

Physiological and climatic aspects of apple flower bud induction

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Apple flower bud induction is a complex physiological transition influenced by climatic conditions, hormonal regulation, and crop management. A field-based study, using station weather records and orchard phenological monitoring, conducted in Kinnaur, Himachal Pradesh during 2022–2024, noted that mid-elevation zone (2,400–3,100 m) encompassing Kalpa, Roghi, and Sangla exhibited a consistent climatic pattern, cool nights, moderate day temperatures, and adequate chilling (900–1,300 h below 7.2°C), that closely matched apple phenology. Management practices such as early fruit thinning, kaolin spray, and micronutrient supplementation (B and Zn) were found useful for enhancing floral induction.

Keywords: Chilling requirement, Climate, Gibberellins, Kinnaur, Phenology

FLOWER bud induction in apple is the biological transition of a vegetative meristem into a floral meristem, which takes place during the summer of one year and determines the flowering and fruiting potential of the next. It is the first and most decisive stage of the apple's reproductive cycle, followed by initiation, differentiation, dormancy, and bloom. This process is regulated by the interaction of crop load, hormonal balance (gibberellins, auxins, cytokinins, ethylene), carbohydrate status, and environmental conditions, especially temperature and photoperiod. In Kinnaur (Himachal Pradesh), situated between 1,500 m and 3,600 m above sea level, microclimates vary sharply. The mid-elevation zone (2,400–3,100 m; Kalpa, Roghi, Sangla, Powari) provides a balance of cool nights (10–14°C), moderate summer days (20–26°C), and sufficient winter chilling (900–1,300 h below 7.2°C), making it one of the favourable apple-flowering belts in the Himalayas, with a climatic profile comparable in several respects to other established temperate apple-growing regions internationally.

Data source and observations

Weather data for 2022–2024 were recorded from the automatic weather station at RHR&TS Sharbo, Kinnaur. Phenological milestones (full bloom, petal fall, fruit set and harvest) for the eight commercial cultivar/rootstock combinations were recorded through routine field monitoring at the cultivar demonstration block at Kalpa (2,749 m) from 2018 to 2024 as part of regular station records. Flower bud induction is not visible in the field and was not assessed by histological bud-sectioning in the study. The induction and initiation windows (expressed as Days After Full Bloom, DAFB) reported here for Kinnaur cultivars were obtained by aligning the locally recorded phenological milestones with DAFB windows established through histological sectioning studies published for the same or closely related cultivars. This distinction between field-record-based observation and directly measured (histologically confirmed) induction timing is stated explicitly so the results can be interpreted with the appropriate level of confidence, and is a candidate area for follow-up

histological work at this station.

Climatic determinants of apple floral induction

Three years of cumulative meteorological data (2022–2024) from Sharbo indicated a consistent mean maximum temperature of 24.4°C in June and 23.7°C in August, with mean night temperatures of 16.8°C and 18.3°C, respectively. Relative humidity during June–August averaged 72–87%, while rainfall remained minimal (<8 mm), producing mildly dry but cool nights, conditions generally considered favourable for apple flower induction. These climatic parameters align closely with the physiological thresholds described in the literature for effective induction, namely 20–26°C during the day and 10–14°C at night. Year-wise observations showed that in 2022, slightly warmer June–July temperatures were associated with delayed bud differentiation; in 2023, more balanced temperature and humidity supported bud development typical of the district; and in 2024, a cooler, stable summer (23°C max, 16°C min) coincided



Phenological stages in apple

apple, though invisible to the naked eye, is a hormonally driven process; briefly, a high crop load leads to more seeds and higher gibberellin levels, which inhibit floral induction, while a low crop load with good carbohydrate status favours induction. This phase represents a critical window of control for the farmer. Climatic data from Kalpa (2022-2024) showed that average June temperatures ranged from a maximum of 24.5°C to a minimum of 16.8°C with 72% relative humidity, while July temperatures ranged from a maximum of 24.2°C to a minimum of 18.7°C with 88% relative humidity, conditions generally considered suitable for apple flower induction. Recommended management practices during this period are early thinning at the King flower or 10–12 mm fruit stage, avoiding high nitrogen application in June-July, and leaf cooling in warmer zones via 3% Kaolin spray.

