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Phenological characterization and thermal requirements of prominent cultivars of litchi in the Indo-Gangetic Plain

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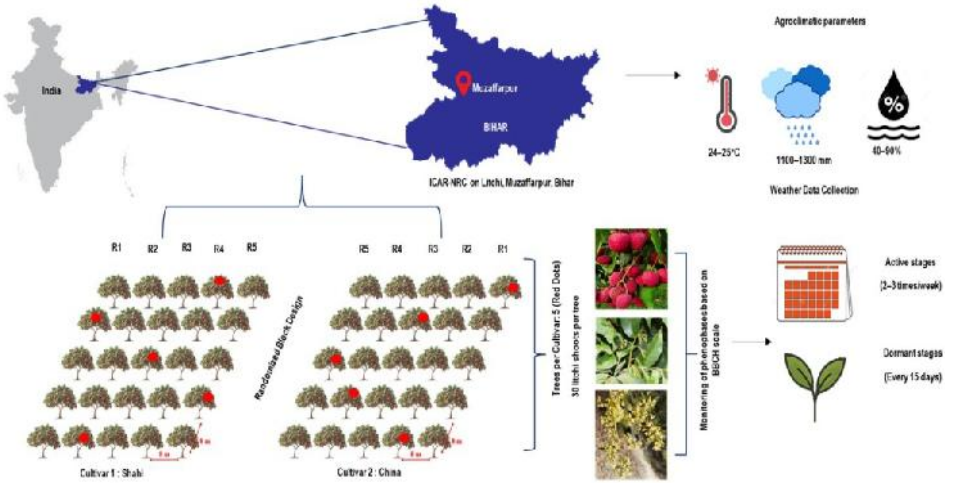
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Abstract

Aim: Litchi (*Litchi chinensis* Sonn.) exhibits marked phenological variability among cultivars, which influences productivity and climate adaptability. This study aimed to characterize and compare the phenological behavior of 'Shahi' and 'China' using the extended BBCH (*Biologische Bundesanstalt, Bundessortenamt* and *Chemische Industrie*) scale and to examine the influence of thermal indices on phenophase progression.

Methodology: The experiment was conducted at the ICAR–National Research Centre on Litchi, Muzaffarpur (Bihar) during 2024–2025. Phenological observations were recorded from bud development to fruit maturity following the BBCH scale. Growing degree days (GDD) and chilling days were computed to assess temperature-driven responses.



Results: Clear cultivar-specific differences were observed in the timing and duration of phenophases. 'Shahi' exhibited early bud break, shoot growth and fruit maturity, whereas 'China' showed delayed but prolonged development. Although flowering intensity was comparable, 'China' recorded higher fruit set (89%) and retention (78%) than 'Shahi' (35% and 22%). Thermal accumulation was also greater in 'China' (1162.9 GDD) compared to 'Shahi' (955.5 GDD). A novel Chill-Triggered Transition and Synchrony (CTTS) model was developed to integrate cultivar-specific chilling thresholds, flowering transition dynamics, and orchard-level flowering synchrony into a unified phenological framework.

Interpretation: 'China' demonstrated superior reproductive efficiency despite its delayed phenology. The BBCH scale together with the newly developed CTTS model provides a robust framework for predicting flowering behaviour and improving climate-resilient orchard management.

Key words: BBCH scale, Chilling days, Growing degree days, Litchi, Phenology

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Introduction

Litchi (*Litchi chinensis* Sonn.) belongs to the family Sapindaceae, is a highly valuable fruit crop well known for its unique flavour, juicy aril and high nutritional value (Castillo-Olvera *et al.,* 2025). It is a tropical and subtropical fruit crop originating from Southern China and Northern Vietnam (Menzel, 2001), and is currently cultivated in more than 20 tropical and subtropical countries of the world. India, along with China, Thailand, and Vietnam, is a leading producer of litchi with an annual production of 5.78 lakh metric tonnes (Kumar *et al.,* 2026). Litchi cultivation in India is characterized by a narrow genetic base (Bajpai *et al.,* 2016) and exhibits high sensitivity to climatic variations, making it vulnerable to environmental fluctuations (Nath *et al.,* 2018). It is primarily cultivated in Bihar, West Bengal, Tripura, and parts of Uttar Pradesh and Uttarakhand (Kumar *et al.,* 2023). The quality and quantity of litchi production are profoundly influenced by the phenological traits of the crop, including leaf flushing, panicle emergence, flowering, fruit set, development, and maturity. These phenophases are strongly influenced and deeply dependent not only on the genetic makeup of the cultivar but also on local environmental factors such as temperature, humidity, rainfall and photoperiod (Szot and Łysiak, 2025).

