | 12.8 | | 11.53 | | 11.06 | | 12.37 | | 13.02 | | 12.80 | |
| | Parameter | | | | | | | | | | | |
| Genotype | Days to physiological maturity | Total filled pods per plant | Days to physiological maturity | Total filled pods per plant | Days to physiological maturity | Total filled pods per plant | Days to physiological maturity | Total filled pods per plant | Days to physiological maturity | Total filled pods per plant | Days to physiological maturity | Total filled pods per plant |
| MNK 1 | 71.5$^{a}$ | 17.7$^{b}$ | 73.5$^{c}$ | 17.7$^{f}$ | 80.0$^{cd}$ | 20.7$^{d}$ | 65.0$^{b}$ | 10.8$^{ef}$ | 51.5$^{b}$ | 3.5$^{d}$ | 69.0$^{b}$ | 25.0$^{d}$ |
| ICE 15654-A | 62.5$^{c}$ | 26.1$^{ab}$ | 63.5$^{d}$ | 29.1$^{b}$ | 80.5$^{bc}$ | 18.7$^{de}$ | 58.5$^{c}$ | 29.6$^{a}$ | 49.5$^{c}$ | 8.7$^{a}$ | 73.0$^{a}$ | 24.5$^{cd}$ |
| IPC 06-11 | 63.0$^{c}$ | 22.3$^{ab}$ | 72.5$^{c}$ | 20.7$^{e}$ | 78.0$^{d}$ | 15.5$^{e}$ | 55.5$^{d}$ | 28.6$^{a}$ | 49.5$^{c}$ | 6.6$^{b}$ | 69.0$^{b}$ | 17.3$^{d}$ |
| JG-11 | 64.5$^{c}$ | 28.9a | 78.5$^{b}$ | 25.4$^{c}$ | 78.5$^{cd}$ | 30.3$^{c}$ | 65.5$^{b}$ | 11.9$^{de}$ | 53.5$^{a}$ | 4.8$^{c}$ | 64.5$^{c}$ | 28.9c$^{d}$ |
| JG-14 | 71.5$^{a}$ | 23.8$^{ab}$ | 74.5$^{c}$ | 23.1$^{d}$ | 82.5$^{b}$ | 30.1$^{c}$ | 55.0$^{d}$ | 20.3$^{b}$ | 50.5$^{bc}$ | 6.0$^{b}$ | 68.5$^{b}$ | 49.0$^{ab}$ |
| JG-16 | 69.0$^{b}$ | 29.4$^{a}$ | 77.5$^{b}$ | 24.7$^{cd}$ | 86.5$^{a}$ | 40.5$^{b}$ | 65.0$^{b}$ | 8.6$^{f}$ | 51.0$^{bc}$ | 3.3$^{d}$ | 74.5$^{a}$ | 39.3$^{abc}$ |
| Vishal | 68.0$^{b}$ | 29.2$^{a}$ | 77.0$^{b}$ | 23.1$^{d}$ | 85.0$^{a}$ | 33.5$^{c}$ | 58.5$^{a}$ | 14.3$^{d}$ | 51.0$^{bc}$ | 1.5$^{e}$ | 74.0$^{a}$ | 35.0$^{bc}$ |
| Vijay | 67.5$^{b}$ | 29.6$^{a}$ | 82.5$^{a}$ | 34.4$^{a}$ | 85.0$^{a}$ | 62.8$^{a}$ | 65.0$^{b}$ | 17.3$^{c}$ | 51.0$^{bc}$ | 5.1$^{c}$ | 74.5$^{a}$ | 53.0$^{a}$ |
| C.D. (0.05) | 2.5 | 9.8 | 2.1 | 2.2 | 2.5 | 3.6 | 2.2 | 2.5 | 1.9 | 2.2 | 2.2 | 16.3 |
| SE(m) | 0.7 | 1.67 | 0.7 | 0.6 | 0.7 | 1.1 | 0.7 | 0.7 | 0.6 | 0.7 | 0.6 | 4.8 |
| SE(d) | 1.0 | 2.4 | 0.9 | 0.9 | 1.1 | 1.5 | 0.9 | 1.0 | 0.8 | 0.9 | 0.9 | 6.8 |
| C.V. | 1.5 | 16.0 | 1.2 | 3.6 | 1.3 | 4.8 | 1.5 | 5.9 | 1.6 | 19.1 | 1.3 | 19.9 |

*Note*: Different letter in the same column indicates significant differences at $P \leq 0.05$.

