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PHENOPHASE-SPECIFIC OPTIMUM TEMPERATURE AND THERMAL SENSITIVITY IN CHICKPEA UNDER RANCHI REGION OF JHARKHAND INDIA

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ABSTRACT

Phenophase-specific optimum temperatures and thermal sensitivity coefficients for chickpea and its effect on grain yield needs quantification under varying climatic condition. Eight years field experiments (2017–18 to 2024–25) with three varieties (JG 14, GNG 1581, Birsa Chana 3) under three staggered sowing dates (10th Nov, 25th Nov and 10th Dec) were conducted at Birsa Agricultural University, Ranchi, Jharkhand. This study aimed to estimate the empirically valid optimum mean temperature (Topt °C) and temperature sensitivity coefficient (*S*, kg ha^{-1} °C^{-1}) at five phenological stages viz. flower initiation, 50% flowering, pod initiation, 50% pod filling and maturity stage. Highest yield was harvested by the 10th Nov sown crop (1,498–1,854 kg ha^{-1}). Topt increased gradually from 12.4–16.2 °C at 50% flowering to 19.4–25.8 °C at maturity stage under different sowing condition. Thermal sensitivity was most pronounced under 25th Nov sowing with GNG 1581 recording the largest positive sensitivity at flower initiation (*S* = +243 kg ha^{-1} °C^{-1}) and Birsa Chana 3 exhibiting the strongest negative sensitivity at 50% flowering under late sowing (*S* = −190 kg ha^{-1} °C^{-1}). The most thermally vulnerable phenophase shifted from flower initiation and 50% flowering under early and normal sowing to pod initiation and maturity under delayed sowing. Rainfall effects were predominantly negative, most markedly for Birsa Chana 3 under early sowing (*r* = −0.69). These findings provide a phenophase--specific thermal profile to support sowing-date optimisation under projected warming in humid subtropical environments.

***Keywords*:** Optimum temperature, Phenophases, temperature sensitivity, Chickpea, heat stress, Sowing date, Crop-weather relationship.

Introduction

Climate change poses an escalating threat to global food security, with mean surface temperatures projected to rise by 1.5–4.0 °C by the end of this century under moderate-to-high emission scenarios (IPCC, 2021). Legumes are particularly vulnerable, as their reproductive physiology operates within narrow thermal windows; once breached, pollen viability declines, pod set fails and phenological development accelerates irreversibly (Devasirvatham *et al*., 2012; Gaur *et al*., 2015). Chickpea (*Cicer arietinum* L.), the world's third most important food legume with global production exceeding 17 million tonnes from approximately 17.8 million ha (FAOSTAT, 2023), is acutely exposed to this risk. It serves as the primary dietary protein source for over 700 million people across South Asia, Sub-Saharan Africa and West Asia regions where smallholder, rainfed farming predominates making yield losses under heat stress a direct threat to household nutrition and food sovereignty (Jha *et al*., 2024; Varshney *et al*., 2013). India alone contributes approximately 70% of global chickpea production, yet national average yields remain below 1,000 kg ha^{-1}, partly because agronomic decisions such as sowing date and variety selection are rarely calibrated to the thermal optima of individual crop growth stages (Kumar *et al*., 2022).

Considerable progress has been made in characterising the broad thermal tolerance of chickpea. A thermal optimum for grain yield in the range of 15–

25 °C and a critical damage threshold above 30–33 °C during reproductive stages have been reported across genotypes (Devasirvatham *et al*., 2012; Krishnamurthy *et al*., 2011). Process-based modelling frameworks such as DSSAT-CROPGRO have extended these estimates to regional scales (Rao *et al*., 2021; Soltani *et al*., 2016), while field-based studies have demonstrated that staggered sowing dates substantially alter the thermal environment during key phenophases, offering a practical, low-cost lever for heat stress management (Jha *et al*., 2024; Kumar *et al*., 2022). Temperature sensitivity analysis quantifying yield change per unit warming has further advanced crop climate understanding in wheat, rice and maize (Lobell & Field, 2007; Rezaei *et al*., 2015). Yet its systematic application to chickpea across individual phenological stages and contrasting sowing environments in the humid subtropical zone of eastern India remains limited.

Two critical gaps persist in the existing literature. First, phenophase-specific optimum temperatures at which yield is maximised as distinct from damage thresholds have rarely been estimated from multi-year field data with biological validity constraints that prevent extrapolation beyond the observed thermal range; most published values originate from controlled environments or simulation models (Devasirvatham *et al*., 2012; Rao *et al*., 2021). Second, the direction and magnitude of thermal sensitivity at each distinct growth stage have not been systematically quantified for released Indian varieties across contrasting sowing windows (Sattar *et al*., 2023); without a phenophase-resolved sensitivity profile, variety-specific sowing recommendations remain operationally ineffective (Ramirez-Castañeda *et al*., 2026).

This study therefore aimed to: (i) estimate empirically valid optimum mean temperatures (T_{opt}, °C) for grain yield of three varieties (JG 14, GNG 1581, Birsa Chana 3) at five phenological stages across three staggered sowing dates using a quadratic regression framework with biological validity constraints; (ii) quantify the temperature sensitivity coefficient (S, kg ha^{-1} °C^{-1}) at each phenophase and identify the most thermally vulnerable growth stage and (iii) characterise phenophase-specific yield–rainfall relationships and evaluate how stage-wise moisture availability modifies yield under contrasting sowing environments. Unlike prior work reporting single season-level thermal thresholds, this study delivers a phenophase-disaggregated, variety-specific thermal and moisture profile grounded in eight seasons of factorial field data, providing a quantitative evidence base for climate-smart sowing-date optimisation in the humid subtropical belt of eastern India and analogous agro-climatic zones globally.

