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Phenology and growing degree day requirement of Royal Delicious apple (*Malus* × *domestica* Borkh.) along an altitudinal gradient in the western Himalaya

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Abstract

Phenology and thermal time requirements of apple are influenced by temperature, but their variation along Himalayan altitudinal gradients remains poorly documented. We recorded five phenological stages (silver tip, green tip, pink bud, full bloom and petal fall) of Royal Delicious apple at four locations representing altitude classes of 1200-1500, 1501-1900, 1901-2300 and 2301-2600 m in Shimla district, Himachal Pradesh, during 2022 and 2023. Phenological timing (days from 1 January) and accumulated growing degree days (GDD) were analysed using three-way ANOVA and stage-wise linear regression against altitude. Phenological timing was generally delayed with increasing altitude, but the pattern was non-monotonic. Full bloom and petal fall occurred 8.3 and 10.9 days later, respectively, at the 1901-2300 m site than at the 1200-1500 m site, while the highest-altitude site reached both stages earlier than the 1901-2300 m site. The association between altitude and timing was weak at silver tip and green tip (R^2 = 0.19-0.20) but stronger from pink bud to petal fall (R^2 = 0.64-0.67). Estimated delays were 6.5 days per 1000 m at full bloom and 8.5 days per 1000 m at petal fall. At petal fall, GDD requirements ranged from 293.5 to 423.6 °C days, with the highest value at 2301-2600 m, approximately 35-44% greater than at the other locations. Location and phenological stage had large effects on calendar timing, whereas the year effect was non-significant (P = 0.654); however, the year × location interaction was significant (P = 0.005), and GDD requirements varied significantly between years. These findings indicate that GDD requirements were not consistent across the altitudinal gradient and support further evaluation of altitude-specific thermal thresholds.

Keywords: Apple phenology; Royal Delicious; altitudinal gradient; growing degree days; Western Himalaya.

1. Introduction

The phenology of temperate fruit trees is strongly influenced by temperature, particularly during dormancy release and spring development. Long-term observations have documented advances in spring phenological events with rising temperatures (Chmielewski et al., 2004; Menzel et al., 2006). In Germany, apple flowering advanced by approximately two days per decade between 1951 and 2014, with March-May temperature explaining much of the variation in bloom timing (Weil et al., 2018). Spring development depends on winter chilling, which fulfils dormancy requirements, followed by heat accumulation that promotes bud development and flowering (Fadón et al., 2020; Luedeling et al., 2021). Apple dormancy is primarily regulated by temperature rather than photoperiod (Heide & Prestrud, 2005). Consequently, warmer winters may reduce chill accumulation and alter subsequent heat requirements, affecting the timing and uniformity of budbreak and flowering (Atkinson et al., 2013; Luedeling et al., 2011). Changes in flowering phenology also influence apple productivity by altering exposure to spring frost. Apple blossoms are particularly vulnerable, and a single frost event during flowering can cause substantial crop losses (Unterberger et al., 2018). Frost risk depends on the relative changes in flowering dates and occurrence of the last damaging frost. Although both have advanced concurrently in some European regions, increased spring frost exposure has been reported at higher elevations in Switzerland (Vitasse & Rebetez, 2018; Vitasse et al., 2018a). Moreover, reduced winter chilling can increase the heat requirement for budbreak, meaning that warming does not necessarily advance phenological development uniformly across locations (Cannell & Smith, 1986). Understanding these interactions is essential for evaluating. Altitudinal gradients provide a useful framework for apple phenology under contrasting climatic conditions investigating temperature-related variation in plant phenology because climatic conditions

change considerably over short distances in mountainous regions (Bigler & Vitasse, 2019). Increasing elevation generally delays spring development, although the magnitude of this delay varies with developmental stage, year and local conditions. In the Swiss Alps, the elevation-related delay in leaf unfolding decreased from 34 to 22 days per 1,000 m between 1960 and 2016, reflecting changes in winter and spring temperatures (Vitasse et al., 2018b). However, radiation, moisture availability, wind exposure and land use may also influence phenological variation along elevation gradients (Körner, 2007). Furthermore, enhanced warming at higher elevations is not universal across mountain regions (Pepin et al., 2022), highlighting the need for location-specific investigations.

Growing degree days (GDD) quantify thermal time by expressing accumulated heat above a specified base temperature and relating it to crop development (McMaster & Wilhelm, 1997). They facilitate comparisons of developmental timing across locations and seasons with different temperature regimes, although estimates depend on the selected base temperature and calculation method. Temperature-based models have been used to predict apple flowering, but their accuracy may decline under unusually warm winters when chilling requirements are inadequately fulfilled (Fernandez et al., 2022; Luedeling et al., 2021). Therefore, the heat accumulation required to attain a particular phenological stage should not automatically be assumed constant across environments. Differences in chilling accumulation and spring temperatures may influence GDD requirements along an altitudinal gradient. These issues are particularly relevant to apple cultivation in the western Himalayan region, where the crop supports rural livelihoods and Himachal Pradesh is a major producing state (Sahu et al., 2020). Apple cultivation has shifted towards higher elevations, from approximately 1,200-1,500 m during the 1980s to 1,500-2,500 m during the 2000s, with cultivation subsequently reported above 3,500 m (Sahu et al., 2020). This shift has been associated with changes in winter chilling and growing-season temperatures, alongside declining suitability in some lower-altitude areas. Temperatures across the north-western Himalaya increased by approximately 1.6 °C during the twentieth century (Bhutiyani et al., 2007). In Himachal Pradesh, Aditya et al. (2019) examined apple phenology and GDD between 1,000 and 1,600 m and reported that early-spring warming at lower elevations advanced phenological stages by 7-13 days. Nevertheless, phenological responses across the wider elevation range occupied by apple orchards require further investigation.

