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Influence Of Temperature And Rainfall On The Phenological Development Of Selected *Crotalaria* Species In Tirupati

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Abstract

Climate change is altering the phenological rhythms of numerous plant species, particularly in tropical regions. This study investigates the impact of key climatic parameters, temperature, rainfall, and humidity, on the phenological events (vegetative growth, flowering, fruiting, and seed dispersal) of four selected Crotalaria species: C. juncea, C. pallida, C. retusa, and C. verrucosa. A three years five months period field study (2022–2026) was conducted in the Tirupati region of Andhra Pradesh, India. Phenological observations were recorded biweekly and correlated with high-resolution climatic data. The results revealed distinct species specific phenological responses. C. verrucosa exhibited the longest flowering duration, while C. juncea showed a highly condensed phenological cycle (180–210 days). High temperatures and the onset of the monsoon were identified as primary triggers for flowering initiation. Rising temperatures correlated with a significant advancement in flowering dates for all species, with C. pallida showing the highest sensitivity. The study provides critical baseline data for predicting the impacts of future climate change on tropical legumes and contributes to the development of adaptive conservation strategies.

Keywords: Crotalaria, Phenology, Climate Change, Legumes, Flowering, Tropical Ecology, Andhra Pradesh

1. Introduction

Plant phenology, the study of recurring lifecycle events, is considered one of the most sensitive and accurate bioindicators of climate change. Shifts in the timing of phenological events such as leaf flushing, flowering, and fruiting can have cascading effects on ecosystem functioning, species interactions, and agricultural productivity. The Intergovernmental Panel on Climate Change (IPCC) has highlighted that tropical regions, despite lower warming magnitudes than temperate zones, are highly vulnerable to even minor climatic changes due to the narrow thermal tolerance of their biodiversity[1-5]. The genus Crotalaria L. (Fabaceae) comprises over 700 species of herbs and shrubs distributed widely across tropical and subtropical regions of the world. Several species hold significant ecological and economic importance, being used as green manure, cover crops, fibre sources, and in traditional medicine. However, many Crotalaria species are also known to be invasive or possess toxic alkaloids, making a thorough understanding of their growth and reproductive biology crucial for management. The Eastern Ghats region of Andhra Pradesh, particularly the Tirupati area, is characterised by a unique tropical climate with distinct wet and dry seasons. With the rising frequency of extreme weather events and rising mean annual temperatures observed in the region over the past two decades, a knowledge gap exists regarding how native and naturalised legume species are responding to these changes. This research addresses the question: How do variations in temperature, precipitation, and relative humidity influence the phenological progression of four selected Crotalaria species in the tropical climate of Tirupati, Andhra Pradesh? The study was conducted over a three years five months period (2022–2026) to capture interannual climatic variability and its impact on critical phenophases, providing essential insights for ecological forecasting and sustainable land management.