Materials and Methods

Experimental Site, Design and Crop Management

Field experiments were conducted at Birsa Agricultural University, Ranchi, Jharkhand, India (23.17°N, 85.19°E; 625 m msl) under humid subtropical climatic conditions across eight consecutive cropping seasons from 2017–18 to 2024–25. A factorial randomised block design (FRBD) with three replications was adopted to evaluate three chickpea (*Cicer arietinum* L.) varieties viz. JG 14, GNG 1581 and Birsa Chana 3 sown under three staggered dates of sowing: D_1 (10 November), D_2 (25 November) and D_3 (10 December). Daily meteorological data comprising maximum temperature (T_{max}), minimum temperature (T_{min}) and rainfall (mm) were systematically recorded across five key phenological stages: Flower initiation (FI), 50% Flowering (FF), Pod Initiation (PI), 50% Pod Filling (PF) and Physiological Maturity (Mat).

Computation of Mean Temperature

For each phenological stage, the mean temperature (T_{mean}; °C) was computed as the arithmetic mean of daily maximum (T_{max}; °C) and minimum (T_{min}; °C) temperatures, following the standard procedure widely adopted in crop–weather analysis (Challinor *et al*., 2005; Srivastava *et al*., 2010):

$$T_{mean} = T_{max} + T_{min}) / 2 \quad (1)$$

where T_{mean} is the phenophase-specific mean temperature (°C), T_{max} is the daily maximum temperature (°C) and T_{min} is the daily minimum temperature (°C). This widely used metric effectively characterises the thermal environment experienced by the crop during each developmental stage.

Estimation of Optimum Temperature

The optimum temperature (T_{opt}; °C) for grain yield at each phenological stage was estimated by fitting a quadratic polynomial regression of grain yield (Y; kg ha^{-1}) on phenophase mean temperature (T; °C) for each variety × sowing date combination (Challinor *et al*., 2005; Lobell & Field, 2007; Srivastava *et al*., 2010):

$$Y = \beta_0 + \beta_1.T + \beta_2.T^2 + \varepsilon \quad (2)$$

where Y is the grain yield (kg ha^{-1}); T is the phenophase mean temperature (°C); β_0 is the intercept; β_1 and β_2 are the linear and quadratic regression coefficients, respectively; and ε is the random error term. The T_{opt} was derived analytically by differentiating Equation (2) with respect to T and equating the first derivative to zero:

$$T_{opt} = -\beta_1/(2.\ \beta_2) \quad (3)$$

A T_{opt} estimate was accepted as biologically valid only when two conditions were satisfied simultaneously: (i) $\beta_2 < 0$, confirming a concave-downward parabola that indicates a genuine yield maximum; and (ii) T_{opt} fell within the observed range of T_{mean} for that particular phenophase–sowing date combination, thereby precluding extrapolation beyond the measured thermal domain. When these conditions were not met, attributable to limited inter-annual thermal variation across the eight-year observational record, the empirical T_{opt} was reported as the observed T_{mean} corresponding to the highest recorded grain yield in that combination (Lobell & Field, 2007).

Phenophase-Specific Temperature Sensitivity of Grain Yield

The sensitivity of grain yield to phenophase-specific temperature was quantified by estimating the slope coefficient from a simple ordinary least-squares (OLS) linear regression of grain yield (Y; kg ha^{-1}) on phenophase mean temperature (T; °C) for each variety × sowing date combination (Lobell & Field, 2007; Rezaei *et al*., 2015):

$$Y = \alpha + S \cdot T + \varepsilon \quad (4)$$

where Y is the grain yield (kg ha^{-1}); T is the phenophase mean temperature (°C); α is the regression intercept (kg ha^{-1}); S is the temperature sensitivity coefficient (kg ha^{-1} °C^{-1}), representing the change in grain yield per unit increase of 1 °C in mean temperature; and ε is the residual error term. A negative S indicates a yield penalty (heat stress) per unit warming, whereas a positive S indicates a yield benefit with increasing temperature. Regression slopes were classified as Very High = $|S| > 200$; High = $|S|$ 100–200; Moderate = $|S|$ 50–100 kg ha^{-1} °C^{-1} (Dhaliwal & Williams, 2022). The phenophase exhibiting the maximum absolute sensitivity value ($|S|_{max}$) was identified as the most temperature-sensitive developmental stage for each variety × sowing date combination.

Model fit was assessed using the coefficient of determination (R^2), calculated as (Hossain, 2010):

$$R^2 = 1 - (SSres / SStot) \quad (5)$$

where $SS_{res} = \Sigma(Y_i - \hat{Y}_i)^2$ is the residual sum of squares and $SS_{tot} = \Sigma(Y_i - \overline{Y})^2$ is the total sum of squares. Statistical significance was evaluated using the Student's t-test at probability thresholds of $p< 0.05$, $p< 0.01$ and $p< 0.001$. Given the eight-year observational record (n = 8 per sowing group; degrees of freedom = 6), statistical power was inherently constrained. Accordingly, temperature sensitivity was interpreted primarily on the basis of the magnitude ($|S|$) and direction of regression slopes and their biological consistency across varieties and sowing dates, following the approach recommended by Lobell & Field, 2007 and Rezaei *et al*., 2015.