Despite these findings, stage-specific phenological responses and thermal requirements of apple across wider altitudinal gradients in the western Himalaya remain insufficiently characterised. In particular, whether the GDD required to attain successive developmental stages remains consistent across elevations and years is unclear. Stage-dependent and potentially non-linear responses also warrant investigation because winter chilling and subsequent heat accumulation jointly influence bud development (Bigler & Vitasse, 2019; Vitasse et al., 2018b). Comparing calendar days and GDD across locations and years would help distinguish differences in developmental timing from variation in thermal requirements. The present study aimed to (i) quantify the timing of five phenological stages *viz.,* silver tip, green tip, pink bud, full bloom and petal fall in Royal Delicious apple across four altitude classes ranging from 1,200 to 2,600 m in Shimla district; (ii) characterise the relationship between altitude and stage-specific phenological timing; (iii) determine whether GDD requirements vary with altitude and year; and (iv) assess the contributions of year, location and developmental stage to variation in calendar days and GDD. It was hypothesised that phenological development would be progressively delayed with increasing altitude, with the magnitude of delay differing among stages, and that GDD requirements would vary across elevations and years.

2. Materials and Methods

2.1 Study area and site selection

The field investigation was conducted across two consecutive growing seasons (2022 and 2023) across Shimla district of Himachal Pradesh, situated in the North-Western Himalayan region of India (31.77°N, 77.17°E). Four distinct locations representing key temperate apple production belts were selected: Rampur (1200-1500 m ASL), Rohru (1501-1900 m ASL), Kotkhai (1901-2300 m ASL) and Mashobra (2301-2600 m ASL). Exact geographic coordinates and baseline elevations were

established using Google Earth Pro and verified in the field with a handheld GPS receiver (Garmin eTrex, ±10 m accuracy). At each location, three representative commercial apple orchards separated by 0.5 to 2.0 km were designated as independent biological replicates (n = 3 orchards per location, totalling 12 orchards across the transect). Within each orchard, five healthy, uniform, mature bearing trees (15-20 years old) of apple (*Malus* × *domestica* Borkh. cv. 'Royal Delicious') grafted on seedling rootstocks (*Malus baccata*) and trained under the modified central leader system were permanently tagged for the duration of the study. All orchards received standard commercial management practices, including uniform dormant season pruning, basin irrigation during growing season, balanced NPK fertilization and plant protection measures following regional extension recommendations.

2.2 Plant material and orchard management

Phenological transitions were tracked in accordance with the extended BBCH (Biologische Bundesanstalt, Chemische Industrie, Bundesverband der Pflanzenschutz) scale for pome fruits and standardized pomological developmental criteria (Meier et al., 1994). Five sequential reproductive phenophases were evaluated: (1) Silver Tip (BBCH 51); (2) Green Tip (BBCH 53); (3) Pink Bud (BBCH 57); (4) Full Bloom (BBCH 65); (5) Petal Fall (BBCH 69) (Meier et al., 1994).

2.3 Phenological observations

Field assessments were conducted at 2- to 3-day intervals beginning during late endodormancy period (January), with frequency shifting to daily inspections from Pink Bud stage through Petal Fall to capture rapid developmental transitions. A developmental stage was recorded as reached when at least 50% of the floral clusters on previously selected representative branches displayed diagnostic features consistent with stage definitions. Phenological progression was indexed as accumulated calendar days from January 1 (Day 1 = January 1), serving as the standardized temporal biofix following fulfillment of endodormancy requirements (Aditya et al., 2019). All recorded phenological date series were verified prior to analysis to confirm strict biological monotonicity across stages (i.e., each stage occurred on a later date than the preceding stage). Phenological records from the five tagged trees within an orchard were averaged to provide a single composite replicate value for each location and year, yielding a balanced dataset across the experimental design (N = 120 total observations: 2 years × 4 locations × 5 phenological stages × 3 orchard replicates).

2.4 Weather data and growing degree days

Daily agrometeorological datasets were acquired from the ECMWF ERA5-Land reanalysis product (spatial resolution: 0.1° × 0.1°; approximately 9 km horizontal grid spacing) using the Google Earth Engine cloud-computing platform(Muñoz-Sabater et al., 2021). Daily maximum (Tmax) and minimum (Tmin) 2-meter air temperatures were retrieved using point-coordinate extraction methods that accessed grid cells corresponding to each study orchard's mapped location. Phenothermal heat requirements were quantified using the Growing Degree Days (GDD) index with a base temperature threshold of Tbase = 4.4°C, which represents the standard and universally accepted baseline for apple phenoclimatic models. To prevent sub-zero winter and early spring temperatures from introducing negative bias while capturing heat accumulated during moderate daytime hours, daily GDD increments were calculated using the modified lower-truncation method (McMaster & Wilhelm, 1997): Daily GDD = MAX{[(Tmax + MAX(Tmin, 4.4))/2] − 4.4, 0}. Total cumulative thermal units (accumulated GDD) required to reach a specific phenological stage on calendar day D were determined by continuous summation from January 1: Accumulated GDD = Σ (Daily GDD) from January 1 to Day D. Thermal requirements for discrete developmental intervals (e.g., Green Tip to Pink Bud; Full Bloom to Petal Fall) were calculated as net thermal energy accumulated between successive phenological stages.