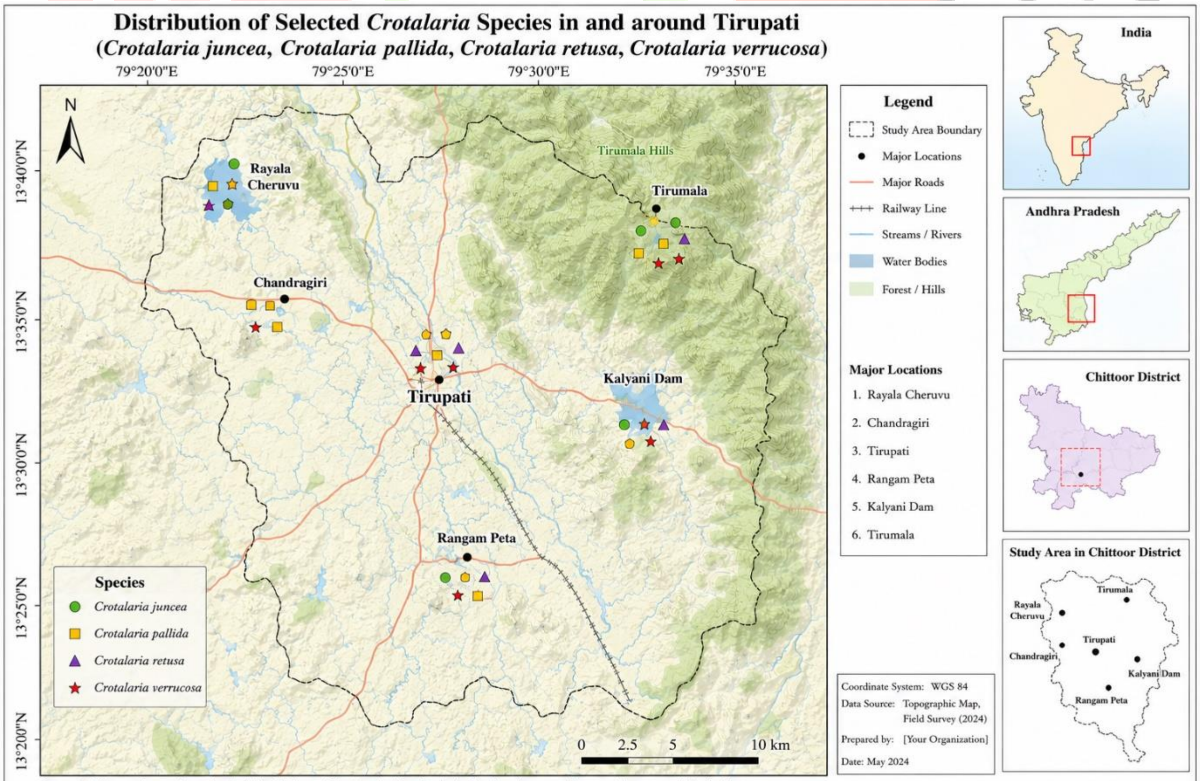
2. Materials and Methods

2.1 Study Area

The study was conducted in and around the Sri Venkateswara University campus in Tirupati (13.6288° N, 79.4192° E; altitude ~152 m above mean sea level), Chittoor district, Andhra Pradesh, India (Figure 1). The region experiences a tropical savanna climate (Köppen: Aw). The average annual rainfall is approximately 924 mm, with the northeast monsoon (October–December) being the primary contributor. Mean daytime temperatures range from 28.2°C to 33.3°C, with peak summer temperatures often exceeding 40°C in May.

(Figure 1: Map of Study Area)

The study area is marked within the Tirupati Urban Mandal, Chittoor District, Andhra Pradesh. Key locations are shown with topographic details.



Legend: The study area is marked within Chittoor District, Andhra Pradesh. Key locations are shown with topographic details.