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**Table 2.** Total seeds per plant and seed yield (kg/ha) of chickpea genotypes in all six seasons

| Season | I. *Kharif* 2021 (19 June to 30 August) | | II. Late *Kharif* 2021 (August 30 to November 22) | | III. Rabi 2021–22 (November 17 to February 12) | | IV. Summer 2022 (19 February to 26 April) | | V. Early *Kharif* 2022 (26 April to 17 June) | | VI. *Kharif* 2022 (23 June to 07 September) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature (°C) | 34.5/19.7 | | 33.6/11.4 | | 32.9/9.3 | | 40.3/12.8 | | 41.4/18.9 | | 34.2/19.6 | |
| Photoperiod (h) | 12.8 | | 11.53 | | 11.06 | | 12.37 | | 13.02 | | 12.80 | |
| Heritability (%) | 69 | | 90 | | 86 | | 61 | | 37 | | 85 | |
| | Parameter | | | | | | | | | | | |
| Genotype | Total seeds per plant | Seed yield (kg/ha) | Total seeds per plant | Seed yield (kg/ha) | Total seeds per plant | Seed yield (kg/ha) | Total seeds per plant | Seed yield (kg/ha) | Total seeds per plant | Seed yield (kg/ha) | Total seeds per plant | Seed yield (kg/ha) |
| MNK 1 | $16.0^{d}$ | $816^{a}$ | $19.5^{d}$ | $750^{b}$ | $20.5^{d}$ | $944^{bc}$ | $11.7^{d}$ | $350^{bc}$ | $4.2^{d}$ | $136.5^{b}$ | $31.8^{e}$ | $299^{cd}$ |
| ICE 15654-A | $27.4^{abc}$ | $695^{b}$ | $30.1^{b}$ | $713^{b}$ | $18.7^{de}$ | $860^{cd}$ | $29.8^{a}$ | $601^{a}$ | $9.2^{a}$ | $238.3^{a}$ | $29.0^{cde}$ | $388^{b}$ |
| IPC 06-11 | $20.2^{cd}$ | $701^{b}$ | $28.7^{b}$ | $538^{c}$ | $15.5^{e}$ | $810^{cde}$ | $26.4^{b}$ | $581^{a}$ | $7.0^{b}$ | $194.3^{ab}$ | $21.3^{de}$ | $220^{d}$ |
| JG-11 | $28.1^{abc}$ | $803^{a}$ | $30.0^{b}$ | $532^{c}$ | $35.8^{b}$ | $1247^{a}$ | $10.0^{de}$ | $101^{d}$ | $5.7^{c}$ | $114.0^{b}$ | $28.1^{de}$ | $402^{b}$ |
| JG-14 | $23.1^{bcd}$ | $810^{a}$ | $24.7^{c}$ | $707^{b}$ | $29.8^{c}$ | $680^{def}$ | $18.3^{c}$ | $403.8^{b}$ | $6.5^{b}$ | $153.1^{ab}$ | $49.2^{ab}$ | $319^{bc}$ |
| JG-16 | $33.5^{a}$ | $819^{a}$ | $28.5^{b}$ | $469^{c}$ | $35.9^{b}$ | $603^{ef}$ | $7.8^{e}$ | $100.8^{d}$ | $3.3^{d}$ | $151.6^{ab}$ | $45.8^{abc}$ | $404^{b}$ |
| Vishal | $18.1^{d}$ | $795^{a}$ | $16.3^{d}$ | $1029^{a}$ | $38.6^{b}$ | $1100^{ab}$ | $11.1^{d}$ | $299.7^{c}$ | $1.5^{e}$ | $132.6^{b}$ | $36.3^{bcd}$ | $477^{a}$ |
| Vijay | $30.2^{ab}$ | $701^{b}$ | $44.4^{a}$ | $445^{c}$ | $61.5^{a}$ | $520^{f}$ | $15.4^{c}$ | $166.0^{d}$ | $6.0^{c}$ | $107.3^{b}$ | $54.7^{a}$ | $271^{cd}$ |
| C.D. (0.05) | 8.8 | 82 | 3.6 | 148 | 3.3 | 232 | 2.9 | 86.8 | 2.4 | 99 | 17.2 | 91 |
| SE(m) | 2.6 | 24.7 | 1.1 | 43.5 | 1.0 | 68 | 0.9 | 25.5 | 0.7 | 29.7 | 6.6 | 26.8 |
| SE(d) | 3.7 | 34.9 | 1.5 | 61.6 | 1.4 | 97 | 1.3 | 36.1 | 1.0 | 41.9 | 9.4 | 37.9 |
| C.V. | 15.1 | 4.6 | 5.4 | 9.5 | 4.3 | 11 | 7.8 | 11.1 | 18.9 | 27.3 | 0.8 | 10.9 |

*Note:* Different letter in the same column indicates significant differences at $P \leq 0.05$