2.5 Statistical analysis

Data are presented as mean ± standard deviation (SD) of the replicates. Calendar days and GDD requirement were analysed separately by a three-way factorial analysis of variance (ANOVA) with year, location (altitude class) and phenological stage as fixed factors, including all two-way and three-way interactions (error df = 80). The magnitude of each effect was expressed as partial eta squared (Richardson, 2011; Lakens, 2013). The assumptions of normality of residuals and homogeneity of variances were checked using the Shapiro Wilk and Levene tests (Shapiro and Wilk, 1965; Levene, 1960). Where the ANOVA showed significant differences, means were separated using Tukey's HSD test (Tukey, 1949) at $P < 0.05$ and different letters indicate significant differences within a column. The relationship between altitude and the accumulated calendar days at each stage was described by ordinary least squares linear regression of the form $y = \beta_0 + \beta_1 x$, where y is the accumulated days, x is the altitude (m), and β_1 is the delay in days per metre. The coefficient of determination (R^2), Pearson correlation coefficient (r) and the associated P-value are reported for each stage (n = 24), with 95% confidence bands shown in Fig. 3. Because each altitude class was represented by one location, altitude and site are confounded in the design, and the regression results describe the trend across the four sites and not an independent effect of altitude (Körner, 2007). Replicates within a site and year share one weather record and are therefore not fully independent units of replication (Hurlbert, 1984), so the P-values are treated as descriptive. All tests were two-sided with $\alpha = 0.05$. Analyses were carried out in [Python with statsmodels (Seabold and Perktold, 2010) and SciPy (Virtanen et al., 2020) / R version x.x] and figures were produced with [matplotlib (Hunter, 2007) and seaborn (Waskom, 2021)].

3. Results

3.1 Phenological timing across altitude classes

The timing of the five phenological stages of Royal Delicious apple varied among the four altitude classes (Table 1; Fig 1.). Phenological timing was expressed as days from 1 January, and the values represent means ± standard deviation (SD) pooled across the 2022 and 2023 growing seasons. The stages occurred in the expected developmental sequence at all locations, with cumulative calendar days generally increasing from silver tip to petal fall. Differences among altitude classes were relatively small during the initial stages of development, although Kotkhai consistently recorded the latest mean dates for silver tip and green tip. Silver tip occurred between 60.4 and 69.8 days from 1 January, with Kotkhai (69.8 ± 4.2 days) significantly later than the other three locations (63.8 ± 3.1 days at Rampur, 60.4 ± 3.3 days at Rohru and 63.9 ± 2.0 days at Mashobra). A similar pattern was observed at green tip, which occurred at 74.8 ± 0.6 days at Kotkhai, compared with 68.2 ± 0.6, 69.8 ± 1.1 and 70.0 ± 1.6 days at Rampur, Rohru and Mashobra, respectively. The latter three locations did not differ significantly from one another at either stage. Differences among locations became more pronounced at pink bud. Rampur (73.1 ± 1.8 days) and Rohru (75.3 ± 1.6 days) reached this stage significantly earlier than Kotkhai (81.4 ± 1.4 days) and Mashobra (80.0 ± 1.3 days). At full bloom, Rampur recorded the earliest mean timing (79.5 ± 1.0 days), followed by Rohru (85.0 ± 1.0 days), Mashobra (86.6 ± 1.9 days) and Kotkhai (87.8 ± 1.0 days). The difference between the earliest and latest locations was 8.3 days. Rampur differed significantly from the other locations, while Mashobra and Kotkhai shared a significance group with Rohru and each other according to the reported letter assignments. At petal fall, all four locations differed significantly. Rampur reached this stage earliest, at 84.5 ± 1.4 days, followed by Rohru (88.6 ± 2.5 days), Mashobra (92.7 ± 1.3 days) and Kotkhai (95.4 ± 0.9 days). The difference between Rampur and Kotkhai was 10.9 days, indicating a wider separation among locations at the end of flowering than at the earliest developmental stages. The relationship between elevation and phenological timing was not consistently linear across the four locations. Although Kotkhai recorded the latest mean timing at every stage, Mashobra, the highest-altitude location, reached full bloom 1.2 days and petal fall 2.7 days earlier than Kotkhai. The interval between silver tip and petal fall, calculated from the pooled means, was shortest at Rampur (20.7 days), followed by Kotkhai (25.6 days), Rohru (28.2 days) and Mashobra (28.8 days). These differences indicate that the timing of individual stages and the duration of the observed developmental period varied among locations rather than following a uniform pattern with increasing elevation.

3.2 Relationship between altitude and phenological timing

Linear regression of accumulated calendar days against altitude showed a positive relationship at all five phenological stages, indicating a general tendency towards delayed development across the altitudinal gradient (Fig. 3). The relationship was relatively weak at silver tip ($R^2 = 0.192$, $r = 0.439$, $P = 0.032$) and green tip ($R^2 = 0.202$, $r = 0.450$, $P = 0.027$). Stronger relationships were observed from pink bud onwards, with R^2 values of 0.674 ($r = 0.821$) for pink bud, 0.636 ($r = 0.798$) for full bloom and 0.651 ($r = 0.807$) for petal fall (all $P < 0.001$). The estimated regression slopes varied among developmental stages. The slope was 0.0044 d m^{-1} at silver tip and 0.0029 d m^{-1} at green tip, increasing to 0.0073 d m^{-1} at pink bud, 0.0065 d m^{-1} at full bloom and 0.0085 d m^{-1} at petal fall. These values correspond to estimated delays of 4.4, 2.9, 7.3, 6.5 and 8.5 days per 1,000 m, respectively. The greatest estimated delay occurred at petal fall, whereas the smallest occurred at green tip, indicating that the strength and magnitude of the relationship between altitude and phenological timing differed among stages. The scatter around the fitted regression lines was more pronounced at the early developmental stages, particularly for silver tip in the 1901–2300 m altitude class, where recorded values extended approximately from 60 to 72 days. This variability was consistent with the relatively low R^2 values observed at silver tip and green tip. In contrast, the stronger relationships from pink bud onwards indicated a closer association between altitude and the timing of later developmental stages across the study locations.