Effect of Rainfall on Grain Yield

The relationship between cumulative seasonal rainfall and grain yield was quantified for each variety × sowing date combination using the Pearson correlation coefficient (r) and OLS linear regression. Total seasonal rainfall ($Rain_{Total}$; mm) was computed as the cumulative sum of rainfall across all five phenological stages (Garg *et al*., 2013; Mishra & Singh, 2019):

$$Rain_{Total} = Rain_{FI} + Rain_{FF} + Rain_{PI} + Rain_{PF} + Rain_{Mat}$$

where $Rain_{FI}$, $Rain_{FF}$, $Rain_{PI}$, $Rain_{PF}$ and $Rain_{Mat}$ represent the cumulative rainfall (mm) recorded during flower initiation, 50% flowering, pod initiation, 50% pod filling and Physiological maturity stages, respectively. Phenophase-wise rainfall sensitivity was further assessed by estimating the OLS regression slope (β; kg ha^{-1} mm^{-1}) of yield on phenophase-specific rainfall to isolate the contribution of individual growth stages to yield variability under varying moisture conditions (Garg *et al*., 2013; Mishra & Singh, 2019). All statistical analyses were conducted in R (version 4.5.1) using the built-in *lm()* function.

Results

Optimum Temperature for Chickpea Grain Yield at the Best-Performing Sowing Date

Among the three sowing dates evaluated, D_1 (10th Nov) consistently produced the highest mean grain yields across all varieties: 1,498 kg ha^{-1} for JG 14, 1,690 kg ha^{-1} for GNG 1581 and 1,854 kg ha^{-1} for Birsa Chana 3 (Table 1). Phenophase-specific optimum mean temperatures (T_{opt}) are therefore reported for D_1, representing the thermal regime that maximised yield potential. Across varieties and phenophases T_{opt} was observed 12.4 °C at 50% flowering and 19.8 °C at maturity stage for Birsa Chana 3. A stage-dependent spread of 7.4 °C followed a consistent progression from cooler optima during anthesis and early pod development to warmer optima approaching maturity (Table 1).

For JG 14 and GNG 1581, T_{opt} at flower initiation and 50% flowering was 15.0 °C and 13.8 °C respectively, reflecting identical thermal requirements during early reproductive stage. The varieties diverged at pod initiation, where T_{opt} was 13.7 °C for JG 14 and 15.2 °C for GNG 1581. A difference of 1.5 °C indicating a comparatively warmer thermal requirement for early pod set in GNG 1581. Both varieties showed similar T_{opt} values at 50% pod filling (16.9 °C) and maturity (19.4 °C), suggesting analogous thermal tolerances during grain filling. Birsa Chana 3, the highest-yielding variety, recorded the lowest T_{opt} at 50% flowering (12.4 °C), approximately 1.4 °C below the other varieties, indicating high thermal sensitivity at anthesis to elevated temperatures. Its T_{opt} at pod initiation (16.9 °C) was the highest among the three varieties at that stage, while later reproductive stage T_{opt} (50% Pod: 16.5 °C; maturity: 19.8 °C) were marginally elevated relative to JG 14 and GNG 1581.

The stage-wise Topt increases from anthesis (~12–16 °C) to pod filling (~16–17 °C) and reaches the highest at maturity (~19–20 °C). This reflects the different thermal requirements of chickpea reproductive stages. Cooler temperatures favour pollen viability and fertilisation, while later stages like starch accumulation and dry matter deposition can tolerate warmer conditions. (Challinor *et al.*, 2005; Devasirvatham *et al.*, 2012). All T_{opt} estimates fell within the documented thermal optimum range for chickpea reproductive stages under field conditions (12–25 °C) (Challinor *et al.*, 2005).

Table 1 : Stage-wise optimum temperature (Topt, °C) and mean grain yield of chickpea varieties under best sowing dates.

Variety	Optimum sowing date	Mean Yield (kg ha⁻¹)	Topt (°C)				
			FI	FF	PI	FP	Maturity
JG 14	D1 (10 Nov)	1498	15.0	13.8	13.7	16.9	19.4
GNG 1581	D1 (10 Nov)	1690	15.0	13.8	15.2	16.9	19.4
Birsa Chana 3	D1 (10 Nov)	1854	15.6	12.4	16.9	16.5	19.8

*FI = Flower Initiation; FF = 50% Flowering; PI = Pod Initiation; FP = 50% Pod.

Temperature sensitivity

The temperature sensitivity (S, kg ha^{-1} $°C^{-1}$) of grain yield varied markedly across phenophases, varieties and sowing dates (Table 2; Fig. 1). Although no regression coefficient attained statistical significance at $p < 0.05$ attributable to the constrained sample size (n = 8, df = 6), the magnitude and direction of S provided meaningful biological insights into stage-specific thermal vulnerability (see Supplementary Table S1 for the complete 45-combination dataset).

Effect of sowing date on temperature sensitivity. Sensitivity was most pronounced under D2 (25 November) for all three varieties (Fig. 1A). GNG 1581 under D2 recorded the largest positive sensitivity at flower initiation (S = +243 kg ha^{-1} $°C^{-1}$, R^2 = 0.155) and at 50% Pod (S = +241 kg ha^{-1} $°C^{-1}$, R^2 = 0.211), while Birsa Chana 3 under D2 showed high positive sensitivity at flower initiation (S = +209 kg ha^{-1} $°C^{-1}$, R^2 = 0.156), indicating sub-optimal temperatures during early reproductive development under this sowing date and a yield benefit from modest warming. JG 14 under D2 was most responsive at 50% flowering (S = +167 kg ha^{-1} $°C^{-1}$, R^2 = 0.315), the strongest model fit across all combinations identifying anthesis as the primary thermal response window for this variety under Late-November sowing.

