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Thermal influence on floral induction in mango (*Mangifera indica* L.): A study on two cultivars under Ultra High-Density Planting (UHDP)

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Abstract

Mango (*Mangifera indica* L.) is a globally significant tropical fruit, with India being the largest producer. Despite its economic importance, off-season mango production remains challenging due to the critical role of environmental factors on floral induction. This study investigates the thermal influence on floral initiation in two mango cultivars, Ratna and Bangalora, grown under the Ultra High-Density Planting (UHDP) system at Jain Irrigation Systems Limited Farms, Udumalpet, from 2022 to 2024. The study comprises the evaluation of flowering responses under both regular and off-season conditions. The experiment followed a randomized complete block design (RCBD) with three replications per cultivar, comprising 72 trees (36 per cultivar). Temperature thresholds for floral induction were determined using logistic regression models and the probability of flowering was analysed in relation to temperature integration periods. Results indicated cultivar-specific differences in temperature sensitivity. During the off-season, Bangalora exhibited 50 % flowering at a minimum temperature of 24.8 °C (95 % CI: 23.5 °C–26.0 °C) and a maximum of 35.5 °C (95 % CI: 34.0°C-37.0 °C). In contrast, Ratna required lower temperatures, with 50 % flowering occurring at a minimum of 21.3 °C (95 % CI: 20.5 °C-22.2 °C) and a maximum of 31.2 °C (95 % CI: 30.2°C-32.5 °C). During the regular season, optimal flowering temperatures were slightly lower, suggesting naturally favourable conditions. Findings confirm that temperature exposure and integration periods significantly affect floral induction, emphasizing the potential for controlled temperature management to optimize off-season production. These results provide critical insights into mango flowering physiology. It plays a crucial role in developing practical guidelines for farmers to regulate temperatures based on specific cultivars, ensuring year-round mango availability.

Keywords

flowering; mango; off-season; temperature; UHDP

Introduction

Mango (*Mangifera indica* L.), a member of the family Anacardiaceae and order Sapindales, is one of the most economically and nutritionally significant tropical fruits (1). It is commonly referred to as the "King of Fruits" and is known for its rich flavor, aroma and health benefits. Mango trees typically grow between 10 to 35 m in height with a dome-shaped canopy (2). The leaves are simple, alternate and leathery, while the small, yellowish-green flowers are borne on terminal panicles. The fruit is a drupe, exhibiting significant variability in size, shape and flavor, depending on the cultivar. Mango trees produce three types of shoots: vegetative, generative (flower-bearing) and mixed shoots. The reproductive phase is strongly influenced by environmental factors, such as temperature and water availability (3, 4).

India is the world's largest mango producer, contributing to approximately 45 % of global production, with key growing regions in Tamil Nadu, Andhra Pradesh, Uttra Pradesh, Gujarat and Maharashtra. Despite this dominance, as of 2023, India's average mango yield is approximately 9.7 tonnes per hectare, which is below the global average of 12 tonnes per hectare, which is attributed primarily to climatic challenges and limited advancements in agronomic practices. Globally, mango production reached 55.4 million metric tons in 2023, with projected growth driven by increasing demand and advancements in cultivation technologies (5). Recent studies have highlighted the potential of adopting innovative farming systems, such as integrated crop management and precision farming, to improve productivity (6).

Off-season mango production holds immense potential to meet market demands and stabilize prices by increasing availability throughout the year (7). Varieties such as 'Ratna' and 'Bangalora' show promise for off-season production due to their adaptability and favorable flowering characteristics. Ratna, a hybrid of Neelum and Alphonso, is valued for its high pulp content, excellent taste and disease resistance. Bangalora, widely cultivated in southern India, is known for its high yield, extended shelf life and adaptability to various climatic conditions (2). The flowering and fruiting behavior of these varieties under controlled environmental conditions can unlock their potential for off-season production (8).