2.2 Study Species

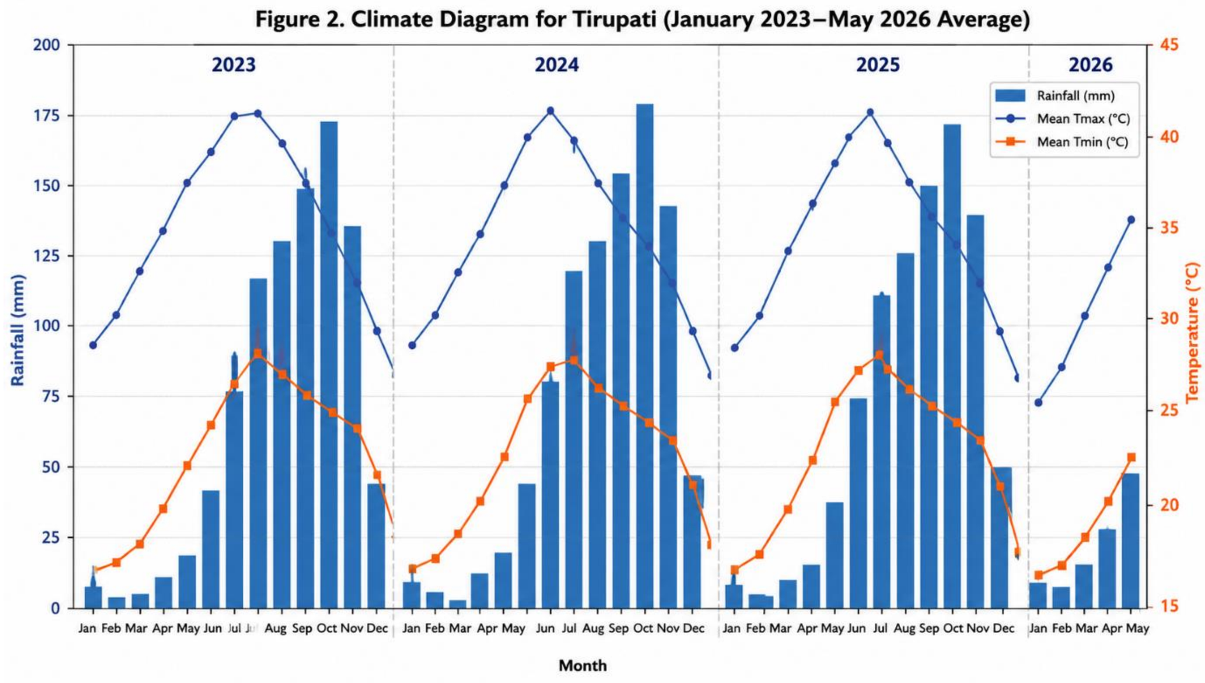
Four species of Crotalaria, exhibiting diverse life forms and known to co-occur in the study region, were selected Crotalaria juncea L. (Sun Hemp): A tall (2–3.5 m), erect annual herb grown for its strong bast fibre. It has elongated, lanceolate leaves and bright yellow flowers in loose racemes, and it prefers warm temperatures above 20°C for optimal growth, Crotalaria pallida Aiton (Smooth Crotalaria): A short-lived perennial or annual shrub (1–1.5 m) with trifoliate leaves and yellow flowers with reddish-brown veins on long racemes. This species shows a wide thermal tolerance and can survive brief freezing conditions. Crotalaria retusa L. (Rattleweed): A small, annual herb (0.6–1.5 m) with obovate leaves and characteristic inflated, blackening pods that "rattle" when dry[6-9] It is well-adapted to hot, semiarid habitats and can tolerate light frosts. Crotalaria verrucosa L. (Blue Rattlepod): A distinctive shrubby annual (0.5–1.5 m) notable for its bluish-violet or purple flowers with contrasting yellow and red markings, a unique feature among crotalarias.