Stage 2: Flower bud initiation (July–August): Initiation in apple becomes histologically visible as the meristem domes. Generally, this phase occurs 45–95 DAFB, corresponding to July–August in Kinnaur. At Kalpa, different cultivars exhibited initiation at varying times.

with strong floral initiation across cultivars such as Royal Delicious and Red Chief. Kinnaur's summer night temperatures consistently remaining below 15°C are associated with suppressed gibberellin (GA) biosynthesis, facilitating the buds' transition to the reproductive phase. Kalpa's induction window for Gala (85–105 DAFB) and Honeycrisp (45–70 DAFB) is broadly consistent with the DAFB ranges reported for the same cultivars in New York orchards, i.e. 85–95 DAFB for Gala and 45–55 DAFB for Honeycrisp. This indicated that despite the very different climates of Kinnaur and the north-eastern United States, the relative sequence and approximate timing of induction across cultivars follows a similar pattern, with local temperature mainly shifting the absolute calendar dates rather than the cultivar order.

Phenological observations: Linking bloom and induction

Phenological data from 2018–2024 at Kalpa demonstrated remarkable consistency in flowering and bud development timing among cultivars.

The average full bloom date across cultivars was 14–26 April,

with fruit set by 6–11 May, meaning flower induction consistently begins mid-June and continues through July, exactly when summer temperatures (20–25°C) and cool nights (10–14°C) prevail in Kalpa.

Stage 1: Flower bud induction (June–July): The induction phase in

Table 1. Phenological observations in apple (2018–2024)

Phenological stage	Physiological implication
Full bloom (14–26 April)	Pollination and fertilisation occur; carbohydrate production increases to support early fruit and shoot growth. The physiological process for next season's flowering begins about 45–60 days later as hormonal balance shifts within buds.
Fruit set (6–11 May)	Developing seeds release gibberellins (GA ₃ , GA ₄₊₇), which suppress floral bud formation in nearby spurs. High fruit load increases GA concentration and reduces flower induction potential for the next year.
Induction period (15 June–30 July)	A hormonal transition occurs where reduced gibberellin and increased auxin, cytokinin, and ethylene activity convert vegetative meristems into reproductive ones. Favourable temperatures (20–26°C day, 10–14°C night) and adequate carbohydrates ensure strong induction.
Initiation (Doming) (15 July–10 August 10)	The apical meristem changes from flat to domed, marking irreversible commitment to flowering. Rapid cell division, RNA synthesis, and activation of floral genes (LFY, AP1) define this stage.
Differentiation (15 August–30 October)	Distinct floral organs (sepals, petals, stamens, carpels) form internally. Balanced nutrition, especially boron and zinc, supports organ development. By late October, buds are fully differentiated but remain dormant externally.
Dormancy (November–March)	Buds enter rest to withstand cold. Accumulated chilling hours (900–1,300 h below 7.2°C) deactivate floral inhibitors (FLC) and activate flowering genes (FT, LFY). Stored carbohydrates maintain bud vitality through winter.
Bloom next year (April–May)	Satisfied chilling and rising temperatures trigger bud swelling and flowering. The uniformity and intensity of bloom reflect the success of the prior summer's induction and nutrient balance.

Table 2. Cultivar-specific induction and bloom characteristics

Cultivar	Rootstock	Full bloom (avg.)	Fruit set (avg.)	Harvest (avg.)	Induction class (DAFB)	Suitability zone in Kinnaur
Royal Delicious	Seedling	April 18–26	May 8–11	Oct 10–18	65–95	Mid and high Kinnaur (ideal)
Red Chief/Super Chief	MM106	April 19–24	May 9–13	Sept 29–Oct 18	65–85	Mid Kinnaur (ideal)
Oregon Spur/Red Velox	M9	April 17–23	May 8–12	Oct 7–15	60–85	Mid Kinnaur
Fuji/Auvil Early Fuji	M9	April 20–28	May 9–12	Late Oct	45–75	Upper Kinnaur (cool belt)
Gala/Redlum Gala/Jeromine	M9	April 14–20	May 6–10	Mid-Oct	85–105	Lower–mid Kinnaur
Golden Delicious	Seedling	April 15–22	May 7–10	Early Oct	85–100	Lower, mid and high Kinnaur
Rich-a-Red	Seedling	April 18–24	May 9–11	Oct 10–15	70–95	Mid Kinnaur
Honeycrisp	M9	April 25–May 5	May 10–13	Late Oct	45–70	Upper Kinnaur

DAFB: Days after full bloom.