Despite the importance of mango as a tropical fruit, research on its off-season production remains underexplored, especially for varieties such as Ratna and Bangalora. Few studies have examined the critical role of environmental factors such as temperature, photoperiod and humidity in influencing flowering and fruiting behaviors (9). Furthermore, most research has focused on mainstream varieties such as Alphonso and Kensington Pride, leaving significant gaps in understanding the performance of other important cultivars under off-season production systems (10).

This research aims to address these gaps by investigating the flowering and fruiting behavior of Ratna and Bangalora under controlled conditions. Specifically, this study seeks to (i) identify critical environmental triggers, such as temperature and humidity, for off-season flowering; (ii) evaluate the adaptability of these varieties to off-season production in different agroclimatic zones; and (iii) develop practical recommendations for farmers to achieve sustainable year-round mango production. By bridging this knowledge gap, the findings will enhance mango productivity, improve farmer incomes and meet the rising consumer demand for off-season fruits.

Materials and Methods

The experiment was conducted from 2022 to 2024 on nine-year-old mango trees (Ratna and Bangalora) maintained under the ultra-high-density planting (UHDP) system at Jain Irrigation Systems Limited Farms, Udumalpet. The selected trees, which were uniform in size, were spaced 3 × 2 m apart. The experimental site is situated at an altitude of 1208 feet above mean sea level (MSL) and receives an average annual rainfall of 501.40 mm. The region experiences an average maximum temperature of 33.58 °C, a minimum temperature of 21.08 °C and a relative humidity of 71 %. The soil comprises black and red soils, with a pH of 6.56 and an electrical conductivity of 0.051 dSm^{-1}.

The study was conducted over two seasons (regular and off-season), which followed a randomized complete block design (RCBD) with three replications, each consisting of twelve trees per replication and a total of 72 trees (36 per cultivar). Tip pruning, involving the removal of the last growth unit from all terminals, was performed between December and January to delay natural flowering and induce off-season production. Twenty shoots per tree were tagged across four sections of the canopy, with 720 branches per cultivar monitored for growth and flowering responses. Paclobutrazol was applied through soil application at the recommended rate of 4 mL per tree in the first week of June. Three months after the paclobutrazol application, flower bud initiation and differentiation were monitored. Standard agronomic practices, including fertigation, pest management and drip irrigation, were followed throughout the study. Meteorological data were collected daily, including daily maximum and minimum temperatures, sunshine hours, humidity and rainfall, which were continuously recorded at the Jain Irrigation Systems Limited meteorological observatory.

Vegetative shoot growth was measured weekly after pruning, whereas flower bud differentiation was assessed by visual observation after the completion of vegetative growth. Shoots reached lengths of 1-40 mm based on a constant elongation rate between successive observations. The temperature integration periods were calculated from 1 to 40 days, centered on the day the buds reached their respective lengths. The floral response was recorded as binary data categorized as either flowered (1) or vegetative (0). Shoots were classified as floral if they developed floral structures at any stage, from bud initiation to full panicle formation.

Panicle emergence was assessed at five-day intervals following initial bud emergence. To evaluate physiological changes, carbohydrate and nitrogen contents in the leaves were analyzed using the KEL PLUS Yellow Nitrogen Distillation Apparatus at regular intervals. Fully developed middle leaves from tagged shoots were collected for biochemical and hormonal analysis throughout the observation period. A generalized linear model (GLM) with logistic regression was used to estimate the probability of flowering based on maximum and minimum temperature variations by using R software (version 4.4.3). The model incorporated temperature as a predictor variable, with confidence intervals (95 % CI) estimated to determine the threshold at which 50 % of terminals flowered, all statistical analyses were performed using R software.

Results and Discussion

The number of inductive days, bud length and temperature integration periods varied across seasons. The detailed cultivar-specific data are presented in Table 1. The temperature response serves as a key indicator of the conditions necessary for floral induction, influencing bud development and panicle emergence. These results suggest that temperature exposure duration and bud length requirement for floral induction vary between cultivars. The shortest observed inductive period was 20 days, whereas the longest extended to 37 days. Similarly, the bud length at which floral induction occurred ranged from 5 mm to 20 mm.