3.3 Thermal (GDD) requirement across altitude classes

The accumulated growing degree days (GDD) required to reach the five phenological stages varied among altitude classes (Table 2; Fig. 2). Across the study locations, the pooled thermal requirement increased from 77.9–128.7 °C days at silver tip to 293.5–423.6 °C days at petal fall. Mashobra (2301–2600 m) recorded the highest GDD requirement at every phenological stage, increasing from 128.7 ± 8.3 °C days at silver tip to 423.6 ± 20.4 °C days at petal fall. At full bloom, its GDD requirement (337.6 ± 12.6 °C days) was approximately 27% higher than that at Rampur (265.5 ± 22.1 °C days), and 51–54% higher than at Rohru (223.4 ± 22.7 °C days) and Kotkhai (219.9 ± 41.1 °C days). At petal fall, Mashobra required approximately 35% more GDD than Rampur (313.2 ± 2.4 °C days), 44% more than Rohru (293.5 ± 2.9 °C days), and 41% more than Kotkhai (301.3 ± 12.1 °C days). Rohru (1501–1900 m) recorded the lowest GDD requirement at silver tip (77.9 ± 16.6 °C days), green tip (122.1 ± 32.7 °C days), pink bud (161.5 ± 27.6 °C days), and petal fall (293.5 ± 2.9 °C days). At full bloom, Kotkhai (1901–2300 m) had a slightly lower value (219.9 ± 41.1 °C days) than Rohru (223.4 ± 22.7 °C days). Rampur (1200–1500 m) generally occupied an intermediate position, with GDD requirements higher than those at Rohru and Kotkhai from green tip onwards. Overall, the pooled results showed a non-monotonic pattern across the altitude classes, with the highest thermal requirement consistently recorded at Mashobra rather than a steady increase with elevation.

The year-wise trends in Fig. 2 showed that Mashobra maintained a high thermal requirement in both seasons. In 2022, it accumulated approximately 121 °C days by silver tip and 405 °C days by petal fall, while the other three locations reached petal fall at approximately 290–315 °C days. GDD requirements were generally higher in 2023 than in 2022 across most location–stage combinations, although exceptions occurred, including Mashobra at full bloom and Rampur at petal fall. The relative ranking of Rohru and Kotkhai also varied between years: Kotkhai had a lower GDD requirement than Rohru at full bloom in 2022, whereas its requirement was higher at all stages in 2023.

3.4 Factorial analysis of variance

Three-way factorial analysis of variance (ANOVA) was used to examine the effects of year, location and phenological stage, along with their interactions, on calendar days and accumulated growing degree days (GDD) (Table 3). Calendar days. Phenological stage had the largest effect on accumulated calendar days ($F(4, 80) = 848.07$, $P < 0.0001$, $\eta^2p = 0.977$), reflecting the progression of flowering from silver tip to petal fall. Location (altitude) also had a significant effect $F(3, 80) = 108.85$, $P < 0.0001$, $\eta^2p = 0.803$) indicating substantial differences in phenological timing among the four study sites. The

main effect of year was not significant ($F(1, 80) = 0.20$, $P = 0.654$, $\eta^2p = 0.003$), suggesting that overall phenological timing did not differ significantly between the two seasons. Among the interaction effects, year × location ($F(3, 80) = 4.57$, $P = 0.005$, $\eta^2p = 0.146$) and location × stage ($F(12, 80) = 3.66$, $P = 0.0002$, $\eta^2p = 0.355$) were significant. The location × stage interaction indicates that differences among locations varied across developmental stages, consistent with the patterns presented in Table 1 and Fig. 1. The year × location interaction suggests that the interannual variation in phenological timing was not uniform across sites. Neither the year × stage interaction ($P= 0.110$) nor the three-way interaction ($F(12, 80) = 1.86$, $P = 0.053$, $\eta^2p = 0.218$) was significant at the 5% level.

GDD requirement: All main effects and interaction terms were reported as significant for accumulated GDD (\(P<0.0001\); Table 3). Phenological stage had the largest reported effect ($F(4, 80) = 255{,}302.00$, $\eta^2p = 0.9999$), followed by location ($F(3, 80) = 90{,}693.45$, $\eta^2p = 0.9997$) and year ($F(1, 80) = 56{,}589.68$, $\eta^2p = 0.9986$). The two-way interactions and the three-way interaction also had reported partial eta-squared values between 0.991 and 0.998. These results suggest that the variation in accumulated GDD was associated with differences among years, locations and developmental stages, with the effects of location and stage also varying between seasons.

3.5 Interannual variation at petal fall

Interannual variation in the timing and thermal requirement of petal fall is presented in Fig. 5. For calendar days (Fig. 5A), the differences between years varied among locations. Kotkhai reached petal fall at approximately 96 days in 2022 and 95 days in 2023, while Mashobra showed relatively little variation, with values of approximately 92-93 days in both seasons. At Rampur, petal fall occurred about 2-3 days later in 2023 than in 2022 (approximately 83 versus 86 days), whereas Rohru showed an earlier occurrence in 2023, shifting from approximately 91 to 86 days. These location-specific patterns are consistent with the significant year × location interaction observed for calendar days. The interannual pattern in accumulated GDD at petal fall (Fig. 5B) differed among locations. At Rampur, Rohru and Kotkhai, thermal requirements generally remained within approximately 290-315 °C days across the two seasons, although Kotkhai showed a notable increase from about 290 to 312 °C days. Mashobra had the highest requirement in both years, increasing from approximately 405 °C days in 2022 to 442 °C days in 2023, equivalent to an increase of about 9%. Its GDD requirement was approximately 29-49% higher than that of the other altitude classes, depending on the comparison and season. Thus, Mashobra consistently showed a substantially higher accumulated thermal requirement at petal fall, despite the relatively small interannual variation in its calendar timing.