Phenological observations provide a scientific basis for understanding cultivar responses to environmental conditions and for predicting key developmental events important for orchard management (Delgado *et al.,* 2011). The BBCH (*Biologische Bundesanstalt, Bundessortenamt* and *Chemische Industrie*) scale has been successfully adapted to several fruit crops including grape, mango, avocado, longan, apple and pomegranate (Lorenz *et al.,* 1995; Rajan *et al.,* 2011; Alcaraz *et al.,* 2013; Pham *et al.,* 2015; Martínez *et al.,* 2019; Kumar *et al.,* 2021). In litchi, Wei *et al.* (2013) highlighted the role of a standardized phenological framework by developing an extended BBCH scale, which allowed precise identification and classification of 41 distinct phenological stages. In this study, the term "phenophase" is used to describe each distinct developmental event defined under the extended BBCH scale, and is preferred over the broader term "phenological stage" for precision and consistency. Although the extended BBCH scale has been developed for litchi, comprehensive BBCH-based phenological characterization integrated with thermal accumulation and flowering synchrony has not been reported for commercially important Indian cultivars (Nath *et al.,* 2018).

Furthermore, no quantitative framework is currently available to evaluate flowering synchrony in relation to chilling accumulation or to define cultivar-specific thermal thresholds under the subtropical conditions of the Indo-Gangetic Plain. Temperature-driven indices such as growing degree days (GDD) provide valuable insights into cultivar-specific thermal requirements, facilitating prediction of key phenological stages and supporting climate-resilient orchard management (Roussos, 2024). In litchi, floral initiation is triggered by prolonged exposure to cool temperatures below 12°C, while insufficient chilling results in poor bud break and irregular flowering (Menzel and Simpson, 1991). Accurate assessment of chilling requirements and GDD is therefore essential for cultivar suitability, regional adaptation, and predicting flowering under changing climatic conditions (Wang *et al.,* 2021). Recent climatic variability in India has been associated with delayed flowering, asynchronous panicle emergence, and yield fluctuations in litchi (Shivandu *et al*., 2026).

Existing phenological models primarily predict flowering based on calendar dates, growing degree days (GDD), or chilling accumulation. However, these approaches do not simultaneously quantify the cultivar-specific chilling thresholds, probabilistic transition from vegetative to reproductive development and flowering synchrony among individual trees. To the best of our knowledge, no published phenological model currently integrates these three components into a single analytical framework for litchi. Therefore, a new conceptual model, designated as the Chill-Triggered Transition and Synchrony (CTTS) model, was developed in the present study. The model integrates cumulative chilling exposure, logistic flowering transition, and orchard-level flowering synchrony into a unified framework for characterizing reproductive behaviour of litchi under subtropical environments.

Therefore, the present study aimed to characterize the phenological development of two commercially important Indian litchi cultivars ('Shahi' and 'China'), using the extended BBCH scale, quantify their chilling and growing degree day (GDD) requirements, and evaluate flowering transition and synchrony using the newly developed CTTS model. The study further aimed to establish a region-specific phenological framework to support climate-resilient orchard management under the subtropical conditions of the Indo-Gangetic Plain.

Materials and Methods

Study area: The study was conducted during the 2024–2025 cropping season at the experimental orchard of ICAR–National Research Centre on Litchi, Muzaffarpur, Bihar, located at a latitude of 26.1°N, 85.4°E, and an elevation of about 60 m above mean sea level, situated in the North-eastern Indo-Gangetic Plain. The region falls under the subtropical agro-climatic zone, characterized by cold winters and hot, humid summers with an average annual rainfall of about 1100–1300 mm, primarily received during the monsoon season.

The average annual temperature ranges between 24 and 25°C. The coldest months are December and January, when temperatures range from 10 to 15°C. The warmest months are April to June, when highs of 40°C are common. The soil of the experimental orchard belongs to the Gangetic alluvial group, typically sandy loam in texture, well-drained and alkaline in reaction. The average soil pH was 7.5 to 8.0, organic carbon content (0.55 to 0.62%), available nitrogen (221 to 242 kg ha^{-1}), phosphorus (10.5 to 12.6 kg ha^{-1}), and potassium (100-110 kg ha^{-1}), indicating moderate fertility status typical of Indo-Gangetic alluvial soils. Such climatic features and edaphic conditions are

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representative of the prime litchi-growing belt of Eastern India, making the site suitable for studying phenological behavior under subtropical conditions.

