# Phenological Responses of Selected Crotalaria Species to Climatic Variability in Tirupati, Andhra Pradesh, India

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***Abstract*—Climate change is causing many plant species, especially in the tropics, to shift their phenological rhythms. The present study analyses the effect of major climatic factors: 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 field study was carried out in the Tirupati region of Andhra Pradesh, India, for a period of three years and five months (2022-2026). Biweekly phenological observations were connected to high-resolution climate data. Results showed species-specific phenological response, C. " verrucosa had the longest length of flowering while C. juncea has a very restricted phenological cycle (180–210 days). High temperature and the arrival of the monsoon were shown to be the key triggers for the initiation of flowering. In all species, rising temperatures were associated with a large shift in flowering dates; C. pallida had the greatest sensitivity. The work provides important baseline data for anticipating the effects of future climate change on tropical legumes and adds to the creation of adaptive conservation measures.**

***Index Terms*—Crotalaria, Phenology, Climate Change, Legumes, Flowering, Tropical Ecology, Andhra Pradesh**

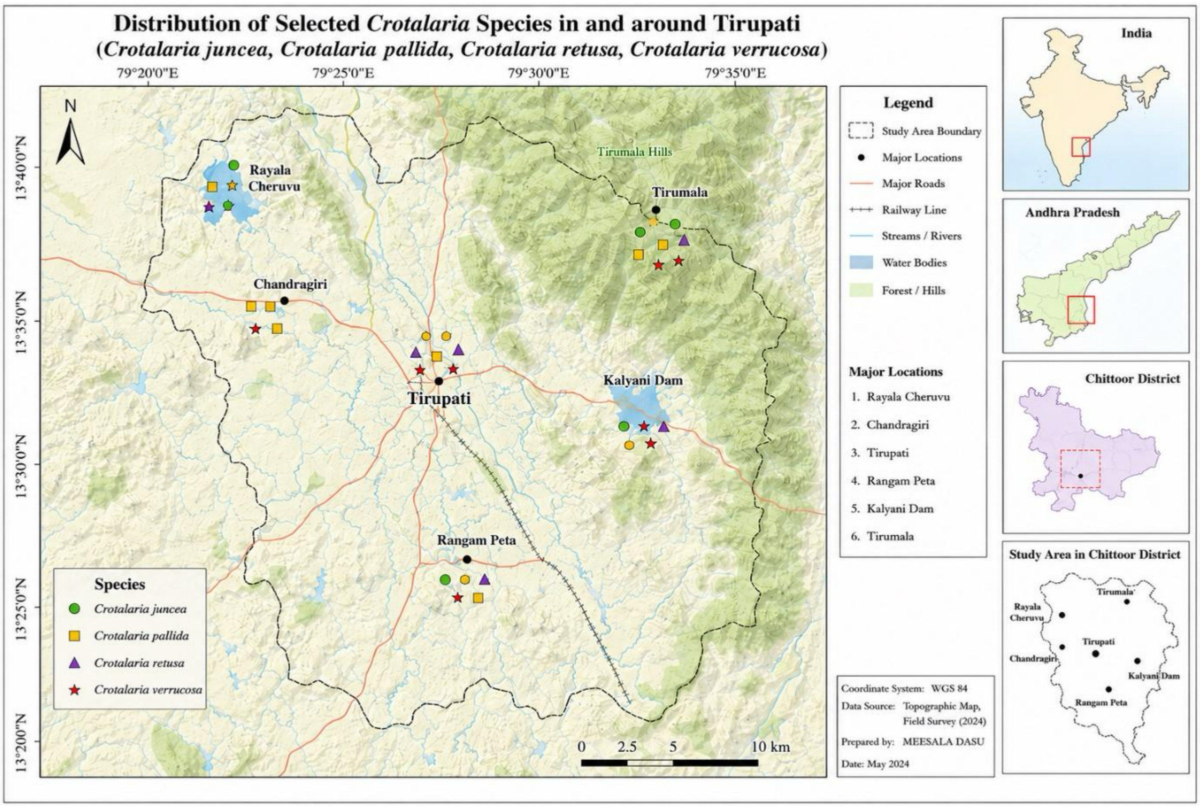
## I. Introduction

Plant phenology, the study of recurrent events in the life cycle of plants, is acknowledged as one of the most sensitive and accurate bioindicators of climate change. Changes in the timing of phenological events such as leaf flushing, flowering and fruiting can cascade through ecosystem functioning, species relationships and agricultural yield. The Intergovernmental Panel on Climate Change (IPCC) points out that tropical regions, albeit warming less than temperate ones, are particularly sensitive to minor climate variations because of the limited temperature tolerance of their biodiversity. Crotalaria L. (Fabaceae) has more than 700 species of herbs and shrubs that occur widely in tropical and subtropical regions of the world. A number of species are ecologically and economically very important, and are utilised as green manure, cover crops, a source of fiber , and in traditional medicine. However, many species of Crotalaria are also known to be invasive or to contain harmful alkaloids therefore a detailed study of their growth and reproductive cycle is important for control. The climate in the Eastern Ghats region of Andhra Pradesh, especially the Tirupati area, is a unique tropical environment with wet and dry seasons. The region has experienced an increased frequency of extreme weather events and rising mean annual temperatures over the last two decades, highlighting a knowledge gap with respect to the response of native and naturalised legume species to these changes. The present study was undertaken to answer the question: How do the fluctuations in temperature, precipitation and relative humidity affect the phenological progress of four selected Crotalaria species in the tropical climate of Tirupati, Andhra Pradesh. The study was done over a period of three years and five months (2022–2026) to capture interannual climate variability and its effects on key phenological phases, giving important information for ecological forecasting and sustainable land management.