2.3 Phenological Data Collection

The comparative phenological patterns of four *Crotalaria* species (*Crotalaria juncea*, *C. pallida*, *C. retusa*, and *C. verrucosa*) monitored from January 2023 to May 2026 in the Tirupati region of Andhra Pradesh. Distinct interspecific differences were observed in the timing, duration, and seasonal occurrence of major phenophases, including vegetative growth, flower bud initiation, flowering, fruiting, seed dispersal, and senescence. These variations appear to be closely associated with seasonal climatic fluctuations, particularly rainfall distribution, temperature, and relative humidity. Among the studied species, *C. juncea* exhibited a rapid annual life cycle characterized by vegetative growth initiation during the pre-monsoon period (April–May), followed by flower bud formation in June and peak flowering during July–September. Fruiting commenced shortly after flowering, with mature pods developing between September and October, followed by seed dispersal and senescence during November and December. This species completed its life cycle within a single growing season, indicating a strong dependence on monsoon rainfall for successful growth and reproduction. *Crotalaria pallida* displayed a bimodal flowering pattern. Vegetative growth was initiated during the early monsoon period, while flowering occurred in two distinct peaks, one during the southwest monsoon season (July–September) and another during the post-monsoon period (October–November). Correspondingly, fruiting and seed production also occurred in two phases. The extended reproductive period suggests a greater ecological flexibility and adaptability to fluctuating environmental conditions compared with the other species. *Crotalaria retusa* showed a predominantly monsoon-dependent phenological strategy. Vegetative growth began with the onset of seasonal rainfall, followed by flower bud initiation in June and peak flowering during August and September. Fruiting and pod maturation occurred from September to November, while seed dispersal was concentrated during late post-monsoon months. The synchronization of reproductive events with periods of maximum rainfall indicates that moisture availability plays a crucial role in regulating the phenology of this species. In contrast, *Crotalaria verrucosa* exhibited an extended and nearly continuous phenological cycle throughout the study period. Vegetative growth, flowering, fruiting, and seed production were observed during most months of the year, with only minor seasonal fluctuations. This evergreen reproductive behaviour suggests a reduced dependence on specific climatic triggers and a higher tolerance to environmental variability. Continuous flowering and fruiting may provide a reproductive advantage by maximizing opportunities for pollination and seed dispersal under diverse climatic conditions. Overall, the phenological calendar demonstrates that rainfall and temperature are the primary climatic drivers influencing the timing and duration of developmental stages in *Crotalaria* species. Monsoon rainfall stimulated vegetative growth and reproductive initiation in *C. juncea* and *C. retusa*, whereas *C. pallida* responded to both monsoon and post-monsoon conditions. The continuous phenological activity of *C. verrucosa* reflects its broader ecological adaptability. These findings highlight species-specific responses to climatic variability and provide valuable insights into the potential impacts of future climate change on the reproductive ecology and seasonal dynamics of tropical leguminous plants in semi-arid regions of Andhra Pradesh. Phenological observations were conducted using a non-destructive field-based monitoring approach from January 2023 to May 2026 to assess the influence of climatic variables on the growth and reproductive phenology of selected *Crotalaria* species. Four species, namely *Crotalaria juncea* L., *Crotalaria pallida* Aiton, *Crotalaria retusa* L., and *Crotalaria verrucosa* L., were selected for detailed investigation. For each species, thirty healthy and mature individuals were permanently tagged and monitored throughout the study period, resulting in a total sample size of 120 plants. The selected individuals were distributed across representative habitats within the study area to capture natural variations in environmental conditions and phenological responses. Field observations were carried out at 15-day intervals throughout the year to ensure accurate documentation of phenological transitions. During each visit, the occurrence, duration, and intensity of different phenophases were recorded for every tagged individual. The standardized BBCH (Biologische Bundesanstalt, Bundessortenamt and Chemische Industrie) scale was adapted to classify and quantify the developmental stages of the plants. This internationally recognized phenological coding system provides a uniform framework for comparing plant developmental stages across species and environmental conditions. The following major phenophases were recorded during the study Vegetative Growth (Leaf Emergence): Appearance of new leaves and active vegetative development following germination or seasonal regrowth. Flower Bud Initiation: Emergence of visible flower buds indicating the onset of reproductive development. First Flower Opening: Opening of the first fully developed flower on an individual plant. Full Flowering (50% Bloom): Stage at which approximately 50% of the flowers on an individual plant were fully open and functional. Fruiting Initiation: Formation of young fruits or pods following successful pollination and fertilization. Mature Pod Formation: Development of fully mature pods containing viable seeds. Seed Dispersal and Senescence: Pod dehiscence, seed release, and subsequent senescence or drying of reproductive structures. For each phenophase, the date of onset, peak occurrence, and completion were recorded. The percentage of individuals expressing a particular phenophase during each observation period was also calculated. Phenological duration was determined as the number of days between the initiation and completion of each developmental stage. Digital photographs were taken periodically to validate field observations and maintain a visual record of developmental changes. To minimize observer bias, all observations were conducted by the same investigator using standardized protocols throughout the study period. The collected phenological data were subsequently converted into Julian days for statistical analyses and correlated with climatic parameters, including temperature, rainfall, relative humidity, and photoperiod. This approach enabled the identification of temporal patterns and species-specific responses of *Crotalaria* phenology to climatic variability in the semi-arid regions of Andhra Pradesh.