Plant material and experimental design: Two commercially grown litchi cultivars, 'Shahi' and 'China', were selected based on their regional importance and variation in phenological behavior. The experiment was conducted on 15-year-old, healthy, and uniformly growing trees with an average height of 4.5–5.0 m, canopy spread of 5.10–6.40 m, and trunk girth of 85–90 cm measured 15 cm above the ground.The trees were planted at a spacing of 8 × 8 m and trained in an open-center system, with light annual pruning carried out after harvest to maintain canopy shape, uniform light interception, and adequate aeration.All experimental trees were maintained under uniform cultural management throughout the study period. The orchard was managed under the recommended package of practices for litchi cultivation in the Indo-Gangetic region. Irrigation was provided at 10–15 day intervals during dry season to maintain adequate soil moisture, while rainfall during monsoon period met the water requirement of the trees. Weed control was achieved by shallow hoeing around the tree basins to conserve soil moisture. Nutrient management followed the standard recommendation of 100 kg farmyard manure, 500 g nitrogen, 250 g phosphorus, and 400 g potassium per tree per year, applied in two equal splits —half after harvest and the remaining after fruit set. Pest and disease control measures were adopted as needed, following integrated pest management (IPM) practices to keep the orchard free of major infestations. No growth regulators were applied during the study period to ensure that the recorded phenological events represented the natural progression of the crop. The experiment was laid out in a Randomized Block Design (RBD) with five biological replications per cultivar, each tree representing one experimental unit. Thirty current-season shoots were tagged on each tree and served as observational units for phenological recordings.

Phenological observations: The BBCH *(Biologische Bundesanstalt, Bundessortenamt* and *Chemische Industrie*) scale suggested by Wei *et al.* (2013) was used to observe the phenological stage of the trees. Observations, measurements, and imaging were performed at a frequency of two to three observations per week depending on the phenological stage. Observations were carried out between 08:00 and 10:00 hr on each observation day to minimize the influence of diurnal temperature variation on the phenophases. Phenological stages within a cultivar were not perfectly synchronized among all tagged shoots of the experimental trees. Consequently, variation was observed in the dates of initiation of key phenophases, including bud break, panicle emergence, flowering, fruit set, and fruit maturity. To objectively determine the representative date for each phenophase, the mode value (most frequently observed date across replications and trees) of the phenophaseswas used. The rationale for this approach was that the mode reflects the date on which the maximum proportion of trees and shoots expressed the given stage. Accordingly, for each phenophase, the frequency distribution of observed dates was prepared, and the date with the highest frequency was selected as the exact date of occurrence for that stage. This methodology ensured standardized and comparable phenological timelines across cultivars, minimizing observational bias and reflecting the most representative biological expression of the phenophase under field conditions.

Collection of weather data: Daily weather information viz. the maximum and minimum temperature, relative humidity, and rainfall was collected from the Automatic Weather Station (AWS). This data was used to correlate the influence of weather conditions on phenological events and to calculate growing degree days and chilling days.

Chilling days: Chilling accumulation was estimated following the approach of Kumar *et al.* (2023), by counting the number of days during bud dormancy period when the daily minimum temperature remained below 12°C. This simplified daily-based method was adopted due to the unavailability of continuous hourly temperature records and provides a practical approximation of cold exposure relevant to subtropical conditions of the Indo-Gangetic Plain. The cool-night exposure (C(t)) was computed as the cumulative number of days with Tmin< 12°C from 1 November 2024 onwards. Floral induction was considered favourable when cumulative cool nights exceeded a critical threshold (C*). Cultivar-specific thresholds were estimated from the observed date of floral induction corresponding to the cumulative number of chilling days.

Growing degree days (GDD): Growing degree days (GDD) also known as heat units was calculated for each phenophase of the litchi cv.'Shahi' and 'China' separately using the formula given by Balog and Pfeiffer (1998):

$$GDD = \sum [(T_{max} + T_{min})/2 - T_{base}]$$

Where, T_{max}=Daily maximum temperature; T_{min}=Daily minimum temperature and T_{base}=Base temperature for litchi (10°C)

A base temperature (T_{base}) of 10°C was adopted for GDD calculation based on previous studies indicating that vegetative and reproductive development in litchi remains negligible below this threshold under subtropical conditions (Rai *et al.,* 2002; Menzel and Simpson, 1991).

Chill-Triggered Transition and Synchrony (CTTS) model: A novel Chill-Triggered Transition and Synchrony (CTTS) model was developed to describe the progression from climatic induction to orchard-level flowering synchrony through three sequential modules: induction, transition and synchrony.

Induction Module: $C(t) = \Sigma I(T_{min}(d) < 12)$

Floral induction status, $I_{induced}(t)$, was assigned a value of 1 when $C(t) \geq C^*$, otherwise 0.