4. Discussion

4.1 Altitude delays apple phenology, but the pattern is not monotonic

Results showed that phenological development in Royal Delicious apple was generally delayed across the altitudinal gradient, although the magnitude of the delay was relatively modest. Full bloom and petal fall occurred 8.3 and 10.9 days later, respectively, at Kotkhai than at Rampur. The corresponding regression slopes indicated delays of 6.5 days per 1000 m at full bloom and 8.5 days per 1000 m at petal fall. This general pattern is consistent with expectation of Hopkins bioclimatic law and with observations of delayed apple flowering at higher elevations in the Himalaya (Shukla et al., 2026) and Germany (Weil et al., 2018). However, the magnitude of observed delay was considerably smaller than 22 days per 1000 m reported for tree leaf-out in the Swiss Alps in 2016, which had declined from 34 days per 1000 m in 1960 (Vitasse et al., 2018b). Although differences between forest trees and managed apple orchards limit direct comparison, the authors attributed the weaker altitudinal gradient to stronger spring warming at higher elevations and warmer winters. Elevation-dependent warming has also been documented in mountain regions, although its magnitude is not spatially uniform (Mountain Research Initiative EDW Working Group, 2015; Pepin et al., 2022). Regional warming in north-western Himalaya, estimated at approximately 1.6 °C during twentieth century (Bhutiyani et al., 2007), provides additional climatic

context. Nevertheless, the present study does not establish whether regional warming contributed to the relatively modest phenological delay observed across the study locations. The relationship between elevation and phenological timing was not consistently linear. Although Kotkhai recorded latest mean timing at every developmental stage, Mashobra, the highest-altitude site, reached full bloom 1.2 days and petal fall 2.7 days earlier than Kotkhai. Similar departures from a simple altitudinal pattern have been reported for apple flowering in Korea, where orchards in mid-mountainous regions flowered earlier than those in other regions (Choi et al., 2025). Such variation may arise from local climatic and topographic conditions, including slope, aspect and cold-air drainage, which influence the temperatures experienced by plants independently of regional elevation patterns (Dobrowski, 2011). An important limitation of the present study is that each altitude class was represented by a single location. Consequently, altitude effects cannot be separated completely from site-specific influences. As other environmental factors also vary with elevation (Körner, 2007), the observed pattern suggests that elevation alone may not reliably predict flowering dates across the study region.

4.2 Relationship between altitude and phenological timing varies with developmental stage

The association between altitude and phenological timing differed across developmental stages. Regression relationships were relatively weak at silver tip and green tip (R^2 = 0.19-0.20) but stronger from pink bud to petal fall (R^2 = 0.64-0.67). Estimated slopes also varied among stages, ranging from 2.9 days per 1000 m at green tip to 8.5 days per 1000 m at petal fall. However, this progression was not strictly monotonic, as estimated slope decreased from 7.3 days per 1000 m at pink bud to 6.5 days per 1000 m at full bloom. Significant location × stage interaction (η^2p = 0.355) further indicated that differences among locations depended on the developmental stage. At silver tip and green tip, Kotkhai was significantly later than other locations, whereas all four locations differed significantly at petal fall. One possible explanation for weaker relationships during earliest stages is that their timing depends on the interaction between winter chilling and subsequent heat accumulation, rather than on spring temperature alone (Campoy et al., 2011; Cannell and Smith, 1986; Fadón et al., 2020). Differences in chilling conditions and short-term temperature fluctuations may therefore contribute to variation that is not captured by elevation alone. Relatively large standard deviation for silver tip at Kotkhai (4.2 days) is consistent with greater variability at this stage, although it does not establish the underlying cause. As development progresses, the cumulative effects of temperature may become more apparent, consistent with evidence that the response of tree phenology to temperature along elevational gradients can be lagged and cumulative (Bigler and Vitasse, 2019). Furthermore, because the calendar-day values are cumulative, differences established during earlier stages may carry forward into subsequent stages. The stronger relationships at later stages should therefore not be interpreted solely as evidence of an increasing physiological sensitivity to altitude (Vitasse et al., 2017). The interval between silver tip and petal fall, calculated from the pooled means, was shortest at Rampur (20.7 days), compared with 25.6-28.8 days at the other locations. This difference indicates that the duration of the observed developmental period varied among sites.

4.3 The thermal requirement is not constant across the altitudinal gradient

A major finding was the substantial variation in accumulated growing degree days (GDD) required to reach same phenological stage. At petal fall, the estimated requirement ranged from 293.5 °C days at Rohru to 423.6 °C days at Mashobra. Mashobra value was approximately 35-44% higher than those recorded at other three locations. Across four sites, pattern was non-monotonic, with lower requirements at the intermediate-altitude locations and higher values at the lowest- and highest-altitude locations. This finding is relevant because thermal time is frequently used as an indicator of apple-growing suitability and phenological development, including in assessments of suitable altitudes for apple cultivation in Himachal Pradesh (Aditya et al., 2019). The observed difference of approximately 130 °C days between Rohru and Mashobra indicates that a single petal-fall GDD threshold may not adequately represent the observed thermal requirements across the entire study gradient. The differences at the lower end of the gradient may partly reflect variation in winter chilling and subsequent heat requirements, although this explanation remains tentative. Rampur accumulated approximately

19-21% more GDD than Rohru and Kotkhai by full bloom. Previous studies have established that reduced winter chilling can increase the subsequent heat requirement for bud development (Cannell and Smith, 1986) and declining chilling has been proposed as a contributor to changes in spring phenology in Europe and the Alps (Fu et al., 2015; Vitasse et al., 2018b). Declining winter chill has also been identified as a potential constraint on apple production in the Himalaya (Sahu et al., 2020). As apple cultivars differ in their chilling and heat requirements, changes in winter temperature may affect high-chill genotypes differently (Delgado et al., 2021a), with greater losses of winter chill projected in warmer regions (Luedeling et al., 2011). Nevertheless, chilling accumulation was not quantified in the present study, and its contribution to the higher GDD requirement at Rampur cannot be established from the available data.

The consistently high GDD requirement at Mashobra presents a different question. Despite reaching full bloom 7.1 days later than Rampur, Mashobra had accumulated approximately 27% more GDD by that stage. This indicates that the calculated thermal sums differed substantially between the two locations, but the reason for this difference remains uncertain. Several explanations warrant investigation. First, local topography and exposure may influence site-level temperature conditions, including through cold-air pooling and differences in solar exposure (Dobrowski, 2011). Second, a linear degree-day model may not fully represent the physiological response to temperature, particularly where temperatures fluctuate around the model's base temperature or where the treatment of sub-base temperatures affects accumulation (Bigler and Vitasse, 2019; McMaster and Wilhelm, 1997). Third, differences in the temperature data sources or their spatial representativeness may have contributed to the observed pattern. These possibilities could not be evaluated using the present dataset because chilling conditions and independently measured canopy-level temperatures were unavailable. Consequently, the Mashobra values should be interpreted as site-specific estimates that require validation before being used to develop predictive phenology models.