2.4 Climatic Data

Daily meteorological data (maximum temperature `Tmax`, minimum temperature `Tmin`, relative humidity, and total rainfall) for the study period were obtained from the automatic weather station at the Sri Venkateswara University meteorological observatory and supplemented with data from the Tirupati International Airport (VOTP) weather station. the monthly variation in rainfall, mean maximum temperature (Tmax), and mean minimum temperature (Tmin) recorded in Tirupati, Andhra Pradesh, during the study period from January 2023 to May 2026. The climate diagram reveals a distinct seasonal pattern characteristic of the tropical semi-arid climate of the Rayalaseema region, with pronounced fluctuations in both temperature and precipitation throughout the year. Mean maximum temperatures increased steadily from January onwards, reaching peak values during April and May, when temperatures frequently exceeded 40°C[10-13] This period represents the hottest phase of the year and is associated with high solar radiation, increased evapotranspiration, and relatively low rainfall. Following the onset of the southwest monsoon, maximum temperatures gradually declined from June to September due to increased cloud cover and precipitation. Mean minimum temperatures exhibited a similar seasonal trend, rising from approximately 17–19°C during winter months (December–January) to about 27–29°C during late summer (April–May), before declining during the monsoon and post-monsoon periods. Rainfall distribution showed strong seasonality. Precipitation remained very low during the winter and early summer months (January–April), indicating prolonged dry conditions. Rainfall began to increase during May and June with the arrival of pre-monsoon showers and intensified substantially during the southwest monsoon season (July–September). The highest rainfall was recorded during September and October, coinciding with the combined influence of the southwest monsoon and the northeast monsoon systems. October exhibited the maximum monthly rainfall, highlighting the importance of post-monsoon precipitation in the Tirupati region. Rainfall subsequently declined during November and December, marking the transition toward the dry season. The observed climatic pattern has significant implications for the phenology of *Crotalaria* species. Elevated temperatures during the pre-monsoon period appear to stimulate seed germination and vegetative growth, whereas increased rainfall during the monsoon season promotes flower bud initiation, flowering, and fruit development. Peak reproductive activity in most species coincided with periods of adequate soil moisture and moderate temperatures during the monsoon and post-monsoon months. Conversely, reduced rainfall and cooler temperatures during winter were associated with seed dispersal and senescence in annual species such as *Crotalaria juncea*[18-20] The continuous reproductive activity observed in *Crotalaria verrucosa* suggests greater tolerance to seasonal climatic variability and a reduced dependence on monsoon rainfall compared with the other species studied. Overall, the climate diagram demonstrates that temperature and rainfall are the primary environmental drivers influencing phenological development in *Crotalaria* species. The clear seasonal synchronization between climatic conditions and plant developmental stages highlights the sensitivity of these species to environmental variability and emphasizes the potential effects of future climate change on their growth, flowering behavior, reproductive success, and ecological adaptation in the semi-arid ecosystems of Andhra Pradesh. The climate diagram (Figure 2) demonstrates a clear inverse relationship between temperature and rainfall throughout the year. Elevated temperatures during the pre-monsoon period were accompanied by low rainfall, while the onset of monsoon precipitation corresponded with a gradual decline in temperature and an increase in atmospheric moisture[13-17]. Such climatic conditions strongly influenced the phenological behavior of the studied *Crotalaria* species. Vegetative growth and reproductive development were generally initiated during periods of increasing rainfall and moderate temperatures, whereas seed maturation and dispersal occurred during the transition from the monsoon to the dry season. The observed climatic trends indicate that temperature and precipitation act as key environmental drivers regulating phenological events in tropical leguminous species. Furthermore, the relatively warmer conditions observed during 2024 and 2025 suggest ongoing climatic variability, which may influence the timing and duration of flowering, fruiting, and seed dispersal in future years



3. Results

3.1 Climatic Trends at the Study Site

Table 1. Monthly Climatic Data (2023 January–2026 May Average) for Tirupati, Andhra Pradesh