The floral response varied between cultivars and seasons, with differences in the proportion of terminals that flowered and the probability of 50 % floral induction at different temperatures. The models for Bangalora and Ratna indicated a clear association between temperature and flowering probability. The influence of cool temperatures on promoting floral induction in mangoes growing in subtropical regions is well understood (11). Additionally, temperature fluctuations have been reported to be critical regulators of floral initiation in mango (12, 13).

For off-season fruit production, the 'Bangalora' variety presented the highest proportion of flowering (76.25 %), with an inductive period of 76.04 days, a maximum temperature integration period of 25 days and a minimum of 32 days. The probability of 50 % flowering occurs at a minimum temperature of approximately 24.8 °C, with a 95 % CI ranging from 23.5 °C to 26.0 °C. The maximum temperature threshold is approximately 35.5 °C, with a 95 % CI between 34.0 °C and 37.0 °C. Flowering in the 'Bangalora' variety significantly decreases below 24.8 °C for minimum temperature and above 35.5 °C for maximum temperature. The confidence intervals highlight the variability in these thresholds. Similarly, for 'Ratna', 50 % of the flowering occurred at a minimum temperature of approximately 21.3 °C, with a 95 % CI ranging from 20.5 °C to 22.2 °C. The intersection of the red curve occurs at a maximum temperature of approximately 31.2 °C, with a 95 % CI ranging from 30.2 °C to 32.5 °C. The graph indicates that flowering decreases significantly below 21.3°C for minimum temperatures and above 31.2 °C for maximum temperatures, suggesting that these are critical thresholds for optimal flowering.

Similar variations in flowering response have been observed in litchi and citrus, where genetic differences affect temperature sensitivity (14-16). These findings support the cultivar-specific responses noted in this study. Moreover, cooler temperatures during the tropical dry season promote floral induction in mango (17). which aligns with the seasonal variations observed in our results.

During the regular season, both cultivars presented a greater floral response. 'Bangalora' presented 87.04 % flowering, with an inductive period of 77.32 days. The minimum temperature for 50 % flowering was approximately 23.7 °C, with a 95 % confidence interval ranging from 22.5 °C to 25.0 °C. For the maximum temperature, the 50 % flowering threshold was observed at approximately 33.6 °C, with a 95 % CI between 32.0 °C and 35.0 °C. Similarly, Ratna' presented a 50 % flowering threshold at approximately 23.5 °C, with a 95 % confidence interval ranging from 22.5 °C to 25.0 °C. For the maximum temperature, the 50 % flowering threshold occurred at approximately 34.5 °C, with a 95 % CI between 33.0 °C and 36.0 °C. These confidence intervals reflect the possible range of variation in the flowering response to temperature changes.

Genetic variation resulting from natural hybridization and breeding contributes to cultivar-specific differences in flowering responses to temperature, which can be leveraged for optimizing mango production (18). The genetic variation between 'Bangalora' and 'Ratna' is likely to contribute to their distinct temperature thresholds for floral induction, as observed in our study. Additionally, temperature integration periods play a crucial role in determining the floral response, with prolonged exposure to favorable temperatures increasing the probability of flowering (8).

Fig. 1 & 2 (Proportion of flowering vs Temperature) illustrate the flowering response of the 'Bangalora' and 'Ratna' mango cultivars to temperature variations across both the off-season and regular seasons. Fig. 1 shows that Bangalora achieves 50 % flowering at a minimum temperature of approximately 24.8 °C and a maximum temperature of 35.5 °C, whereas Ratna reaches 50 % flowering at a lower minimum temperature of 21.3 °C and a maximum of 31.2 °C. These results indicate that Bangalora requires relatively high-temperature conditions for optimal flowering, whereas Ratna exhibits a flowering response at relatively low temperatures. These findings align with previous research suggesting that floral induction in mango is significantly influenced by temperature variations, with lower temperatures playing a crucial role in promoting flowering (8). Additionally, the diversity in flowering sensitivity across mango cultivars supports the cultivar-specific differences observed in the present study (14, 15).