4.4 Interannual variation: calendar timing was relatively stable, but thermal requirements varied

Overall effect of year on calendar-day timing was not significant ($P = 0.654$, $\eta^2p = 0.003$), suggesting that phenological timing, averaged across locations and stages, was broadly similar between the two seasons. However, the significant year × location interaction ($P = 0.005$, $\eta^2p = 0.146$) indicated that interannual differences were not consistent across sites. At petal fall, Rohru reached the stage approximately four days earlier in 2023, whereas Rampur was approximately 2-3 days later. Changes at Kotkhai and Mashobra were comparatively small. Thus, the nonsignificant overall year effect should not be interpreted as an absence of interannual variation at individual locations. In contrast, accumulated GDD varied significantly between years and values were generally higher in 2023 across most location stage combinations. The difference was particularly evident at Mashobra, where petal-fall requirement increased from approximately 405 °C days in 2022 to 442 °C days in 2023, an increase of about 9%. These observations indicate that similar overall calendar timing between seasons did not necessarily correspond to similar accumulated thermal sums. Differences in winter chilling and subsequent temperature accumulation could potentially contribute to this pattern, because both processes influence apple flowering (Delgado et al., 2021b). However, the absence of direct chilling estimates prevents attribution of the observed interannual differences to winter chill alone (Luedeling, 2012) . Photoperiod has been proposed as a constraint on early-season phenology in some tree species (Fu et al., 2015), but temperature is generally considered a major driver of dormancy release and spring development in apple (Heide and Prestrud, 2005). Previous studies have also highlighted limitations in the accuracy of heat-based phenology models under unusually warm winter conditions (Fernandez et al., 2022). Long-term observations from Germany have demonstrated a close relationship between spring temperature and apple bloom timing (Weil et al., 2018), while European spring phenology has broadly reflected regional warming patterns (Menzel et al., 2006). Nevertheless, two growing seasons are insufficient to distinguish normal interannual variability from a longer-term change in the relationship between thermal accumulation and phenological timing. The significant year × location interaction also highlights the importance of considering site-specific and seasonal variation when interpreting altitude-based phenological patterns.

4.5 Implications for orchard management and climate adaptation

Across the approximately 1400 m altitudinal range, full bloom varied by 8.3 days between the earliest and latest locations. This relatively narrow spread suggests that increasing elevation did not necessarily result in a proportionately large delay in flowering (Vitasse et al., 2009).Consequently, higher elevation alone may not provide a reliable buffer against late spring frost. Apple blossoms can be damaged by frost during flowering (Unterberger et al., 2018) and previous research in Switzerland has documented increased spring-frost exposure at higher elevations where phenological advancement outpaced the occurrence of last frost (Vitasse et al., 2018a). In the present study, frost events and blossom injury were not monitored, so the actual frost risk at the four locations cannot be determined. Nevertheless, the relatively small differences in bloom timing indicate that frost exposure should be assessed using local temperature records rather than inferred from elevation alone. The Korean observations of severe frost damage in mid-mountainous orchards despite generally delayed flowering at higher elevations provide a further example of the importance of regional and site-specific conditions (Choi et al., 2025). Flowering synchrony with pollinators is another consideration for apple production across an altitudinal gradient. Plant and pollinator phenology can shift in parallel, but temporal mismatches have also been documented (Hegland et al., 2009).

The upward shift of apple cultivation in Himachal Pradesh, reported in association with changing climatic suitability (Sahu et al., 2020), is consistent with broader evidence of upslope shifts in species distributions (Parmesan and Yohe, 2003). However, present results suggest that changes in cultivation altitude should not be evaluated using phenological delay alone. At Mashobra, the site above 2300 m, the estimated GDD requirement at petal fall was 35–44% higher than at the other locations, despite the relatively small differences in calendar timing across the study sites. This finding supports the need to evaluate and validate altitude-specific thermal thresholds rather than assuming that a single GDD requirement applies throughout the region (Aditya et al., 2019). For practical orchard management, phenological-stage-based scheduling, supported by local weather observations, is likely to be more informative than reliance on calendar dates alone. Process-based models that account for chilling and forcing separately, such as PhenoFlex (Luedeling et al., 2021), provide a promising direction for future work. Their application to the western Himalaya would require longer-term observations, reliable site-level temperature measurements and calibration for the cultivars and locations concerned.

5. Conclusion

This study demonstrated that phenological timing and growing degree day (GDD) requirements in Royal Delicious apple varied across the altitudinal gradient in the western Himalaya, although the patterns were not consistently linear. Phenological delays were generally more pronounced at later developmental stages, but differences among locations did not increase uniformly with elevation. GDD requirement also varied among locations and between seasons, indicating that a single thermal threshold may not adequately represent phenological development across the study gradient. These findings suggest that altitude-specific, phenological-stage-based assessments, supported by local weather observations, may provide a more appropriate basis for orchard planning and frost-risk assessment than fixed calendar dates or a single GDD threshold. However, the findings are based on four locations, each representing one altitude class, over two growing seasons. Further studies involving replicated sites, longer-term observations, orchard-level temperature measurements and estimates of winter chilling are required to validate these patterns and clarify the factors underlying the observed variation.

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Data Availability

The meteorological data used in this study were obtained from the publicly accessible ERA5-Land reanalysis dataset through the Google Earth Engine platform. Relevant secondary datasets were obtained from publicly accessible sources. Field observation data generated during the study are available from the corresponding author upon reasonable request.