Where, *C(t)* is the cumulative number of chilling days below 12°C from 1 November; *t* denotes the calendar day; *d* represents the daily observation; *I(Tmin< 12°C)* is an indicator function taking the value 1 when the daily minimum temperature is below 12°C and 0 otherwise; C* is the cultivar-specific chilling threshold; and *I*_{induced} denotes the induction status (0 = vegetative, 1 = flowering competent).

Transition Module: $p(w) = 1 / [1 + e^{-(\alpha + \beta \Delta w)}]$

Where, *p(w)* is the weekly probability that a tree transitions from vegetative to flowering status; α is the intercept of the logistic transition function; *β* is the rate of increase in flowering probability; and *Δ*w is the number of weeks elapsed after attainment of the chilling threshold.

Synchrony Module: $Y(w) = A / [1 + e^{-(k(w - w50)}]$

Where, *Y(w)* is the cumulative flowering percentage; *A* is the asymptotic flowering percentage; *k* is the steepness parameter of the flowering curve; *w* denotes the week after induction; w₅₀ is the week at which 50% flowering is achieved; w₁₀ and w₉₀ represent the weeks corresponding to 10% and 90% flowering, respectively; W (= w₉₀ − w₁₀) is the flowering window; and the Synchrony Index (SI) is calculated as 1/W.Thus, smaller flowering windows indicate greater flowering synchrony and consequently higher Synchrony Index values.

An initial threshold of 40 chilling days (Tmin< 12°C) was selected empirically based on long-term field observations at ICAR–NRC on Litchi, where years receiving approximately 40 cool nights generally exhibited regular flowering (Kumar et al., 2023). For each cultivar, the effective chilling threshold (C* was estimated as the cumulative number of chilling days corresponding to the median date of flowering initiation. A logistic function was selected because flowering transition is a bounded cumulative process that progresses from 0 to 100% flowering over time. Weekly flowering observations from all experimental trees were used to estimate transition probabilities and fit the logistic flowering curves separately for each cultivar. The CTTS model integrates cumulative chilling exposure, flowering transition, and orchard-level flowering synchrony to characterize cultivar-specific reproductive behaviour under subtropical conditions.

Statistical analyses: Initial data screening involved computation of the mode and standard deviation (SD) to evaluate variation in the duration of phenophases within and between cultivars. Differences among cultivars for phenological parameters and thermal requirements were analyzed using One-way analysis of variance (ANOVA) under a Randomized Block Design (RBD) in R software (version 4.3.2). Treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at $P \leq 0.05$. Phenological transition probabilities [p(w)] were derived from weekly flowering observations of individual trees. Logistic regression and non-linear least-squares fitting were performed using the Stats Package to estimate the CTTS model parameters (α, β, A, k, w_{50}) and to fit cumulative flowering curves for each cultivar. Model performance was evaluated by comparing predicted and observed flowering progression using the coefficient of determination (R^2) and root mean square error (RMSE), where higher R^2 and lower RMSE values indicated better model performance.

Results and Discussion

The phenological development of two commercially important litchi cultivars, 'Shahi' and 'China', was characterized using the extended BBCH scale from bud development to fruit maturity (Figs. 1–3). Both cultivars followed the same sequence of developmental stages; however, significant differences were observed in the timing and duration of individual phenophases. Dormancy commenced during mid-September 2024 and continued until late September in both cultivars. Bud swelling and bud burst occurred almost simultaneously, and leaf development progressed uniformly, with fully expanded leaves observed by mid-November, indicating minimal genotypic variation during the early vegetative phase. Differences became evident during shoot growth and reproductive development. Shoot elongation (BBCH 311–319) commenced earlier in 'Shahi', reaching approximately 90% of final shoot length by 29 December 2024, whereas 'China' attained the same stage about one week later. This earlier vegetative growth was subsequently reflected in reproductive development, with inflorescence emergence (BBCH 500–509) beginning on 23rd December 2024 in 'Shahi', compared with 30 December 2024 in 'China'. Likewise, successive stages of panicle development, including bud swelling, panicle elongation, and flower separation, occurred 7–10 days earlier in 'Shahi', indicating a more rapid and synchronized transition from vegetative to reproductive growth.