Fig. 2 depicts the regular flowering season and shows a shift in the optimal temperature thresholds for both cultivars. Bangalora exhibited 50 % flowering at a minimum

Table 1. Floral response to maximum and minimum temperature for regular and off-season mango production

season	Cultivar	Inductive days (May - Aug) / (Oct - Dec)	Terminals flowered (%)	Index temperature and integration period	Bud length (mm)	Temperature for the probability of 50% flowered terminals (95% CI range)
Off-season	Bangalora	76.04	76.25	Maximum (25 days)	15 mm	31.2 (30.2, 32.5)
				Minimum (32 days)	20mm	21.3 (20.5,22.2)
	Ratna	79.41	70.83	Maximum (20 days)	5 mm	35.5 (34.0,37.0)
				Minimum (30 days)	15 mm	24.8 (23.6,26.0)
Regular season	Bangalora	77.32	87.04	Maximum (29 days)	20mm	23.70 (22.5,25.0)
				Minimum (35 days)	20mm	33.60 (32.0,35.0)
	Ratna	80.12	89.28	Maximum (24 days)	10mm	23.50 (22.5,25.0)
				Minimum (37 days)	15mm	34.5 (33.0,36.0)

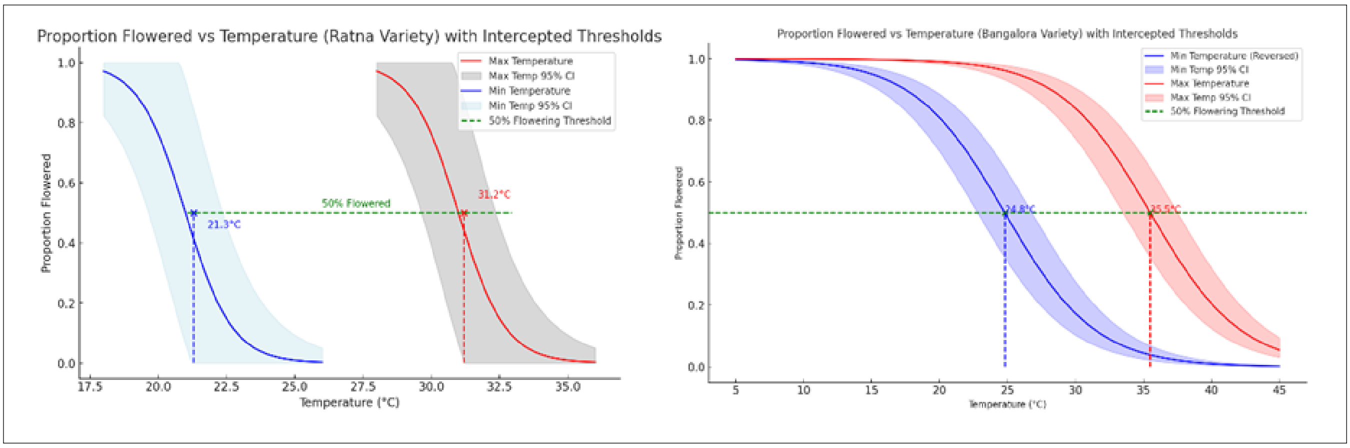

Fig. 1. The proportion of flowering buds as predicted by generalized linear model for off-season fruit production for Ratna and Bangalora.