Negative sensitivities and yield penalties from warming. Negative S values were most prominent under D1 and D3 at early reproductive stages. JG 14 under D1 exhibited the highest negative sensitivity at flower initiation (S = −121 kg ha^{-1} $°C^{-1}$, R^2 = 0.120) and GNG 1581 under D1 at 50% flowering (S = −139 kg ha^{-1} $°C^{-1}$, R^2 = 0.079). Under D3, Birsa Chana 3 recorded the largest negative sensitivity at 50% flowering (S = −190 kg ha^{-1} $°C^{-1}$, R^2 = 0.249), the highest R^2 among all negative-direction combinations highlighting the exceptional vulnerability of late-sown Birsa Chana 3 to thermal stress during the flowering phase.

Most temperature-sensitive phenophase. The phenophase with maximum $|S|$ differed by variety and sowing date (Table 2; Fig. 1B). Flower initiation was the critical stage for JG 14 under D1 and for both GNG 1581 and Birsa Chana 3 under D2. The 50% flowering stage dominated under GNG 1581 (D1) and Birsa Chana 3 (D3), while pod initiation was most sensitive for Birsa Chana 3 (D1) and GNG 1581 (D3). When averaged across sowing dates, Birsa Chana 3 exhibited the highest mean $|S|$ at pod initiation (118 kg ha^{-1} $°C^{-1}$) and 50% flowering (105 kg ha^{-1} $°C^{-1}$), whereas JG 14 showed comparatively lower but consistent sensitivity across phenophases (60–82 kg ha^{-1} $°C^{-1}$). Sensitivity was generally attenuated at maturity (56–89 kg ha^{-1} $°C^{-1}$), indicating that terminal grain-filling stages are relatively more thermally buffered than the reproductive window (Fig. 1C).

Table 2 : Most temperature-sensitive phenological stage, sensitivity coefficient (S, kg ha^{-1} $°C^{-1}$) and R^2 for chickpea varieties across sowing dates.

Variety	Sowing Date	Most Sensitive Phenophase	S (kg ha^{-1} C^{-1})	R^2	Direction	Magnitude
JG 14	D1 (10 Nov)	Flower Initiation	**−121**	0.120	Negative	High
JG 14	D2 (25 Nov)	50% Flowering	**+167**	0.315	Positive	High
JG 14	D3 (10 Dec)	Maturity	**+71**	0.243	Positive	Moderate
GNG 1581	D1 (10 Nov)	50% Flowering	**−139**	0.079	Negative	High
GNG 1581	D2 (25 Nov)	Flower Initiation	**+243**	0.155	Positive	Very High
GNG 1581	D3 (10 Dec)	Pod Initiation	**+138**	0.154	Positive	High
Birsa Chana 3	D1 (10 Nov)	Pod Initiation	**+100**	0.081	Positive	High
Birsa Chana 3	D2 (25 Nov)	Flower Initiation	**+209**	0.156	Positive	Very High
Birsa Chana 3	D3 (10 Dec)	50% Flowering	**−190**	0.249	Negative	High

S = temperature sensitivity coefficient (kg ha^{-1} $°C^{-1}$). Magnitude categories: Very High = |S| > 200; High = |S| 100–200; Moderate = |S| 50–100 kg ha^{-1} $°C^{-1}$.