Flowering also differed significantly between cultivars. 'Shahi' initiated flowering on 16th March 2025 and reached full bloom by 24th March, whereas flowering in 'China' commenced approximately ten days later, with full bloom occurring on 3rd April. In contrast to 'Shahi', which completed flowering within 11 days, 'China' exhibited a longer flowering duration (15 days), suggesting a more extended reproductive phase. The differences observed during flowering were maintained throughout fruit development. Fruit set (BBCH 700) was recorded approximately one week earlier in 'Shahi', and all subsequent fruit developmental stages (BBCH 701–707) occurred 5–7 days ahead of 'China'. Consequently, physiological maturity (BBCH 800) and harvest maturity (BBCH 809) were attained 10–12 days earlier in 'Shahi', whereas 'China' reached full maturity during early June. Overall, fruit development extended for approximately 34 days in 'Shahi' compared with 45 days in 'China', confirming that 'Shahi' is an early-maturing cultivar whereas 'China' follows a comparatively prolonged developmental cycle. The observed differences indicate distinct cultivar-specific phenological strategies. The rapid progression of 'Shahi' from shoot development to fruit maturity enables earlier harvests and may

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Fig. 1: Illustration of important phenophases of litchi cv. 'Shahi'.

allow the crop to escape late-season heat stress, making it suitable for early-season production. In contrast, the extended reproductive period of 'China' provides a longer duration for fruit growth and development, which may contribute to its superior fruit retention and productivity. Similar cultivar-dependent differences in phenological progression have been reported in litchi under Chinese conditions by Wei *et al.* (2013), although the duration of several phenophases observed in the present study was longer, reflecting the influence of subtropical climate of the Indo-Gangetic Plain. Environmental conditions, particularly winter temperature and heat accumulation, are known to modify the duration of reproductive development in perennial fruit crops (Menzel, 2001; Huang and Chen, 2003). The BBCH scale proved to be an effective tool for documenting cultivar-specific phenological variation and identifying critical transitions between vegetative and reproductive growth (Kumar *et al*., 2026). Such standardized phenological characterization provides a reliable basis for comparing cultivars across environments and supports improved orchard management through timely scheduling of irrigation, nutrient application, plant protection measures, and harvesting (Wang *et al*., 2026). Furthermore, the observed differences between 'Shahi' and 'China' provide valuable information for breeding programmes, cultivar selection, and market planning through staggered harvesting and extended fruit availability.

Both cultivars exhibited 100% panicle emergence, indicating that the prevailing winter conditions were sufficient to induce floral initiation in all experimental trees (Fig. 4). However,

