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Thermal accumulation and phenology shifts in agroforestry trees of Himachal Pradesh

Karina[1], M.S. Jangra[1], S.K. Bhardwaj and Komal Thakur[1]*

ABSTRACT: *The present study was conducted during 2022–23 and 2023–24 at two altitudinal gradients, namely 1200–1400 m and 1400–1600 m above mean sea level (AMSL), to investigate phenological behaviour and thermal requirements of selected agroforestry tree species under institutional plantation conditions in the mid-hills of Himachal Pradesh. Two multipurpose tree species, Grewia optiva and Toona ciliata, were selected due to their ecological and economic importance in regional agroforestry systems. Key phenological stages were recorded at weekly intervals, and thermal accumulation was quantified using growing degree days (GDD). Meteorological data were obtained from the University Meteorological Observatory. The results revealed clear altitudinal variation in phenophase initiation and completion, with earlier occurrence of most phenophases at 1200–1400 m AMSL compared to 1400–1600 m AMSL. Accumulated GDD requirements increased with altitude for both species, indicating the influence of cooler temperature regimes at higher elevations. R Studio–based visualization further highlighted species- and altitude-specific phenological trends. The study demonstrates that phenological timing and thermal accumulation are strongly regulated by altitude-driven microclimatic variation, providing valuable insights for agroforestry planning and adaptive management in the Himalayan region.*

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1. INTRODUCTION

Phenology refers to the study of periodic biological events such as leaf flushing, flowering, fruiting, and leaf fall, and their relationship with environmental factors, particularly temperature and moisture availability. In perennial tree species, phenological timing plays a crucial role in determining productivity, ecological interactions, and adaptation to local environments (Kailash *et al.*, 2023). Understanding phenological patterns is therefore essential for sustainable forest management, conservation of genetic resources, and optimization of agroforestry systems.

The timing of key phenological events in plants is largely governed by thermal accumulation during the growing season. This accumulated heat requirement is commonly expressed using the concept of growing degree days (GDD), which integrates daily temperature conditions above a species-specific base temperature (Baskerville & Emin, 1969). GDD-based approaches are widely used to explain and predict plant developmental stages and their response to environmental variability (Chuine, 2000; Richardson *et al.*, 2013).

In tree species, earlier phenophase initiation is generally associated with warmer temperature regimes, whereas delayed phenology occurs under cooler conditions, such as at higher altitudes (Basler & Körner, 2012; Ma *et al.*, 2019). Several recent studies have emphasized that altitudinal gradients serve as natural laboratories for examining temperature-driven phenological responses, particularly in mountainous ecosystems (Egea *et al.*, 2022).

In Himachal Pradesh, agroforestry systems commonly integrate multipurpose tree species such as *Grewia optiva* and *Toona ciliata*, which provide fodder, timber, fuelwood, and ecological services. Despite their importance, limited information is available on their phenological behaviour and thermal requirements across different altitudinal zones under managed plantation conditions. Therefore, the present study was undertaken with the following objectives:

(i) to record major phenological stages of selected agroforestry tree species, and

(ii) to compute and compare growing degree day accumulation across altitudinal gradients.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted at Nauni (≈30.86°N, 77.16°E) and Kandaghat (≈30.97°N, 77.10°E) representing two altitudinal gradients (Figure 1)

- 1200–1400 m AMSL: Dr. Y.S. Parmar University of Horticulture and Forestry, Nauni

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✉ Komal Thakur
komalthakurkt606@gmail.com

[1] Department of Environmental Science,
Dr. YS Parmar University of Horticulture and Forestry
Nauni-173230 Solan, (HP)