The 2024 weather data indicated an average maximum temperature of 23.7°C, minimum of 18.3°C, and relative humidity of 86% in August, providing conditions supportive of meristem differentiation.

Stage 3: Flower differentiation (August–October):

Following initiation, apple buds undergo internal differentiation, forming sepals, petals, stamens, and carpels. This stage thrives under stable late-summer temperatures and adequate micronutrient availability. In Kalpa, August–October temperatures averaged a maximum of 23.7°C and a minimum of 18°C, providing optimal conditions for uninterrupted organ formation. Farmers commonly apply boron (200 g) and zinc sulphate (1 kg) + 1/2 kg Lime/200 L of water as foliar sprays during this period to enhance cellular activity and support ovule development. By late October, the buds have developed into fully formed floral structures, although they remain dormant.

Stage 4: Dormancy and chilling (November–March):

Once differentiation is complete, apple buds enter dormancy during the winter months. Cumulative weather data indicate that in Kalpa, mean minimum temperatures from November to March ranged between 6.8°C and 1.6°C, providing 1,000–1,300 chilling hours (<7.2°C), which are sufficient for floral reactivation in spring. The subsequent blooming stage, occurring from March to May of the following year, is well-documented in phenological records from 2018–2024. Average full bloom dates fall between April 14–26, petal fall occurs around April 30–May

10, and fruit set is achieved by May 6–11. These timings align perfectly with Kalpa’s spring temperature window, where average maximum temperatures range from 16–22°C and minimum temperatures from 7–10°C. Varietal bloom sequences further ensure effective cross-pollination: Gala, Red Velox, and Jeromine bloom early (April 10–20); Royal Delicious, Red Chief, Super Chief, and Oregon Spur bloom mid-season (April 18–26); and Fuji and Honeycrisp bloom late (April 25–May 5).

Alternate (Biennial) bearing in Kinnaur apples

Because seed-derived gibberellin from a heavy current crop suppresses floral induction in adjacent spurs, apple is inherently prone to alternate (biennial) bearing where crop load is not managed early. Cornell University trials showed that percentage return bloom declines sharply as crop load rises above about 5 fruits/cm² trunk cross-sectional area, and that thinning at the king-flower stage restores substantially more return bloom than thinning delayed to the 10–12 mm fruitlet stage, in both Honeycrisp and Fuji. In Kinnaur, spur-type strains such as Red Chief, Super Chief and Oregon Spur, widely planted for their compact canopy and precocity showed a somewhat greater tendency toward alternate bearing than Royal Delicious under heavy crop loads. Multi-year, cultivar-wise yield records to quantify the extent of this tendency locally are not yet available and are recommended as a subject for follow-up study. Until such

data are available, early manual or chemical thinning remains the most practical lever available to Kinnaur growers to reduce the severity of alternate bearing.

Rootstock influence on vigour and floral induction

Rootstock is one of several indirect factors, alongside crop load, variety, training system, nutrition and climate, known to influence flower bud formation in apple. Dwarfing rootstocks such as M9 (Malling 9), used in Kinnaur for Oregon Spur, Fuji, Gala and Honeycrisp, restrict vegetative vigour and are generally associated with earlier, more precocious flower induction than semi-vigorous rootstocks such as M106 (Malling 106) and even on seedling rootstock, used locally for Red Chief/Super Chief, Royal Delicious and Rich-a-Red. This pattern is broadly consistent with the earlier induction windows (lower DAFB) observed for the M9-rootstocked cultivars at the Kalpa demonstration block relative to the M106-rootstocked cultivars, and aligns with the wider horticultural literature identifying rootstock vigour as a determinant of flower induction timing and intensity.

Yield and productivity context

Consistent flower induction and bloom timing are one of several factors reflected in district productivity trends. Himachal Pradesh’s average apple productivity is reported at about 4.32 t/ha, while productivity in Kinnaur’s better-managed orchards has been reported in the range of 6–9