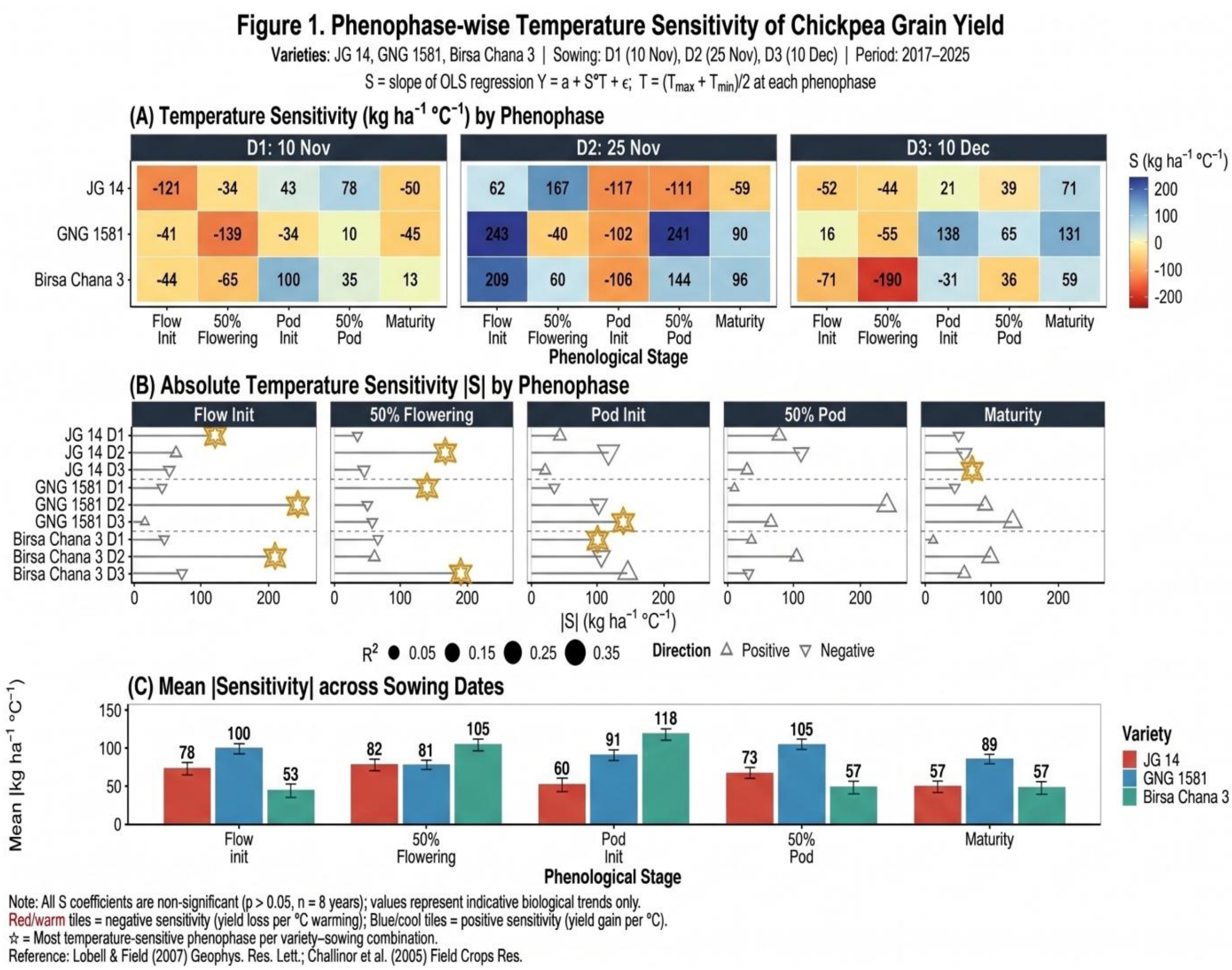

Fig. 1 : Phenophase wise temperature sensitivity of chickpea grain yield

(A) Diverging heatmap of S (kg ha^{-1} $°C^{-1}$); red = negative, blue = positive sensitivity. (B) Lollipop chart of |S|; gold star (★) marks the peak-sensitive phenophase per variety–sowing combination; point size proportional to R^2; ▲/▼ indicates positive/negative thermal response. (C) Grouped bar chart of mean |S| averaged across sowing dates with ± SE error bars.

Effect of Seasonal Rainfall on Chickpea Grain Yield

Low and erratic cumulative seasonal rainfall, averaging 53.9, 70.1 and 71.3 mm under D1, D2 and D3, respectively, reflecting the predominantly dry post-monsoon conditions at the study site. The direction of the rainfall–yield association varied systematically with sowing date and variety (Fig. 2).

Under D1, all three varieties exhibited a negative rainfall–yield relationship, with Birsa Chana 3 recording the strongest tendency (r = −0.69), attributable to the elevated risk of post-monsoon residual rainfall events coinciding with the prolonged crop duration of this variety under early sowing. JG 14 showed a moderate negative association (r = −0.46), while GNG 1581 was comparatively less responsive (r = −0.27). Under D2, the relationship shifted towards positive territory for GNG 1581 (r = +0.46), indicating that moderate supplementary moisture during Late-November sowing conditionally benefits this variety, while JG 14 and Birsa Chana 3 remained near-neutral (r = +0.03 and +0.04, respectively). Under D3, all associations were weak ($|r| \leq 0.18$), demonstrating that the yield of the latest-sown treatment was governed predominantly by thermal conditions rather than moisture availability, consistent with the strongly negative temperature sensitivity observed at 50% flowering and pod initiation under this sowing date (Section 3.2).

Phenophase-wise rainfall sensitivity. Stage-specific OLS regression slopes (β, kg ha^{-1} mm^{-1}) revealed that the maturity stage under D1 was the most consequential site of negative rainfall sensitivity (Fig. 3). Birsa Chana 3 recorded a significant negative slope at maturity under D1 (β = −18.54 kg ha^{-1} mm^{-1}, p = 0.012) and JG 14 exhibited a significant negative slope at the same stage (β = −9.35 kg ha^{-1} mm^{-1}, p = 0.047). These findings indicate that pre-harvest rainfall under early sowing conditions suppresses yield through grain shattering, delayed physiological maturity and heightened fungal pressure at pod dry-down, with the effect being approximately twice as large in Birsa Chana 3 as in JG 14, likely reflecting the greater maturity-stage exposure of this longer-duration variety.

Conversely, the 50% flowering stage under D2 was the dominant site of positive rainfall sensitivity. GNG 1581 recorded the strongest significant positive slope across all phenophase combinations (β = +50.98 kg ha^{-1} mm^{-1}, p = 0.003), followed by Birsa Chana 3 at the same stage (β = +38.50 kg ha^{-1} mm^{-1}, p = 0.021). These relationships demonstrate that supplementary rainfall during anthesis under late november sowing substantially enhances yield, most plausibly by improving canopy water status, sustaining pollen viability and promoting pod set under the comparatively warmer flowering environment of D2. GNG 1581 also returned a significant positive slope at flower initiation under D2 (β = +14.85 kg ha^{-1} mm^{-1}, p = 0.039) and Birsa Chana 3 showed a significant positive slope at flower initiation under D3 (β = +11.35 kg ha^{-1} mm^{-1}, p = 0.039), highlighting the sensitivity of floral initiation to early-season moisture across contrasting sowing environments. Together, the finding that rainfall is yield-suppressing at maturity under D1 but yield-promoting at 50% flowering under D2 is internally consistent across varieties and aligns with the established physiology of chickpea reproductive development under moisture-variable dryland conditions (Garg *et al*., 2013; Mishra & Singh, 2019).