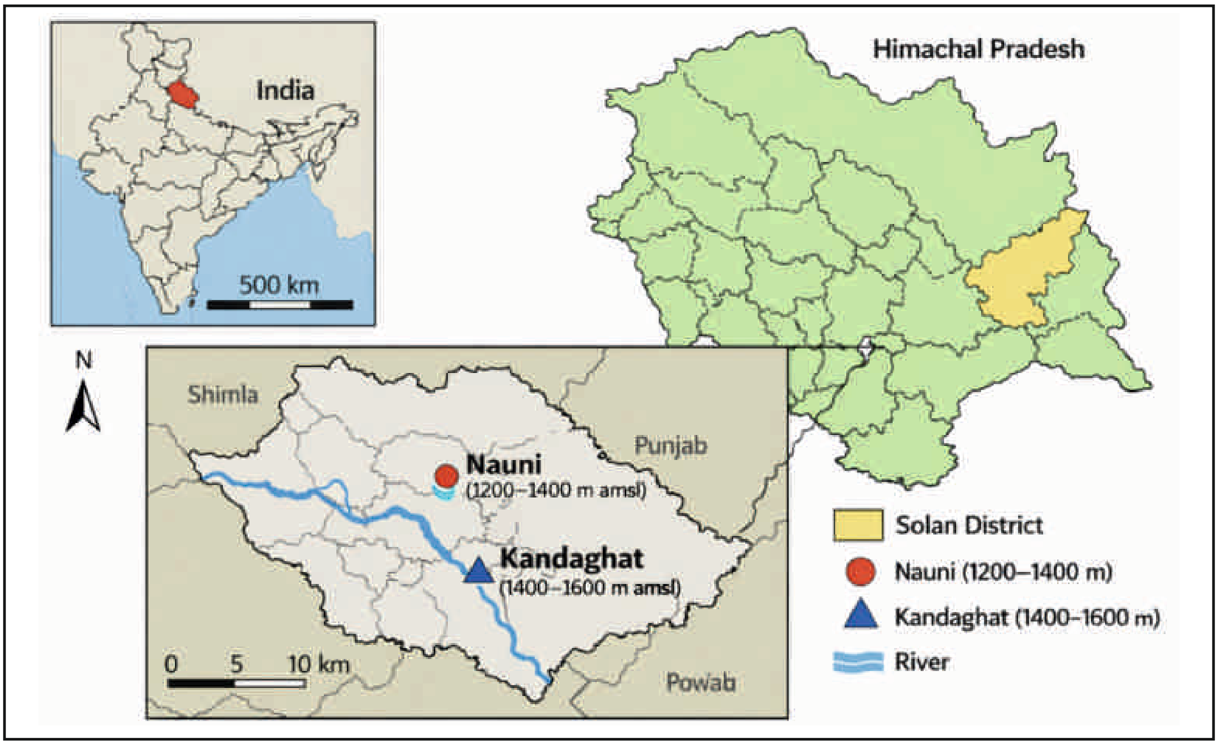

Figure 1. Map of the study area showing the research locations in Solan district, Himachal Pradesh, India

- 1400–1600 m AMSL: Krishi Vigyan Kendra, Kandaghat

The region experiences a sub-temperate climate with moderately warm summers and cold winters. Mean annual rainfall is approximately 1140 mm, primarily received during the monsoon season (June–September).

2.2 Experimental Design and Plant Material

The study was carried out under institutional plantation (open-grown) conditions, without intercrops or understory agricultural components. Two agroforestry tree species were selected:

- *Grewia optiva*
- *Toona ciliata*

At each site, two trees per species were selected in three replications, resulting in six trees per species per altitude. The same trees were observed continuously for two years (2022–23 and 2023–24).

2.3 Meteorological Data

Meteorological data including maximum temperature (T_{max}), minimum temperature (T_{min}), relative humidity, rainfall, and sunshine hours were obtained from the University Meteorological Observatory, Dr. Y.S. Parmar University of Horticulture and Forestry, Nauni (Figure 2).

2.4 Phenological Observations

Phenological observations were recorded at weekly intervals. The following phenophases were monitored (Figure 3):