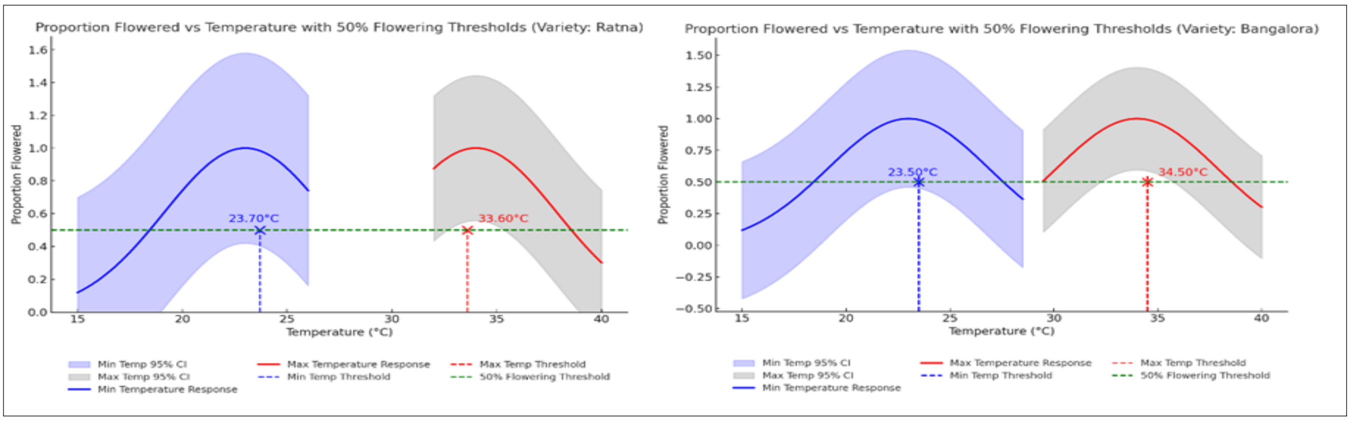

Fig. 2. The proportion of flowering buds as predicted by generalised linear model for regular season fruit production for Ratna and Bangalora.

temperature of 23.5 °C and a maximum of 34.5 °C, whereas Ratna reached this threshold at 23.7 °C and 33.6 °C. The slightly lower temperature requirements for flowering during the regular season suggest that naturally occurring environmental conditions are more favorable for induction than the off-season scenario is. These trends corroborate earlier findings that seasonal variations significantly impact floral initiation in mango (16). Moreover, the influence of cool temperatures in subtropical regions has been well documented, emphasizing the role of chilling in floral induction.

The observed differences between the two seasons highlight the role of temperature integration periods in determining flowering success. These results reinforce the hypothesis that mango cultivars exhibit varied flowering responses due to their genetic composition and adaptation to climatic conditions (18). The confidence intervals depicted in the graphs further emphasize the variability in floral response, indicating that slight deviations in temperature can lead to significant changes in flowering proportions. These findings reinforce the importance of temperature thresholds in mango floral induction, highlighting the potential for strategic temperature management and agronomic interventions to optimize off-season production.

Conclusion

This study highlights the critical role of temperature in regulating mango flowering, particularly under off-season conditions. The findings demonstrate that cultivar-specific temperature thresholds significantly influence floral induction, with 'Bangalora' requiring higher temperatures compared to 'Ratna.' These insights can help farmers adopt climate-resilient practices by implementing temperature management strategies, such as integrating microclimate modification techniques to optimize flowering. By leveraging these findings, growers can enhance off-season mango production, ensuring a more stable and predictable yield. Ultimately, this research contributes to the development of precision agriculture approaches for mango cultivation, promoting year-round availability and improved economic returns for farmers.

Future research could focus on validating these results across different agroclimatic regions to refine temperature-based flowering models. Ultimately, this research contributes to the development of precision agriculture approaches for mango cultivation, promoting year-round availability and improved economic returns for farmers.

Authors' contributions

HT carried out data curation, methodology, investigation, wrote original draft and visualization. MI carried out the conceptualization, supervision and designed the methodology; reviewed and edited the manuscript. PS gathered resources, designed methodology and took part in data curation. MK, BP, IRC and DG reviewed, edited and validated the manuscript. All authors read and approve the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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