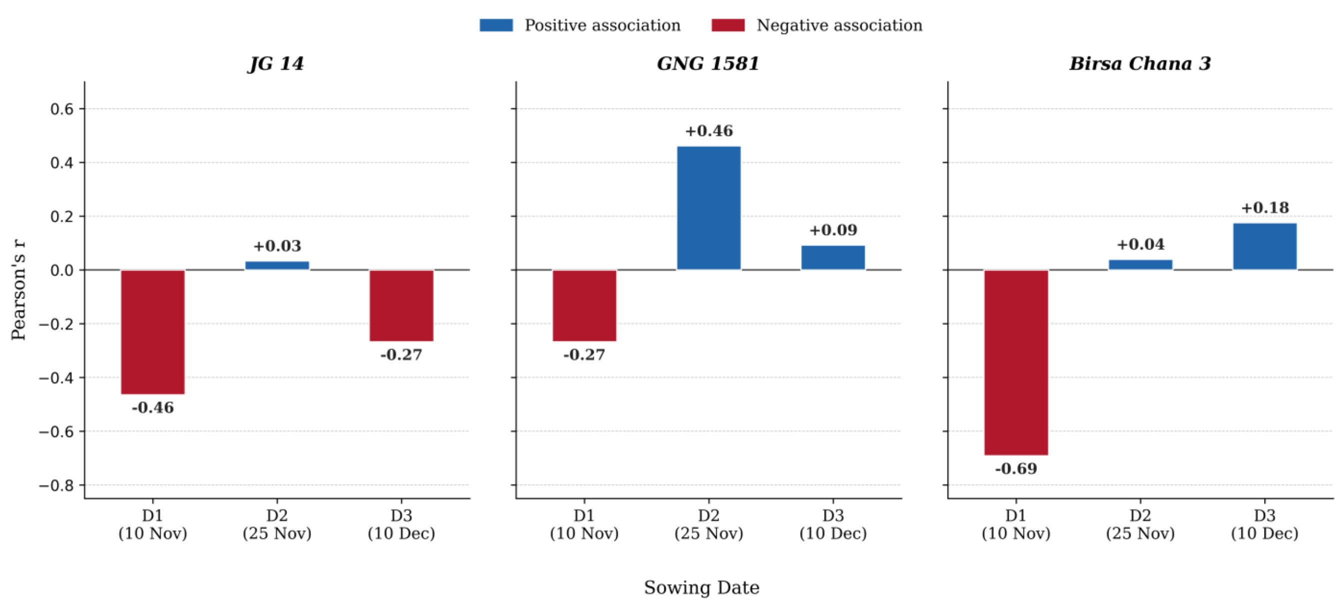

Fig. 2 : Pearson correlation (r) between seasonal rainfall and grain yield of chickpea varieties at different sowing dates (2017–2025).