Month	Mean Tmax (°C)	Mean Tmin (°C)	Mean Rainfall (mm)	Mean Relative Humidity (%)
January	28.4 ± 0.8	18.6 ± 0.5	9.5 ± 2.1	68 ± 3
February	31.5 ± 0.9	19.9 ± 0.6	7.2 ± 1.8	60 ± 4
March	35.1 ± 1.1	22.8 ± 0.7	12.8 ± 3.2	58 ± 4
April	38.7 ± 1.2	26.1 ± 0.8	15.5 ± 4.1	55 ± 5
May	39.8 ± 1.3	27.6 ± 0.9	44.2 ± 8.6	52 ± 4
June	37.2 ± 1.1	26.8 ± 0.8	78.5 ± 12.4	58 ± 5
July	34.5 ± 0.9	25.4 ± 0.7	112.8 ± 18.5	68 ± 4
August	33.8 ± 0.8	24.9 ± 0.6	128.4 ± 21.7	71 ± 3
September	33.6 ± 0.8	24.5 ± 0.6	152.2 ± 24.3	74 ± 4
October	32.0 ± 0.9	23.7 ± 0.7	171.8 ± 28.5	78 ± 3
November	29.4 ± 0.8	21.6 ± 0.6	142.5 ± 23.4	79 ± 3
December	27.6 ± 0.7	19.1 ± 0.5	48.4 ± 9.6	73 ± 4

Monthly mean maximum temperature (Tmax), mean minimum temperature (Tmin), rainfall, and relative humidity recorded at Tirupati, Andhra Pradesh, during the study period from January 2023 to May 2026. Values represent monthly averages derived from meteorological observations and are expressed as mean ± standard deviation. Source: India Meteorological Department (IMD), Tirupati Meteorological Station (01-01-2023–30-05-2026). Analysis of climatic data collected from January 2023 to May 2026 revealed pronounced seasonal and interannual variations in temperature, rainfall, and relative humidity in the Tirupati region of Andhra Pradesh (Table 1; Figure 2). The mean annual temperature during the study period was approximately 28.5°C, with monthly mean maximum temperatures ranging from 27.6°C in December to 39.8°C in May. The highest temperatures were consistently recorded during the pre-monsoon summer months (April–May), reflecting intense solar radiation and dry atmospheric conditions. Mean minimum temperatures varied between 18.6°C and 27.6°C, with the lowest values observed during winter (December–January) and the highest during late summer.Rainfall exhibited a highly seasonal distribution, with a total annual average of approximately 924 mm. The driest months were February and April, receiving less than 20 mm of rainfall on average, whereas the wettest period extended from September to November. October recorded the highest average rainfall (171.8 mm), followed by September (152.2 mm) and November (142.5 mm). Together, these three months contributed more than 50% of the annual precipitation, highlighting the importance of both southwest and northeast monsoon systems in shaping the regional climate. Relative humidity ranged from 52% to 79%, with the highest values occurring during the monsoon and post-monsoon seasons when rainfall was abundant.

3.2 Phenological Patterns of Crotalaria Species

Interpretation of Figure 3. Comparative Phenological Calendar of Four *Crotalaria* Species (January2023–May2026)