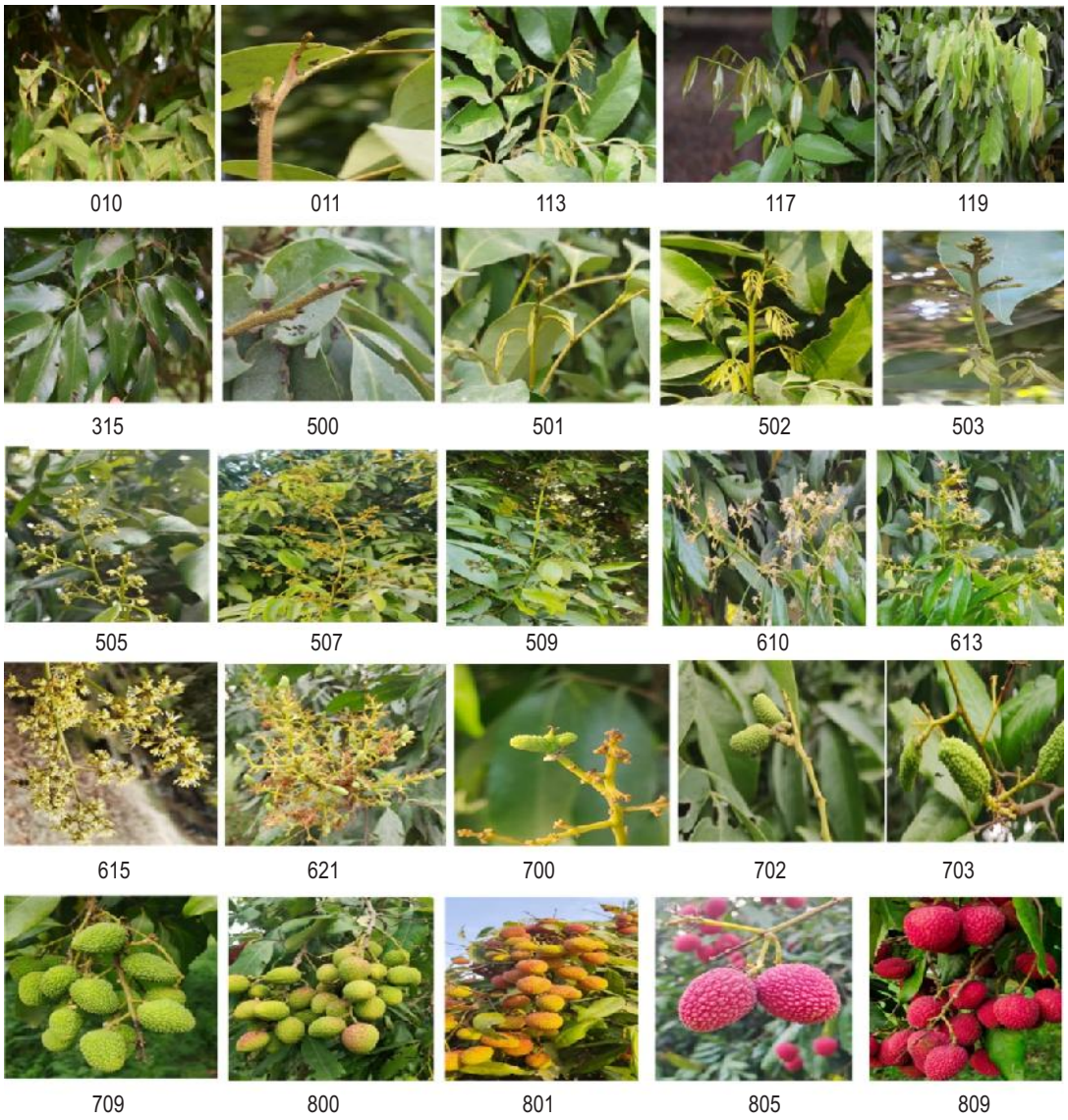


Fig. 2: Illustration of important phenophases of litchi cv. 'China'.

clear cultivar-specific differences became evident during flowering and fruit development. At full flowering (BBCH 613), 'China' recorded a significantly higher flowering intensity (98%) than 'Shahi' (92%), suggesting better flowering synchrony and greater reproductive potential. This difference became more pronounced during fruit set (BBCH 700), where 'China' achieved 89% fruit set, significantly higher than 'Shahi' (35%). Despite high initial fruit set, both cultivars exhibited physiological fruit drop during subsequent stages of fruit development. At mid-fruit development stage (BBCH 705), fruit retention declined to 27% in 'Shahi' and 83% in 'China'. By the advanced ripening stage (BBCH 805), retention further decreased to 22% in 'Shahi' and 78% in 'China', indicating substantially greater reproductive stability in 'China'. These results demonstrate that while both cultivars experienced fruit abscission during development, 'China' consistently maintained higher fruit retention than 'Shahi', contributing to its greater production potential.

The lower fruit retention observed, particularly in 'Shahi', is likely attributable to inherent genetic differences rather than orchard management, as all trees were maintained under identical cultural practices. Physiological fruit drop is a characteristic feature of litchi and is influenced by assimilate competition, hormonal regulation, and prevailing environmental conditions during early fruit development (Lal *et al.,* 2025). The superior fruit retention in 'China' may therefore reflect greater genetic adaptation to the prevailing subtropical environment, resulting in improved assimilate partitioning, enhanced sink