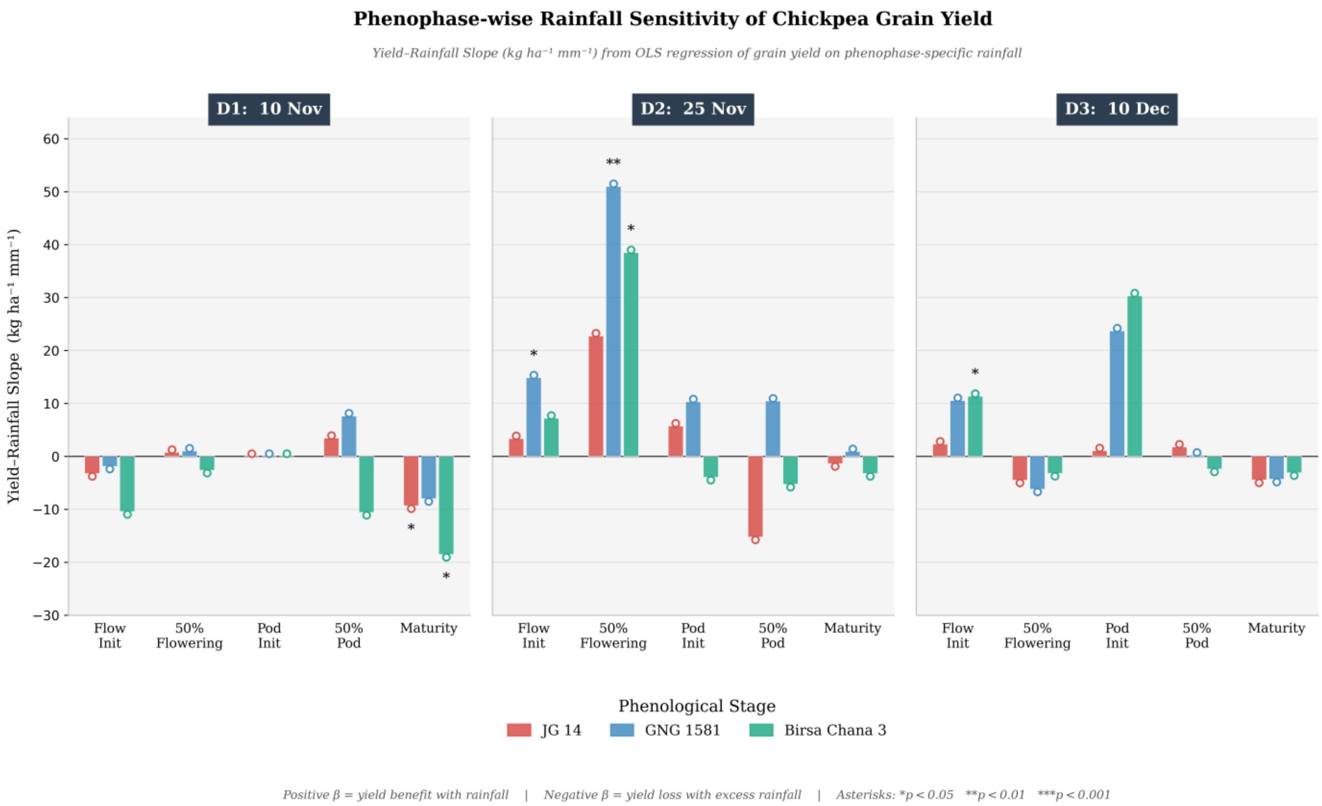

Fig. 3 : Phenophase-wise rainfall–yield sensitivity (β, kg ha^{-1} mm^{-1}) of chickpea across sowing dates.

Discussion

The progressive increase in T_{opt} from ~12.4–16.2 °C at 50% flowering to ~19.4–25.8 °C at maturity is biologically consistent with the thermal hierarchy of chickpea reproductive processes: pollen viability requires comparatively cool temperatures, whereas post-fertilization starch deposition and dry-matter accumulation tolerate a progressively warmer range (Devasirvatham *et al*., 2012; Gaur *et al*., 2015). The low T_{opt} for Birsa Chana 3 at 50% flowering under D_1 (12.4 °C) reflects its cool-adapted breeding background and the established principle that genotype-specific optima are shaped by selection environments (Krishnamurthy *et al*., 2011). Critically, T_{opt} was not a fixed varietal constant but rose systematically under delayed sowing from 19.4–19.8 °C at maturity under D_1 to 24.6–25.8 °C under D_3 confirming that the thermal optimum is contingent on the cumulative thermal trajectory of the crop cycle and directly challenges single-threshold sowing frameworks (Challinor *et al*., 2005; Kumar *et al*., 2022).

The most thermally vulnerable phenophase shifted dynamically with the variety and sowing date. Large positive sensitivities under D_2, GNG 1581 at flower initiation (S = +243 kg ha^{-1} °C^{-1}) and Birsa Chana 3 at flower initiation (S = +209 kg ha^{-1} °C^{-1}) indicate that late-November-sown crops enter the reproductive phase under sub-optimal cool temperatures where modest warming enhances pollen performance and pod set (Jha *et al*., 2024; Soltani *et al*., 2016). Conversely, negative sensitivities for JG 14 under D_1 at flower initiation (S = −121 kg ha^{-1} °C^{-1}) and Birsa Chana 3 under D_3 at 50% flowering (S = −190 kg ha^{-1} °C^{-1}) confirm that these combinations place flowering within the heat-stress zone (Devasirvatham *et al*., 2012). Birsa Chana 3 showed the highest mean absolute sensitivity at pod initiation (118 kg ha^{-1} °C^{-1}) and 50% flowering (105 kg ha^{-1} °C^{-1}), while JG 14 was more thermally stable (60–82 kg ha^{-1} °C^{-1}), pointing to exploitable genotypic variation in thermal plasticity (Rezaei *et al*., 2015). Sensitivity was attenuated at maturity across all varieties, confirming that terminal grain filling is comparatively thermally buffered.

Rainfall effects were predominantly negative or negligible, indicating that chickpea at this site is susceptible to excess rather than deficit moisture. The strongest adverse association (Birsa Chana 3, D_1, r = −0.69) reflects post-monsoon residual rainfall on the Chota Nagpur Plateau promoting waterlogging and fungal pressure, amplified by the longer crop duration of this variety (Garg *et al*., 2013). Rainfall at maturity-imposed yield penalties under D_1 (most severely for Birsa Chana 3, ~−20 kg ha^{-1} mm^{-1}), whereas rainfall at 50% flowering was yield-promoting under D_2 (~23–50 kg ha^{-1} mm^{-1}) (Mishra & Singh, 2019). The absence of statistically significant slopes across 45 phenophase combinations reflects the constrained sample size (*n* = 8); however, the consistent directional patterns align with established chickpea physiology (Lobell & Field, 2007). Future work should extend these analyses to multi-location datasets and process-based models incorporating vapour pressure deficit and elevated CO_2 to formally validate the phenophase-specific thermal profiles reported here.

Conclusion

This study demonstrates that the optimum temperature for chickpea grain yield and the magnitude of thermal sensitivity are phenophase-specific and sowing-date-contingent, rather than fixed varietal characteristics. T_{opt} ranged from 12.4 °C at 50% flowering under the earliest sowing to 25.8 °C at maturity under the latest, rising systematically with delayed sowing across all three varieties. The most thermally vulnerable phenophase shifted from flower initiation and 50% flowering under D_1 and D_2 to pod initiation and maturity under D_3, a stage-sowing interaction that fixed, single-threshold management frameworks are structurally incapable of capturing. Birsa Chana 3 and GNG 1581 were markedly more thermally responsive than JG 14, particularly during early reproductive development, pointing to exploitable genotypic variation in thermal plasticity that breeding and variety deployment programs can leverage. Rainfall effects were predominantly negative or negligible, most severely for early-sown Birsa Chana 3 ($r = -0.69$), confirming that both the thermal and moisture environments at individual phenophases must be jointly considered when designing sowing-date strategies for this agro-ecological zone.