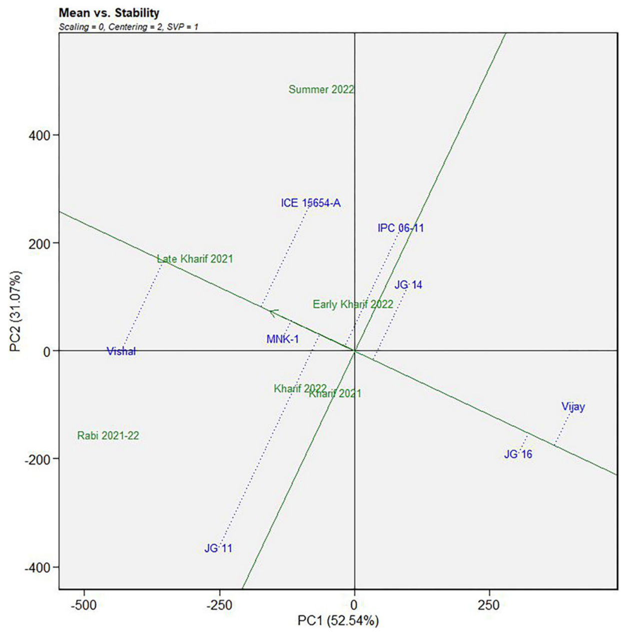


**Figure 2.** Mean versus stability view of the G.G.E. biplot based on a genotype with seasons (environment) yield data of eight chickpea genotypes evaluated in six seasons, 2021–22. The biplot was based on the genotype-focused singular value partitioning (SPV = 2). The PC1 and PC2 explained 52.54 and 31.07% yield variation.

reached physiological maturity early, since early flowering and pod formation restrict vegetative growth in indeterminate crops like chickpea, thereby reduces the time to physiological maturity (Ladizinsky and Adler, 1976; Berger *et al*., 2006; Anbessa *et al*., 2007). Compared to the I season, flowering in the II and III seasons was delayed in some genotypes; it might be due to a lower range of minimum temperature (9–11°C) and sunshine (<10.4 h) and resulting in a delay of days to physiological maturity but even this temperature range some genotypes show early flowering such as MNK-1, ICE 15654-A, IPC 06-11 and JG-14. But even with a high temperature range in the IV and V seasons, JG-16, Vishal and Vijay (>35 days) show a delay in flowering compared to the remaining genotypes (<35 days) and these genotypes also showed late flowering in the remaining four seasons. The VI season of sowing took place in comparatively the same months as I season sowing but the genotypes showed early flowering compared to the I season. The results were similar for 50% flowering, as it depends on the first flowering. The genotypes reach 50% flowering within 5–6 days after initiation of the first flower in most of the seasons but some genotypes in the II season took more than 6 days, such as MNK-1, IPC 06-11, JG-14 and in the III season, all genotypes took almost 10 days to reach 50% flowering (online Supplementary Table S4). Among seasons, days to pod initiation was lower in the V and VI seasons. As mentioned earlier, the early flowering resulted in early pod initiation and physiological maturity. The genotypes such as MNK-1, ICE 15654-A, IPC 06-11 and JG −14 showed early pod onset in considering all seasons and produced 50% pod within 10 days. With the exception of some genotypes, pod initiation took less than 50 days (online Supplementary Table S5). The genotypes show early physiological maturity in the V and IV seasons, with 50–65 days to maturity compared to other seasons due to the maximum range of high temperature (>35°C) and the length of the photoperiod (>12 h) as reported by the phenology can be modified under high temperature (Summerfield *et al*., 1984) and also under relatively high temperature, high RH and long day length, the onset of flowering and pod formation was very rapid (Pratap *et al*., 2014) and in the III season, they reach the maturity in 76–86 days due to less range of maximum temperature and length of photoperiod. Daba *et al*. (2016) reported that under high temperature and longer photoperiod, photoperiod-sensitive genotypes of chickpea took more days to flower. Among the eight genotypes, MNK-1, ICE 15654-A, IPC 06-11 and JG-14 were early-maturing genotypes and JG-16, Vishal and Vijay were late maturing in all seasons (Table 1).

## *Yield parameters and heritability of selected eight chickpea genotypes*

The four genotypes JG-14, ICE 15654-A, IPC 06-11 and MNK-1 exhibited the maximum yield despite varied climatic and stress