Ethical Standards and Use of Generative Artificial Intelligence

Generative artificial intelligence (AI) tools were used solely to improve the language, grammar, clarity, and readability of the manuscript. No generative AI tools were used to generate, fabricate, or modify research data, field observations, analytical results, or scientific findings. The authors take full responsibility for the accuracy, integrity, interpretation, and originality of the research and its conclusions.

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Tables

Table 1. Pooled Phenological Timing (Days) Across Altitudinal Gradients (2022–2023)

Altitude Class (Location)	Silver tip	Green tip	Pink bud	Full bloom	Petal fall
1200–1500 m (Rampur)	63.8 ± 3.1[a]	68.2 ± 0.6[a]	73.1 ± 1.8[a]	79.5 ± 1.0[a]	84.5 ± 1.4[a]
1501–1900 m (Rohru)	60.4 ± 3.3[a]	69.8 ± 1.1[a]	75.3 ± 1.6[a]	85.0 ± 1.0[b]	88.6 ± 2.5[b]
1901–2300 m (Kotkhai)	69.8 ± 4.2[b]	74.8 ± 0.6[b]	81.4 ± 1.4[b]	87.8 ± 1.0[c]	95.4 ± 0.9[c]
2301–2600 m (Mashobra)	63.9 ± 2.0[a]	70.0 ± 1.6[a]	80.0 ± 1.3[b]	86.6 ± 1.9[bc]	92.7 ± 1.3[d]

Table 2. Pooled Phenothermal Requirement (GDD) Across Altitudinal Gradients (2022–2023)

Altitude Class (Location)	Silver tip	Green tip	Pink bud	Full bloom	Petal fall
1200–1500 m (Rampur)	94.1 ± 17.9	173.6 ± 18.5	219.3 ± 23.9	265.5 ± 22.1	313.2 ± 2.4
1501–1900 m (Rohru)	77.9 ± 16.6	122.1 ± 32.7	161.5 ± 27.6	223.4 ± 22.7	293.5 ± 2.9
1901–2300 m (Kotkhai)	94.4 ± 28.2	146.9 ± 44.2	178.3 ± 51.5	219.9 ± 41.1	301.3 ± 12.1

Altitude Class (Location)	Silver tip	Green tip	Pink bud	Full bloom	Petal fall
2301–2600 m (Mashobra)	128.7 ± 8.3	227.0 ± 15.6	294.3 ± 18.5	337.6 ± 12.6	423.6 ± 20.4

Table 3. 3-Way Factorial ANOVA Results for Calendar Days and GDD Requirements

Response Variable	Source of Variation	df	Sum of Sq.	F-statistic	P-value	η^2p
Calendar Days	Year	1	0.68	0.20	0.6539 (ns)	0.0025
Calendar Days	Location (Altitude)	3	1088.49	108.85	< 0.0001 ***	0.8032
Calendar Days	Phenological Stage	4	11307.63	848.07	< 0.0001 ***	0.9770
Calendar Days	Year × Location	3	45.72	4.57	0.0052 **	0.1464
Calendar Days	Year × Stage	4	26.02	1.95	0.1099 (ns)	0.0889
Calendar Days	Location × Stage	12	146.53	3.66	0.0002 ***	0.3546
Calendar Days	Year × Loc × Stage	12	74.28	1.86	0.0527 (ns)	0.2179
GDD Requirements	Year	1	42352.66	56589.68	< 0.0001 ***	0.9986
GDD Requirements	Location (Altitude)	3	203629.47	90693.45	< 0.0001 ***	0.9997
GDD Requirements	Phenological Stage	4	764289.09	255302.00	< 0.0001 ***	0.9999

Response Variable	Source of Variation	df	Sum of Sq.	F-statistic	P-value	η^2p
GDD Requirements	Year × Location	3	9007.97	4012.01	< 0.0001 ***	0.9934
GDD Requirements	Year × Stage	4	6422.32	2145.30	< 0.0001 ***	0.9908
GDD Requirements	Location × Stage	12	24839.00	2765.73	< 0.0001 ***	0.9976
GDD Requirements	Year × Loc × Stage	12	7121.00	792.90	< 0.0001 ***	0.9917

Figures

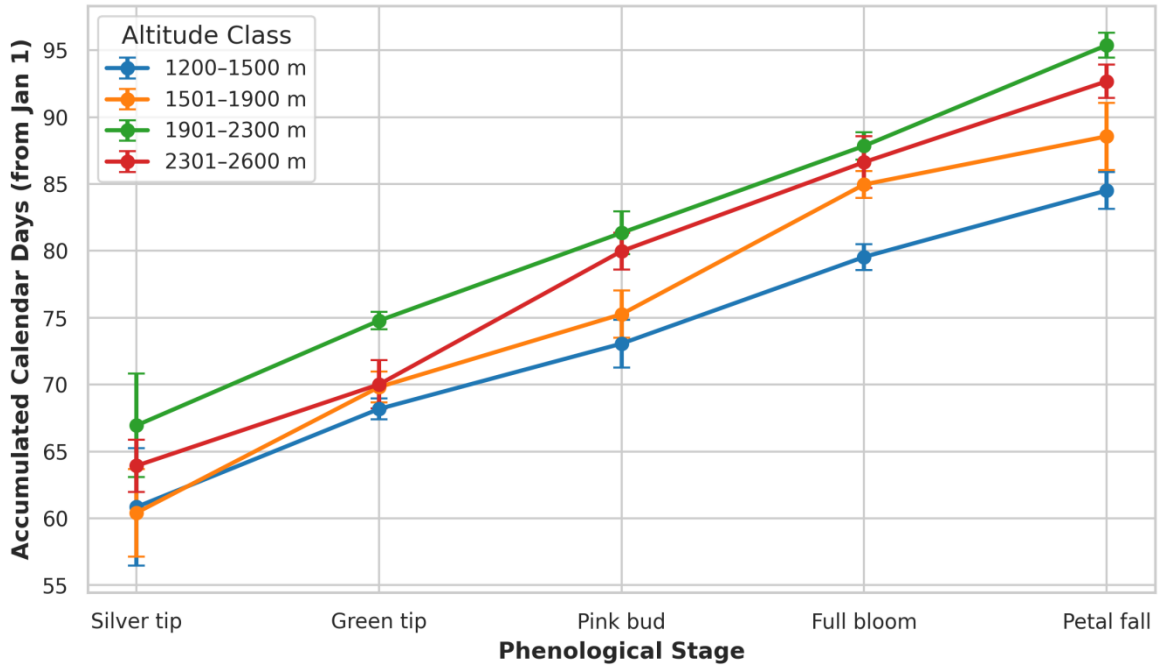


Fig 1. Pooled phenological progression (accumulated calendar days) of Royal Delicious apple across four altitudinal gradients in Shimla district (2022–2023). Error bars represent ±1 SD.