These findings provide a phenophase-resolved, variety-specific thermal and moisture evidence base applicable to chickpea cultivation at the study site and potentially transferable to agro-climatically similar rainfed environments of eastern India, subject to multi-location validation.

The primary limitation is an eight-year observational record, which constrains statistical power. Future work should combine multi-location, long-term phenological monitoring with process-based model validation, incorporating extreme temperature events, vapor pressure deficit and projected CO_2 enrichment. All expected to intensify across South Asia to improve transferability of these estimates to on-farm recommendations under real-world climate change scenarios.

Author Contributions

- Satya Pragyan Kar: Conceptualization, Data collection, Formal analysis, Investigation, Methodology, Visualization, Lab work, Writing – Original Draft.
- Dr. Pragyan Kumari: Resources, Software, Supervision, Review & Editing.
- Dr. C. S. Singh: Validation, Writing–Review & Editing, Data curation.
- Dr. P. Mahapatra: Validation, Writing–Review & Editing, Data curation. All authors reviewed and approved the final manuscript.

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Competing Interests

The authors declare no competing interests.

Data Availability

All data supporting the findings of this study are included within the article and its supplementary materials.

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Supplementary Material

Table S1 : Complete temperature sensitivity coefficients (*S*, kg ha^{-1} °C^{-1}) and coefficients of determination (R^2) from OLS linear regression of grain yield on phenophase mean temperature for three chickpea varieties across three sowing dates and five phenological stages (2017–18 to 2024–25). Bold *S* values identify the peak-sensitivity phenophase for each variety × sowing combination (as summarised in Table 2 of the main text).

Variety	Sowing Date	Phenophase	S (kg ha^{-1} °C^{-1})	R^2	Direction
JG 14	D1	Flower Initiation	**−121**	0.120	Negative
JG 14	D1	50% Flowering	−34	0.008	Negative
JG 14	D1	Pod Initiation	+43	0.044	Positive
JG 14	D1	50% Pod	+78	0.067	Positive
JG 14	D1	Maturity	−50	0.019	Negative

JG 14	D2	Flower Initiation	+62	0.025	Positive
JG 14	D2	50% Flowering	**+167**	0.315	Positive
JG 14	D2	Pod Initiation	−117	0.354	Negative
JG 14	D2	50% Pod	−111	0.111	Negative
JG 14	D2	Maturity	−59	0.101	Negative
JG 14	D3	Flower Initiation	−52	0.036	Negative
JG 14	D3	50% Flowering	−44	0.042	Negative
JG 14	D3	Pod Initiation	+21	0.014	Positive
JG 14	D3	50% Pod	+29	0.042	Positive
JG 14	D3	Maturity	**+71**	0.243	Positive
GNG 1581	D1	Flower Initiation	−41	0.009	Negative
GNG 1581	D1	50% Flowering	**−139**	0.079	Negative
GNG 1581	D1	Pod Initiation	−34	0.017	Negative
GNG 1581	D1	50% Pod	+10	0.001	Positive
GNG 1581	D1	Maturity	−45	0.010	Negative
GNG 1581	D2	Flower Initiation	**+243**	0.155	Positive
GNG 1581	D2	50% Flowering	−49	0.011	Negative
GNG 1581	D2	Pod Initiation	−102	0.110	Negative
GNG 1581	D2	50% Pod	+241	0.211	Positive
GNG 1581	D2	Maturity	+90	0.096	Positive
GNG 1581	D3	Flower Initiation	+15	0.001	Positive
GNG 1581	D3	50% Flowering	−56	0.017	Negative
GNG 1581	D3	Pod Initiation	+138	0.154	Positive
GNG 1581	D3	50% Pod	**+65**	0.054	Positive
GNG 1581	D3	Maturity	+131	0.207	Positive
Birsa Chana 3	D1	Flower Initiation	−44	0.005	Negative
Birsa Chana 3	D1	50% Flowering	−65	0.009	Negative
Birsa Chana 3	D1	Pod Initiation	**+100**	0.081	Positive
Birsa Chana 3	D1	50% Pod	+36	0.005	Positive
Birsa Chana 3	D1	Maturity	+13	0.000	Positive
Birsa Chana 3	D2	Flower Initiation	**+209**	0.156	Positive
Birsa Chana 3	D2	50% Flowering	+60	0.022	Positive
Birsa Chana 3	D2	Pod Initiation	−106	0.160	Negative
Birsa Chana 3	D2	50% Pod	+104	0.054	Positive
Birsa Chana 3	D2	Maturity	+98	0.155	Positive
Birsa Chana 3	D3	Flower Initiation	−71	0.021	Negative
Birsa Chana 3	D3	50% Flowering	**−190**	0.249	Negative
Birsa Chana 3	D3	Pod Initiation	+147	0.223	Positive
Birsa Chana 3	D3	50% Pod	−31	0.015	Negative
Birsa Chana 3	D3	Maturity	+59	0.054	Positive

All p-values non-significant ($p > 0.05$). *S* estimated from $Y = \alpha + S \cdot T + \varepsilon$; $T = (T_{max}+T_{min})/2$ at each phenophase. Positive (blue) = yield tends to increase with warming; Negative (red) = yield tends to decrease with warming. Thin rules separate variety × sowing groups. Results are indicative biological trends given n = 8, df = 6.