Table 3. Management practices for enhanced flower induction

Month/Period	Practice	Objective/Role	Kinnaur-specific remarks
May-June	Early fruit thinning (manual/NAA 10 ppm/Ethephon 400 ppm)	Reduces crop load and seed-derived GA, promoting floral induction and carbohydrate balance.	Essential from late May–mid June in Royal Delicious, Super Chief and Red Chief; cool nights (10–12°C) favour carbohydrate retention.
June-July	Kaolin (3%) spray + Paclobutrazol drench (0.5–1 g a.i./m ²)	Kaolin lowers leaf temp (4–6°C); Paclobutrazol inhibits GA, aiding flower induction.	Ideal under 22–25°C, 70–80% RH; useful in warmer lower belts (Tapri-Reckong Peo).
July-August	Light summer pruning + branch girdling (3–4 mm)	Improves light and photosynthesis; girdling raises sugar near buds, aiding initiation.	In mid-Kinnaur (Kalpa, Roghi, Sangla), coincides with floral initiation; best in early July.
Sept-Oct	Boron (200 g) + ZnSO ₄ (1 kg) + Lime (0.5 kg)/200L water	Enhances floral differentiation and pollen fertility; improves bud health.	Apply during post-monsoon (RH 65–75%) for better bloom in Oregon Spur, Red Velox and Super Chief.
Nov-Feb	Maintain chilling; Dormex (2–3%) in upper zones (>3,100 m)	Ensures uniform bud break; Dormex activates enzymes to overcome deep dormancy.	In upper Kinnaur (Moorang–Sumra), >1,500 chilling hours delay bloom; Dormex (late Feb) aligns with mid-Kinnaur.
March-April	Bee hives (4–5/ha) + pollination management	Promotes cross-pollination and fruit set.	Golden Delicious and Fuji pollinize Royal Delicious and Red Chief; avoid sprays during bloom.

Note: These practices, including specific plant growth regulators (NAA, ethephon, paclobutrazol, Dormex) and doses are compiled from research literature and field observation to build farmer and extension awareness of the underlying principles. As of December 2025, they are not part of the official YSPUHF/HP State Package of Practices for apple. They are presented here for scientific and extension discussion, not as a direct-use recommendation; growers should consult the current official Package of Practices and their local KVK/Horticulture Department advisory, and follow all label and regulatory directions, before applying any plant growth regulator or agrochemical.

t/ha and rising, alongside expansion of area under apple from 670 ha in 1970–71 to over 10,937 ha in 2024–25. Productivity is influenced by many factors beyond flower induction, pollination, nutrition, pest management and post-harvest handling among them, so this comparison should be read as contextual rather than as evidence of a direct causal link. The district's comparatively consistent induction and bloom timing documented in this study is a plausible contributing factor, and correlating induction timing/intensity with final yield and fruit-quality parameters (fruit size, colour, TSS) at plot level is recommended as a direction for future work.

Climatic and genetic synergy of Kinnaur's apple belt

The Kalpa, Roghi and Sangla zone (2,400–3,100 m amsl) closely matches the physiological needs of Royal Delicious, Red Chief, Super Chief, and Oregon Spur. Upper zones like Pooh, Giaboong, Moorang, Leo, Hango, Chulling, Chango, Namgya, Shalkhar and Sumra (3,100–3,600 m) provide suitable conditions for late-flowering cultivars such as Royal Delicious, Fuji and Honeycrisp, while lower belts (Kilba, Nichar, Powari, Chaura, Nigulsari) support high colour strains like Jeromine, Scarlet Spur, Super Chief and pollenisers like Tydeman's Early Worcester, Gala and Golden Delicious. Among all zones, mid-

Kinnaur provides one of the more balanced flowering environments in the western Himalayan apple belt, owing to its moderate summers, cool nights, and stable chilling accumulation.

SUMMARY

Flower bud induction in Kinnaur apples is a climate-linked and hormonally regulated process shaped by altitude and management. Over the 2022–2024 period, day temperatures (24–25°C) and cool nights (16–18°C) during June–August coincided with consistent flower induction, particularly in Royal Delicious and its spur derivatives (Red Chief, Super Chief, Oregon Spur). Phenological records over six years indicated that Kalpa's climatic pattern is well suited to apple's developmental physiology, supporting reliable annual flowering, though inter-annual variation (as observed in 2022) showed this is not guaranteed every year. Cultivar-wise induction timing broadly followed trends reported from other apple-growing regions, with biennial-bearing types initiating flowers earlier than annual-bearing types. Overall, the study indicated that the interaction between Kinnaur's microclimate and apple physiology supports uniform flowering and productivity, positioning it as one of the more climatically favourable apple belts in the Himalayan region. By integrating early thinning, balanced nutrition, hormonal regulation, and attention to microclimate, Kinnaur growers can work toward high flowering uniformity and fruit quality; continued monitoring, particularly of alternate bearing and yield/quality outcomes is recommended to build on the findings presented here.

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