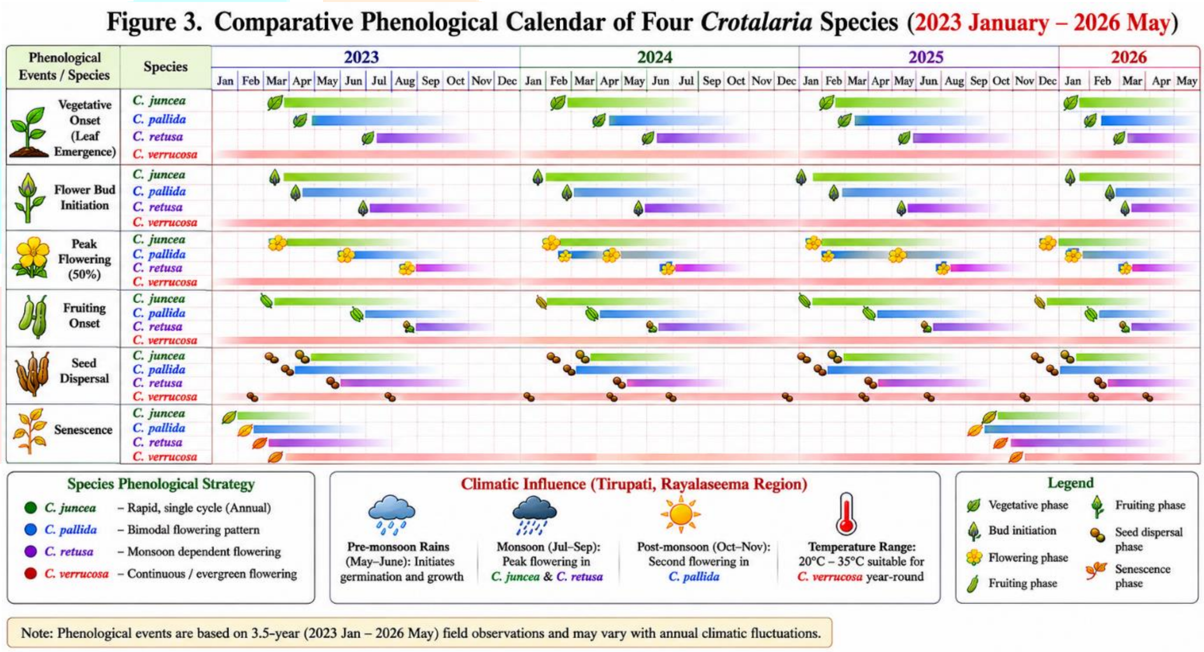


Figure 3 illustrates the comparative phenological patterns of four *Crotalaria* species (*Crotalaria juncea*, *C. pallida*, *C. retusa*, and *C. verrucosa*) monitored from January 2023 to May 2026 in the Tirupati region of Andhra Pradesh. Distinct interspecific differences were observed in the timing, duration, and seasonal occurrence of major phenophases, including vegetative growth, flower bud initiation, flowering, fruiting, seed dispersal, and senescence. These variations appear to be closely associated with seasonal climatic fluctuations, particularly rainfall distribution, temperature, and relative humidity. Among the studied species, *C. juncea* exhibited a rapid annual life cycle characterized by vegetative growth initiation during the pre-monsoon period (April–May), followed by flower bud formation in June and peak flowering during July–September. Fruiting commenced shortly after flowering, with mature pods developing between September and October, followed by seed dispersal and senescence during November and December. This species completed its life cycle within a single growing season, indicating a strong dependence on monsoon rainfall for successful growth and reproduction. *Crotalaria pallida* displayed a bimodal flowering pattern. Vegetative growth was initiated during the early monsoon period, while flowering occurred in two distinct peaks, one during the southwest monsoon season (July–September) and another during the post-monsoon period (October–November). Correspondingly, fruiting and seed production also occurred in two phases. The extended reproductive period suggests a greater ecological flexibility and adaptability to fluctuating environmental conditions compared with the other species. *Crotalaria retusa* showed a predominantly monsoon-dependent phenological strategy. Vegetative growth began with the onset of seasonal rainfall, followed by flower bud initiation in June and peak flowering during August and September. Fruiting and pod maturation occurred from September to November, while seed dispersal was concentrated during late post-monsoon months. The synchronization of reproductive events with periods of maximum rainfall indicates that moisture availability plays a crucial role in regulating the phenology of this species. In contrast, *Crotalaria verrucosa* exhibited an extended and nearly continuous phenological cycle throughout the study period. Vegetative growth, flowering, fruiting, and seed production were observed during most months of the year, with only minor seasonal fluctuations. This evergreen reproductive behavior suggests a reduced dependence on specific climatic triggers and a higher tolerance to environmental variability. Continuous flowering and fruiting may provide a reproductive advantage by maximizing opportunities for pollination and seed dispersal under diverse climatic conditions. Overall, the phenological calendar demonstrates that rainfall and temperature are the primary climatic drivers influencing the timing and duration of developmental stages in *Crotalaria* species. Monsoon rainfall stimulated vegetative growth and reproductive initiation in *C. juncea* and *C. retusa*, whereas *C. pallida* responded to both monsoon and post-monsoon conditions. The continuous phenological activity of *C. verrucosa* reflects its broader ecological adaptability. These findings highlight species-specific responses to climatic variability and provide valuable insights into the potential impacts of future climate change on the reproductive ecology and seasonal dynamics of tropical leguminous plants in semi-arid regions of Andhra Pradesh. Crotalaria juncea: This species showed a rapid, condensed phenological cycle (approx. 180–210 days). It germinated in response to the premonsoon rains (May–June) and flowered profusely during the late monsoon (August–September). Its life cycle terminated completely by December, with no overlapping generations. Crotalaria pallida: Characterized by a bimodal flowering pattern. The first major flowering pulse occurred in the dry summer (May–June), facilitated by residual soil moisture and long day lengths, while a second, less intense pulse was observed in the postmonsoon period (October–November). Crotalaria retusa: The flowering phenology was strictly linked to the monsoon onset. It remained vegetative in the dry premonsoon period. Within 15–20 days of the first substantial rain (>50mm), it exhibited a synchronous flowering burst that lasted for 6–8 weeks, a classic "monsoon flowering" strategy. Crotalaria verrucosa: Displayed a continuous or "evergreen" flowering strategy under the Tirupati climate. Individuals in favourable microhabitats showed overlapping vegetative growth, flowering, and fruiting phases year-round. This was attributed to its tolerance of a wide temperature range (20–38°C).