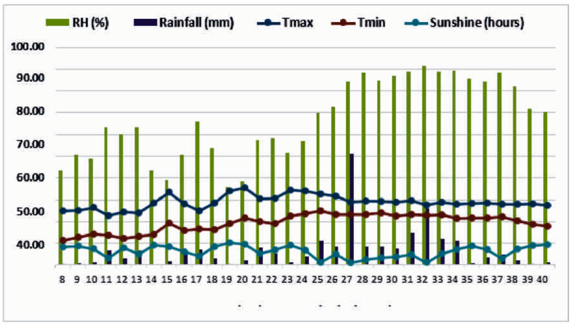

Figure 2: Climatograph of study area

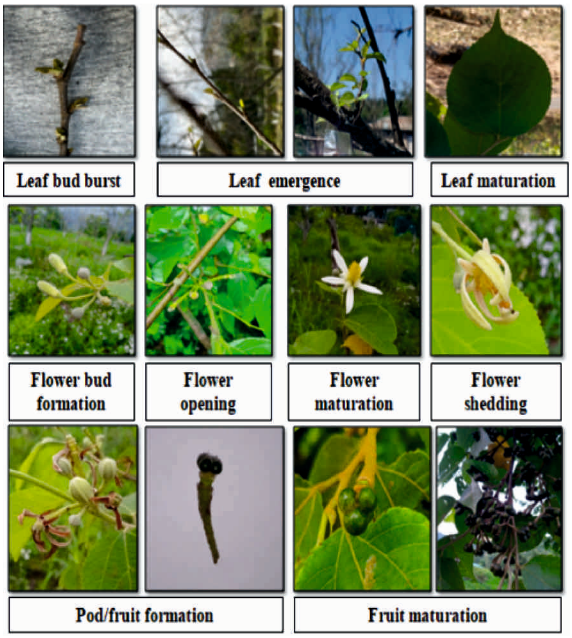

Figure 3: Phenological stages of *Grewia optiva*

- Leaf bud burst
- Leaf emergence
- Flower bud formation
- Flower opening
- Flower maturation
- Flower shedding
- Pod/fruit formation
- Fruit maturation
- Leaf maturation

Phenological timing was expressed as number of days after the reference date.

2.5 Computation of Growing Degree Days (GDD)

Growing degree days were calculated for each phenophase using the following formula (Snyder *et al.*, 1999):

$$\text{GDD (°C days)} = \sum \frac{T_{max} + T_{min}}{2} T_{base}$$

where,

T_{max} = daily maximum temperature (°C)

T_{min} = daily minimum temperature (°C)

T_{base} = base temperature (species-specific)

2.6 Statistical Analysis and Data Visualization

Statistical analysis was performed using SPSS (version 16.0). Graphical visualization of phenological timing and thermal indices was carried out using R Studio software employing the ggplot2 package, which enabled clear representation of species-, altitude-, and year-wise variations.

3 RESULTS AND DISCUSSION

3.1 Phenological Variation across Altitudes

Distinct variation in phenological timing was observed between the two altitudinal gradients (Table 1). For both *Grewia optiva* and *Toona ciliata*, phenophases such as leaf bud burst, flowering and fruit maturation occurred earlier at 1200–1400 m AMSL compared to 1400–1600 m AMSL. This advancement ranged from 4–6 days and was consistent across both years of observation.

R Studio–based visualization clearly demonstrated the systematic delay in phenophase occurrence with increasing altitude, reflecting the influence of lower temperature regimes at higher elevations.

The selected tree species with respect to the timing of leaf bud, leaf emergence, flower opening, flower maturation, shedding of flowers, pod fruit^{-1} formation, fruit maturation and leaf maturation showing widely varying timing and duration of deciduousness. The general phenological stages of both the species have been presented in Table 1. It was found that the leaf flushing stages of *Grewia optiva* and *Toona ciliata* was

Table 1: Variation in different phenological stages (no. of days) of agroforestry trees altitudinal gradients (m amsl)

Phenophases	***Grewia optiva***								
	2023		**Mean**	**2024**		**Mean**	**Pooled**		**Mean**
	1200-1400	**1400-1600**		**1200-1400**	**1400-1600**		**1200-1400**	**1400-1600**	
Leaf bud burst	56.8	62.5	59.6	52.3	62.8	57.5	54.5	62.6	58.6
Leaf emergence	72.8	78.5	75.6	70.0	74.5	72.3	71.4	76.5	73.9
Flower bud formation	93.0	97.0	95.0	86.5	91.8	89.1	89.8	94.4	92.1
Flower opening	103.0	110.0	106.5	96.5	103.3	99.8	99.8	106.6	103.2
Flower maturation	113.0	117.5	115.3	106.5	114.3	110.4	109.8	115.9	112.8
Shedding of flower	121.3	126.5	123.9	118.3	123.5	120.9	119.8	125.0	122.4
Pod/fruit formation	129.5	136.5	133.0	127.3	133.5	130.4	128.4	135.0	131.7
Fruit maturation	181.5	186.3	183.9	177.3	183.5	180.4	179.4	184.9	182.1
Leaf maturation	291.5	296.3	293.9	284.3	290.5	287.4	287.9	293.4	290.6
	Toona ciliata								
Leaf bud burst	45.5	53.5	49.5	44.0	50.5	47.3	44.8	52.0	48.4
Leaf emergence	57.8	62.8	60.3	55.5	61.5	58.5	56.6	62.1	59.4
Flower bud formation	73.3	76.8	75.0	70.3	74.8	72.5	71.8	75.8	73.8
Flower opening	83.3	89.0	86.1	81.3	87.8	84.5	82.3	88.4	85.3
Flower maturation	93.3	97.5	95.4	91.3	96.8	94.0	92.3	97.1	94.7
Shedding of flower	102.3	107.0	104.6	100.3	105.0	102.6	101.3	106.0	103.6
Pod/fruit formation	113.3	120.0	116.6	110.2	117.0	113.6	111.8	118.5	115.1
Fruit maturation	158.5	163.5	161.0	154.3	160.0	157.1	156.4	161.8	159.1
Leaf maturation	255.5	259.0	257.3	249.3	255.0	252.1	252.4	257.0	254.7