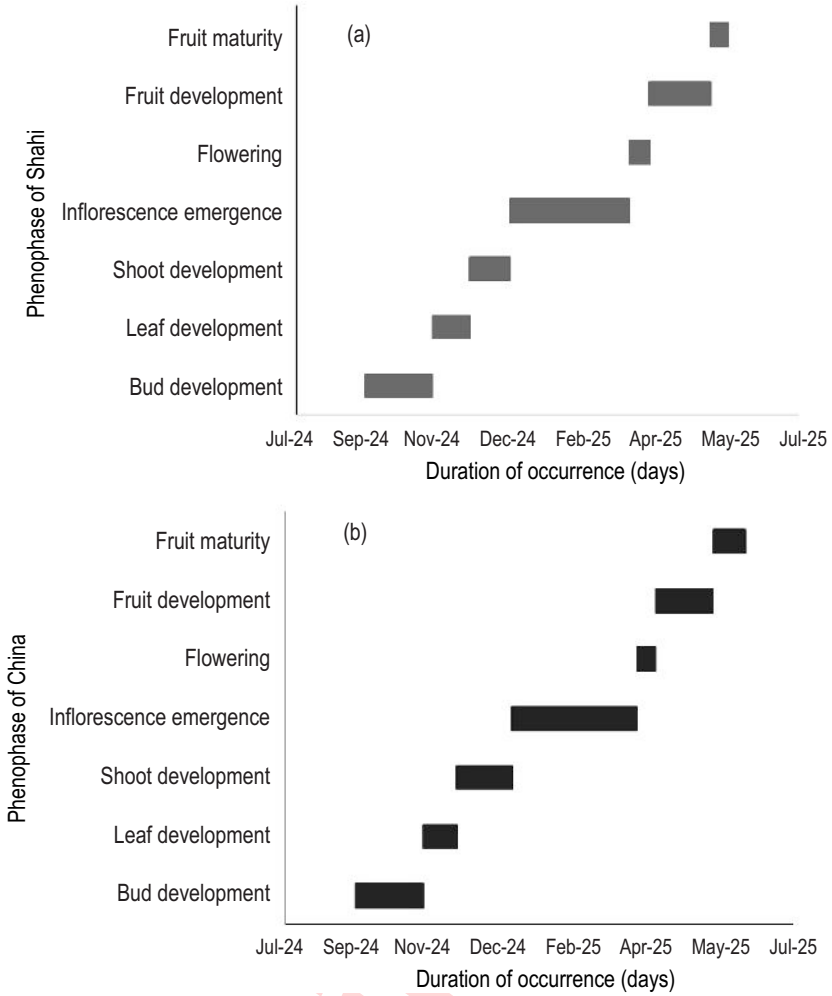


Fig. 3: Chronological progression of phenophases in litchi cv. 'Shahi' (a) and 'China' (b).

strength, and reduced fruit abscission. These findings indicate that cultivar selection plays an important role in improving fruit retention and productivity under the Indo-Gangetic conditions.

Winter chilling is a critical environmental cue regulating floral induction in litchi. During the 2024–2025 season, 87 chilling days (minimum temperature below 12°C) were accumulated between November and March, with the maximum contribution from December (29 days) and January (30 days) (Table 1). The prolonged cool period extended into early March, providing favourable conditions for floral induction and synchronized panicle emergence. The extended chilling period observed during the study exceeded that generally experienced under normal subtropical winters and probably contributed to the uniform flowering observed in both cultivars. Previous studies have demonstrated that cool winter temperatures are essential for floral induction in litchi, whereas inadequate chilling results in delayed or irregular flowering (Menzel and Simpson, 1991; Kumar et al., 2023). The results, therefore, confirm that the accumulated chilling during the study period was sufficient to satisfy the floral induction requirements of both cultivars.

Thermal accumulation differed significantly between the two cultivars across major phenological stages (Fig. 5). While both cultivars required similar thermal units for bud and leaf development (848.95 and 364.20 GDD, respectively), significant differences emerged during subsequent developmental stages. Shoot development required higher thermal accumulation in 'China' (293.70 GDD) than in 'Shahi' (213.05 GDD). Likewise, inflorescence emergence required 731.80 GDD in 'China' compared with 642.30 GDD in 'Shahi'. Although the difference during flowering was relatively small, 'China' still accumulated significantly more heat units (211.50 GDD) than 'Shahi' (207.50 GDD). The maximum difference was observed during fruit development and maturation, where 'China' required 1162.90 GDD, whereas 'Shahi' completed fruit development with only 955.50 GDD, confirming its earlier maturity. The maximum thermal requirement of 'China' indicates that its phenological

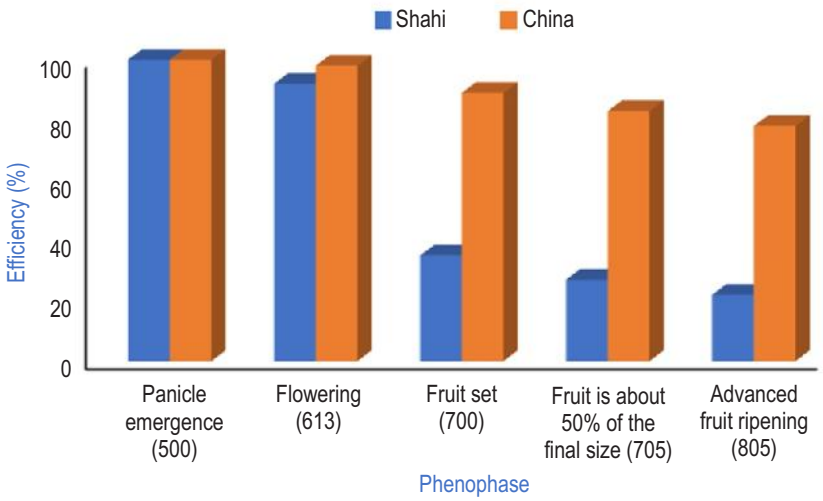


Fig. 4: Panicle emergence and fruit retention efficiency in litchi cvs. 'Shahi' and 'China'.