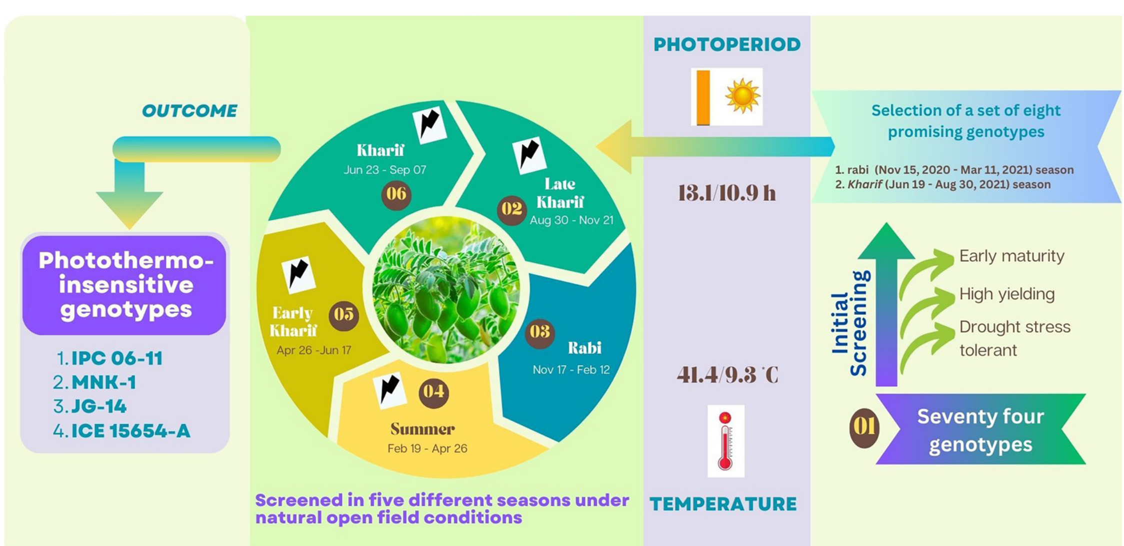


**Figure 3.** Complete field experiment during the six seasons is depicted diagrammatically, from initial screening for two seasons to the final selection of four photothermo-insensitive chickpea genotypes. Number indicates different seasons.

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conditions. Despite being a cool-season crop, chickpea is resilient enough to flower and set pods even when exposed to high temperatures, reaching up to 40°C during the summer season. Interestingly, certain genotypes within the chickpea species have demonstrated remarkable adaptability to varying temperature conditions. For instance, as reported by Pratap *et al.* (2014), some *Vigna* spp. genotypes being a warm season crop, exhibit photothermo-insensitivity, enabling them to flower and produce pods even in cooler temperatures as low as 2.7°C. This adaptability underscores the resilience and versatility of these crop varieties in adapting to diverse environmental conditions.

Since chickpea is a heat-sensitive crop, it reduces yield above 35°C (Kaushal *et al.*, 2011); in present studies in the IV and V seasons high temperature (>35°C) during the reproductive phase causes yield losses. High temperature after flowering and grain filling reduced chickpea yield (Devasirvatham and Tan, 2018; Rani *et al.*, 2020) due to increased senescence and reduced number of pods, grain set and grain weight per plant (Wang *et al.*, 2006). All eight chickpea genotypes survived and plants were in good condition. During high temperatures, pod setting is a problem not flowering in chickpea. The flowering was present but there was no pod setting in the susceptible genotypes and it was normal in PTI genotypes. Thus, delay in pod setting increased the vegetative growth thereby increasing the maturity period in susceptible genotypes. Similarly, Gurumurthy *et al.* (2023) reported that the negative association between days to maturity and yield was observed subjected to combined stress conditions.

The maximum yield, however, was found in the early matured genotype MNK-1 (941.52 kg/ha) as previously reported by Gurumurthy *et al.* (2022). Using vegetal protein hydrolysates during off-season coupled heat and drought stress increased the yield potential of the IPC 06-11 chickpea genotype (Mamatha *et al.*, 2023). As a result, only the PTI genotypes performed well during the off-season, which differed from the chickpea crop's regular growing season.

The donor genotypes carrying the identified PTI trait provide valuable genetic resources for enhancing chickpea varieties by introducing the trait, thereby creating superior cultivars with improved characteristics. Additionally, the PTI gene identification and molecular breeding work will be taken forward further to strengthen chickpea against environmental challenges. In the demanding environment of hot, dry regions, this will increase production and increase the amount of chickpea with high-quality pod yield available throughout the year and in most of the locations.

## Conclusion

In the present study, the genotypes which were completed their reproductive phase early with higher seed yield in different ranges of temperature and photoperiod were considered as climate-smart photothermal-insensitive genotypes. Among the genotypes, IPC 06-11, MNK-1, JG-14 and ICE 15654-A showed early flowering, and completed early physiological maturity with high-yield potential and yield stability. These genotypes have the ability to perform better throughout the year in all seasons with different ranges of temperature (10–40°C) with day length (10–13 h) and have high seed-yielding capacity over other genotypes, therefore classified as photothermal-insensitive genotypes. Hence, these genotypes could be used as donors for the development of early-maturing, drought-tolerant, photothermo-insensitive chickpea genotypes.

**Supplementary material.** The supplementary material for this article can be found at https://doi.org/10.1017/S1479262124000108

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