advanced by 4 to 5 days during 2nd year of study, whereas, Thakur *et al.* (2008) reported a leaf flush advancement of 5 to 40 days. Increased rainfall in March–April months during 2nd year compared to that of the 1st year might result in the advancement in leaf flush of tree species. The leaf initiation of tree species was strongly influenced by temperature and precipitation (moisture) (Bajpai *et al.* 2012, 2017, Chaturvedi and Raghubanshi 2016).

The initiation of flowering by the end of winter, during high temperature and increasing day length had also been reported (Yadav and Yadav 2008, Kushwaha *et al.* 2011, Gritto et al 2015, Bajpai *et al.* 2017). *Grewia optiva* and *Toona ciliata* flowering soon after leaf flushes. The similar results were recorded by Singh and Khushwaha (2006). Both the tree species fruiting started in late summer. The peak fruiting and ripening of fruits in the latter part of pre-monsoon dry period or close to rainfall recorded in our study was similar to that in subtropical forests of Manipur (Kikim and Yadava 2001).

The phenological progression of *Grewia optiva* and *Toona ciliata* across altitudinal gradients is illustrated in Figures 4 and 5. Across all phenophases, both species exhibited earlier initiation at 1200–1400 m amsl (Nauni) compared to 1400–1600 m amsl (Kandaghat). Leaf bud burst, leaf emergence, flowering and fruiting stages occurred 5–8 days earlier at lower altitude, reflecting warmer microclimatic condition.

The delayed phenophase occurrence at higher altitude can be attributed to reduced thermal accumulation, which is visually evident from Figure 6. Accumulated growing degree days (GDD) required for each phenophase were consistently higher at 1400–1600 m amsl. For instance, leaf bud burst in *Grewia optiva* required 253.2 °C days at higher altitude compared to 237.9 °C days at lower altitude, while leaf maturation required 2220.2 °C days at higher altitude as compared to 2205.1 °C days at lower altitude.

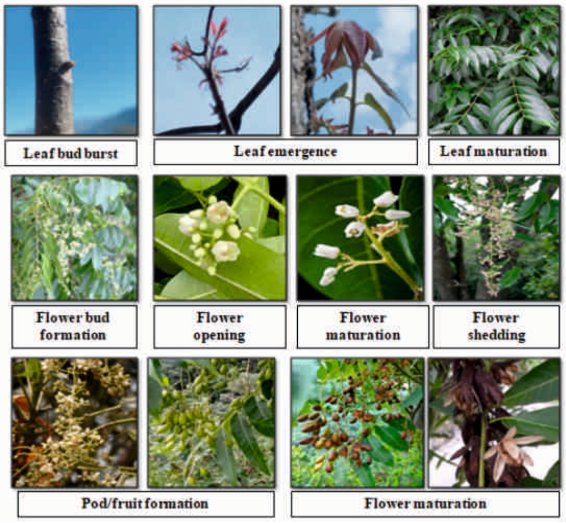

Figure 4: Phenological stages of *Toona ciliata*

Similarly, *Toona ciliata* showed a consistent delay in phenological events at higher altitude (Figure 5), indicating strong temperature sensitivity of the species. The observed altitudinal variation in