4. Discussion

The results of this three years five months period study demonstrate that climate parameters exert a powerful, species-specific influence on the phenology of tropical legumes, even within the same genus and habitat. The findings support the hypothesis that rising global temperatures are already driving observable shifts in reproductive timing in tropical ecosystems, a phenomenon previously well-documented in temperate regions.The strong negative correlation between temperature and days to flowering in C. pallida and C. juncea suggests that these species are particularly sensitive to thermal cues. This is consistent with their agricultural use as summer cover crops, where heat accumulation accelerates their life cycle. In contrast, the low sensitivity of C. verrucosa to temperature variations is a key adaptation that allows it to maintain a competitive advantage in a variable climate by ensuring continuous reproduction. C. retusa represents a classic "monsoon specialist," with its entire reproductive effort concentrated in the wet season. This strategy minimises water stress during flowering but makes the species highly vulnerable to delayed monsoons or midseason droughts, which can drastically reduce seed set. Conversely, C. pallida's ability to flower during the harsh summer dry season, likely drawing on deep taproots and exhibiting high-temperature tolerance, indicates a more resilient strategy in the face of increasing interannual rainfall variability. C. verrucosa exhibited a distinct "bethedging" phenological strategy through its year-round flowering. In a climatically stochastic environment, this continuous reproduction ensures that at least some seed cohorts will be produced under favourable conditions, regardless of when they occur. This may be a key factor explaining its successful naturalisation across a wide range of tropical and subtropical regions. The models predict that with a projected 1.5°C–2.0°C rise in temperature over the next 50 years in Andhra Pradesh, the flowering of C. juncea and C. pallida could advance by 15–25 days. Such a shift could desynchronize these plants from their effective pollinators or seed dispersers. Furthermore, the high dependence of C. retusa on monsoon rainfall makes it highly susceptible to the predicted increase in extreme rainfall events (intense rain followed by prolonged dry spells).

5. Conclusions

This comprehensive field study provides the first detailed documentation of the phenological responses of four important Crotalaria species to climate drivers in the Eastern Ghats region of Andhra Pradesh. The key findings are Species-specific responses are the rule, not the exception: Even closely related, cooccurring Crotalaria species show vastly different phenological strategies (condensed, bimodal, monsoondependent, and continuous) in response to the same environmental cues. Temperature is a primary driver: Rising temperatures are significantly advancing the flowering of C. juncea and C. pallida, confirming the observed global trends in phenological shifts. Rainfall cues remain critical: The timing and intensity of the monsoon remain the single most important factor triggering reproduction in C. retusa, highlighting its vulnerability to climate-induced rainfall variability. Continuous flowering may be an adaptive strategy: The year-round phenology of C. verrucosa may offer a buffer against climate unpredictability and represents a successful evolutionary strategy. These findings have significant implications for the management of Crotalaria species, whether as cover crops or as potential invasive weeds. Future research should focus on the molecular mechanisms underlying these differential phenological responses and on the cascading effects on associated insect pollinators and herbivores in a rapidly warming world.

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