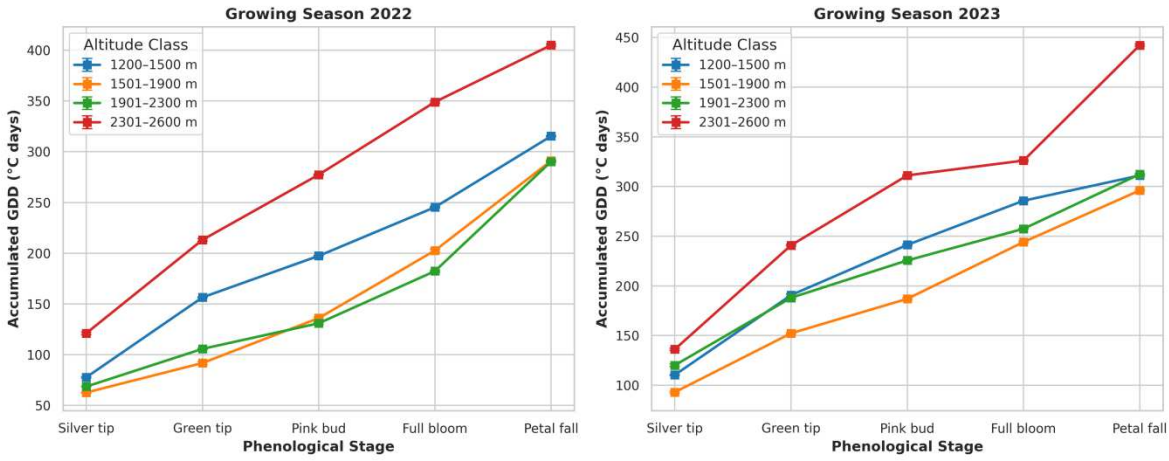


Fig 2. Phenothermal requirement (accumulated GDD) across altitudinal gradients presented separately for the 2022 and 2023 growing seasons. Error bars represent ±1 SD.

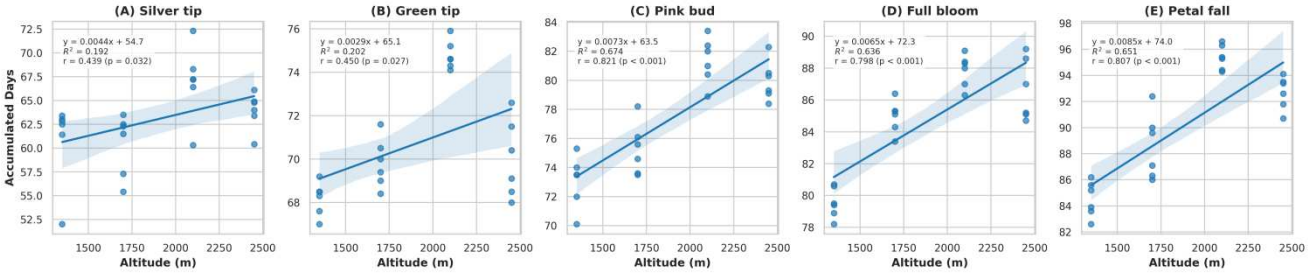


Fig 3. Five-panel scatter plots and linear regression trends relating altitude (m) to accumulated calendar days across individual phenological growth stages.

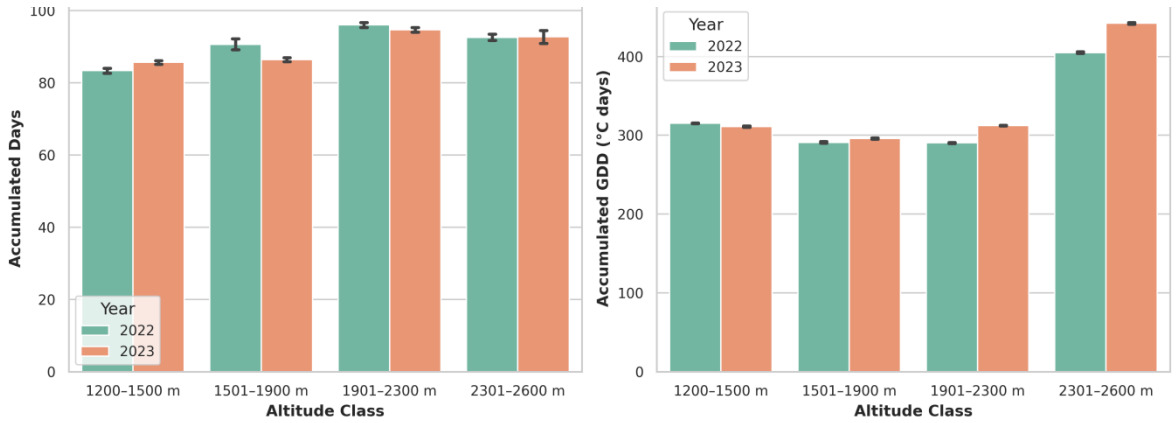


Fig 5. Bar chart comparison of accumulated calendar days (A) and accumulated GDD (B) at Petal fall between the 2022 and 2023 growing seasons across four altitude classes.