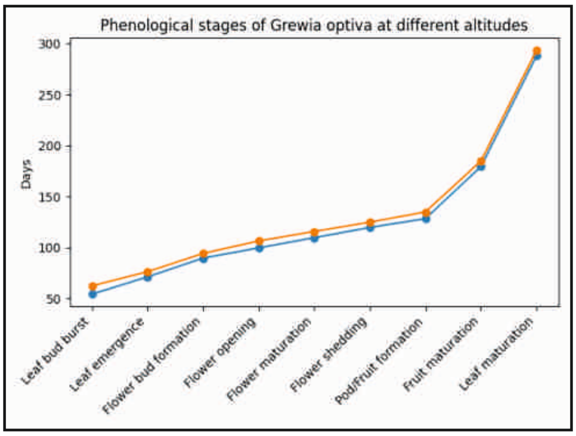

Figure 4: Year-wise phenophase timing of *Grewia optiva* at Nauni (1200–1400 m amsl) and Kandaghat (1400–1600 m amsl) during 2023 and 2024 based on pooled observations, visualized using R Studio (ggplot2).

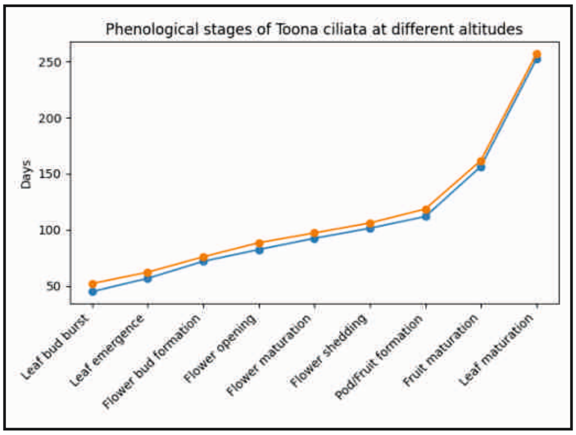

Figure 5: Altitude-wise variation in phenophase timing of *Toona ciliata* at Nauni (1200–1400 m amsl) and Kandaghat (1400–1600 m amsl) based on pooled observations using R Studio (ggplot2)

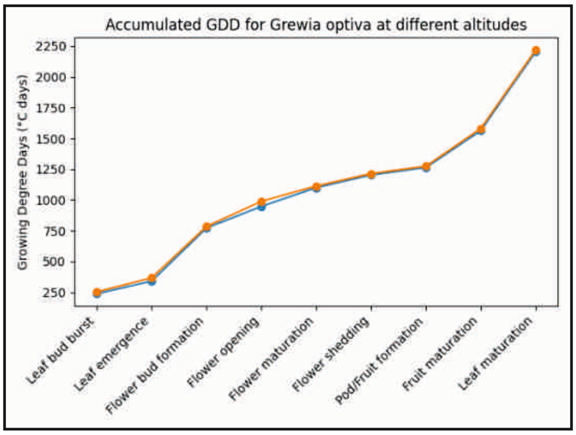

Figure 6: Species-wise comparison of phenophase timing of *Grewia optiva* and *Toona ciliata* based on pooled observations, visualized using R Studio (ggplot2).

phenological timing can be attributed to differences in thermal regimes across elevations. Lower temperatures at higher altitudes delay heat accumulation, thereby postponing phenophase initiation. Similar altitude-driven phenological delays have been reported earlier in temperate tree species (Basler & Körner, 2012; Ma *et al.*, 2019), supporting the present findings.

3.2 Growing Degree Day Accumulation

Accumulated GDD required to attain different phenophases increased with altitude for both species (Table 2). *Grewia optiva* exhibited higher GDD requirements compared to *Toona ciliata*, indicating species-specific thermal sensitivity. Higher GDD accumulation at 1400–1600 m AMSL suggests prolonged heat requirement under cooler microclimatic conditions.

These findings are consistent with earlier reports highlighting delayed phenological development under lower temperature regimes in tree species (Basler & Körner, 2012; Ma *et al.*, 2019).

Growing degree days (GDDs) were counted as maximum at 1400-1600m amsl (239.6 ˚C days) in 2023 and minimum at 1200-1400m amsl (225.9 ˚C days) during the same year for attaining leaf bud burst phenophases in *Grewia optiva.* Similarly in *Toona ciliata* the maximum GDD was observed at 1400-1600m amsl (157 ˚C days) and minimum at 1200-1400m amsl (133.5˚C days) during 2023. The similar trend was followed in second year of study (table 2). The results were in conformity with that of (Basler and Korner (2012), Ma *et al.* (2019) and Egea *et al.* (2022)) who found that lower temperatures significantly delayed different phenophases in the temperate forest tree species examined.