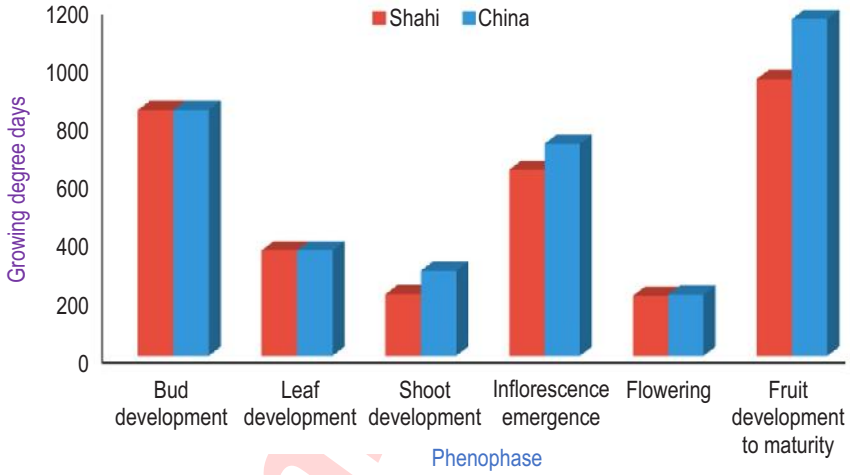


Fig. 5: Growing degree day requirements for different phenological stages in litchi cvs. 'Shahi' and 'China'.

progression is more strongly dependent on heat accumulation, resulting in delayed flowering and fruit maturity. In contrast, the lower GDD requirement of 'Shahi' enables earlier completion of reproductive development, making it suitable for regions where rising temperatures during late spring may adversely affect fruit quality. Similar cultivar-specific differences in thermal requirements have been reported in litchi (Rai *et al.,* 2002; O'Hare, 2002; Das *et al.,* 2004; Chen *et al.,* 2016; Hassan *et al*., 2026).

The combined analysis of chilling accumulation and GDD indicates that flowering and fruit development in litchi are jointly regulated by winter chilling and subsequent heat accumulation. Under the subtropical conditions of the Indo-Gangetic Plain, 'Shahi' appears to require comparatively lower thermal accumulation to complete reproductive development, whereas 'China' depends on prolonged chilling and greater heat accumulation, explaining its delayed but more sustained phenological progression.

Cool-night accumulation and floral induction: During the 2024–2025 season, 87 chilling days (<12°C) were recorded, of which the CTTS model identified effective floral induction thresholds of approximately 22 cool nights for 'Shahi' and 29 for 'China'. These cultivar-specific thresholds indicate that floral induction occurred considerably earlier than the preliminary threshold of 40 nights, demonstrating the need for adaptive chill thresholds under subtropical conditions. Following attainment of the effective chilling threshold, flowering transition occurred rapidly in both cultivars. Approximately, 99% of 'Shahi' trees and

Table. 1: Chilling days requirement for flowering in litchi

Study period	Days in month	No. of days with < 12°C
November, 2024	30	2
December, 2024	31	29
January, 2025	31	30
February, 2025	28	22
March, 2025	31	4

all 'China' trees reached flowering within one week, indicating that flowering behaved as a threshold-triggered rather than a gradual developmental process. The cumulative flowering curves exhibited an abrupt increase, indicating exceptionally high flowering synchrony in both cultivars. The narrow flowering window resulted in a very high Synchrony Index, demonstrating that flowering occurred almost simultaneously once the chilling threshold had been satisfied. The CTTS model successfully linked cumulative chilling exposure with flowering transition and orchard-level synchrony. Cultivar-specific chilling thresholds (22 nights in 'Shahi' and 29 nights in 'China') accurately explained the early flowering of 'Shahi' and the delayed but synchronized flowering of 'China'. These findings demonstrate the potential of the CTTS model as a predictive tool for estimating flowering windows, optimizing orchard operations, and assessing phenological responses under changing climatic conditions.

Collectively, the BBCH phenological framework, thermal indices, and CTTS model provide a robust scientific basis for predicting flowering behaviour, optimizing orchard operations, selecting suitable cultivars, and developing climate-resilient litchi production strategies under subtropical environments. Future validation of the CTTS model across diverse agro-climatic regions will further strengthen its applicability for phenological prediction and precision orchard management.

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Authors' contribution: D. Mageshwari: Conceptualization, Methodology, Investigation, Writing – original draft; **S. Kumar:** Conceptualization, Data curation, Formal analysis, Writing – original draft; **B. Das:** Conceptualization, Data interpretation, Writing – revision and editing; **I. Samal:** Methodology, Formal analysis; **P. Patil:** Writing – revision and editing; **V. Nath:** Data interpretation; **M.K. Dhakar:** Writing – revision and editing; **D.K. Gupta:** Data interpretation; **A. Dhakad:** Methodology, Formal analysis; **R. Kumar:** Methodology, Formal analysis.

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Data availability: All relevant data supporting the findings of this study are included within the article. Additional datasets generated during the study are available from the Corresponding author upon reasonable request.

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