3.3 Species-wise and Year-wise Trends

Year-wise comparison showed minor inter-annual variation in phenophase timing, likely associated with differences in seasonal rainfall and temperature distribution rather than long-term climatic shifts. Visualization through R Studio effectively highlighted consistent altitudinal trends across both years, reinforcing the robustness of the observed patterns.

3.4 Implications for Agroforestry Management

The study clearly demonstrates that phenological behaviour and thermal accumulation in agroforestry tree species are strongly influenced by altitude-driven microclimatic variability. Understanding these relationships is essential for selecting suitable species for specific altitudinal zones and optimizing management practices under institutional and farm-based agroforestry systems.

4. CONCLUSION

The present study revealed clear altitudinal variation in the phenological behavior and thermal requirements of *Grewia optiva* and *Toona ciliata* under mid-hill conditions of Himachal Pradesh.

Table 2: Accumulation of GDD required for attaining different phenophases in agroforestry trees

Phenophases	***Grewia optiva***								
	2023		**CV (%)**	**2024**		**CV (%)**	**Pooled**		**CV (%)**
	1200-1400	**1400-1600**		**1200-1400**	**1400-1600**		**1200-1400**	**1400-1600**	
Leaf bud burst	225.9	239.6	4.2	249.8	266.7	4.6	237.9	253.2	4.4
Leaf emergence	326.9	349.9	4.8	353.1	383.3	5.8	340.0	366.6	5.3
Flower bud formation	756.4	763.1	0.6	787.6	806.6	1.7	772.0	784.9	1.2
Flower opening	962.9	978.1	1.1	986.1	999.0	0.9	947.5	988.6	3.0
Flower maturation	1089.0	1107.0	1.2	1110.7	1120.3	0.6	1099.9	1113.7	0.9
Shedding of flower	1199.9	1209.9	0.6	1206.7	1219.0	0.7	1203.3	1214.5	0.7
Pod/fruit formation	1258.0	1264.0	0.3	1269.5	1284.9	0.9	1263.8	1274.5	0.6
Fruit maturation	1554.7	1570.8	0.7	1573.4	1592.0	0.8	1564.1	1581.4	0.8
Leaf maturation	2193.5	2204.5	0.4	2216.6	2235.9	0.6	2205.1	2220.2	0.5
	Toona ciliata								
Leaf bud burst	133.5	157.0	11.4	163.4	180.1	6.9	148.5	168.6	9.0
Leaf emergence	168.7	187.9	7.6	183.2	199.3	6.0	176.0	193.6	6.7
Flower bud formation	342.7	369.9	5.4	378.5	387.9	1.7	360.6	378.9	3.5
Flower opening	515.6	543.4	3.7	549.0	568.2	2.4	532.2	555.8	3.1
Flower maturation	587.7	599.2	1.4	608.9	617.1	0.9	598.3	608.2	1.2
Shedding of flower	696.9	708.4	1.2	719.0	728.4	0.9	708.0	718.4	1.0
Pod/fruit formation	910.4	931.0	1.6	937.1	953.1	1.2	923.8	942.1	1.4
Fruit maturation	1164.9	1189.4	1.5	1178.4	1196.0	1.0	1171.7	1192.7	1.3

Phenophases such as leaf bud burst, flowering, fruiting, and leaf maturation consistently occurred earlier at 1200–1400 m amsl compared to 1400–1600 m amsl, indicating the strong influence of altitude-driven temperature variation.

Accumulated growing degree days (GDD) differed significantly across altitudes and species, with higher GDD requirements observed at higher elevations, reflecting delayed phenophase attainment under cooler thermal regimes. The graphical representation of phenological timing and GDD accumulation clearly demonstrates the temperature sensitivity of both agroforestry tree species.

These findings highlight the importance of thermal accumulation in regulating phenological events and underscore the role of altitude-induced microclimatic variation in agroforestry systems. The results provide useful baseline information for agroforestry planning, species selection, and adaptive management strategies in mountainous regions experiencing variable temperature regimes.

Author Contributions

Karina conceived and designed the study, conducted field observations, analyzed data, and prepared the manuscript. M. S. Jangra supervised the research and provided technical guidance. Komal Thakur assisted in data collection and critically reviewed the manuscript. All authors approved the final version.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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