## II. Materials and Methods

### 2.1 Study Site

The study area was in and around the campus of Sri Venkateswara University, Tirupati (13.6288° N, 79.4192° E; elevation ~152 m above mean sea level), Chittoor district, Andhra Pradesh, India (Figure 1). The area has a tropical savanna climate (Köppen: Aw). Average annual rainfall is about 924 mm, with the northeast monsoon (October–December) being the main provider. Average daytime temperatures are from 28.2°C to 33.3°C. Summer maximum temperatures are regularly above 40°C in May.(Figure 1. Map of the study area) The research area comes within Tirupati Urban Mandal of Chittoor District, Andhra Pradesh. Topographic detail is given for key places.




(Figure 1)

### 2.2 Studied species

Crotalaria juncea L. of four species with different life styles and known to co-exist in the research region were selected Sun Hemp (Crotalaria juncea): Tall (2–3.5 m), erect annual plant used for its strong bast fibre. It has long lanceolate leaves and bright yellow flowers in loose racemes. It prefers warm temperatures (above 20°C) for optimum 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 has a broad heat tolerance and can withstand short periods of freezing. Crotalaria retusa (Rattleweed) Small annual plant (0.6–1.5 m) with obovate leaves. Characteristic inflated blackening pods that “rattle” when dry. It is highly suited to hot, semi-arid conditions and may endure minor cold. Crotalaria verrucose (Blue Rattlepod): A striking shrubby annual (0.5-1.5 m) with bluish-violet or purple blooms with contrasting yellow and red patterns not found in any other crotalarias.

### 2.3 Collection of phenological data

Comparative phenology of four Crotalaria species (Crotalaria juncea, C. pallida, C. retusa and C. verrucosa) studied during Jan 2023 to May 2026 in the Tirupati region, Andhra Pradesh. Major phenophases, such as vegetative development, flower bud initiation, blooming, fruiting, seed dissemination and senescence, differed greatly in timing, duration and seasonal occurrence amongst species. These variations seem to be directly related to the seasonal climate variations, especially the distribution of rainfall, temperature and relative humidity. Among the examined species, C. juncea has a fast yearly cycle with vegetative growth initiated in pre-monsoon (April–May), flower bud formation in June and peak flowering in July–September. Fruiting began soon after flowering, with ripe pods being formed from September to October, with seed distribution and senescence from November to December. This species was an univoltine, and its life cycle was completed within a growing season, suggesting a high dependence on monsoon rains for successful growth and reproduction. Bimodal flowering was noted in Crotalaria pallida. Vegetative growth was began in the early monsoon period, and flowering occurred in two separate peaks, one in the southwest monsoon season (July-September) and the other in the post-monsoon period (October-November). Therefore, fruiting and seed production likewise took place in two periods. The prolonged reproductive cycle indicates higher ecological flexibility and adaptation to altering environmental conditions compared to the other species. Crotalaria retusa displayed a phenological approach mostly dependent on the monsoon. Vegetative growth commenced with the arrival of seasonal rains, flower bud initiation in June and peak flowering in August and September. Fruiting and pod development were seen throughout September to November, and seed dissemination was concentrated in the late post-monsoon months. The synchrony of reproductive episodes with periods of maximum rainfall suggests that moisture availability is a key factor regulating the phenology of this species. In contrast, Crotalaria verrucosa had a long and almost continuous phenological cycle throughout the research period. Vegetative development, blooming, fruiting and seed production were seen in most months of the year with very modest seasonal variations. Such evergreen reproductive conduct shows a lesser dependency on specific climate cues and a greater tolerance to environmental change. Continuous flowering and fruiting could offer a reproductive advantage by enhancing opportunities for pollination and seed distribution under different environmental circumstances. In conclusion, the phenological calendar shows that rainfall and temperature are the main climatic factors affecting the time and duration of developmental phases in Crotalaria species. Monsoon rains were conducive to vegetative development and reproduction start of C. juncea and C. retusa, whereas C. pallida responded to monsoon and post monsoon conditions. The current phenological activity of C. verrucosa exhibits a greater ecological plasticity. These results indicate the species-specific responses to climatic variability and provide useful insights into the possible consequences of future climate change on the reproductive ecology and seasonal dynamics of tropical leguminous plants in semi-arid parts of Andhra Pradesh. From January 2023 to May 2026, phenological observations were carried out using a non-destructive field-based monitoring approach to investigate the impact of climatic factors on the growth and reproductive phenology of selected Crotalaria species. Out of these four species, viz. Crotalaria juncea L., Crotalaria pallida Aiton, Crotalaria retusa L. and Crotalaria verrucosa L. were selected for detailed examination. A total of 120 plants were sampled. Thirty healthy and mature individuals of each species were permanently tagged and monitored over the study period. The selected individuals were distributed in representative habitats of the research area to reflect natural variability in environmental circumstances and phenological responses. Field observations were done at 15 days interval throughout the year to ensure reliable documentation of phenological shifts. For each visit, the presence, duration and strength of the different phenophases were recorded for each tagged subject. Stages of plant development were classified and quantified on the basis of the BBCH (Biologische Bundesanstalt, Bundessortenamt and Chemische Industrie) scale. This widely accepted system of phenological coding offers a standardized method to compare stages of plant development among species and environmental situations. The study documented the following key phenophases: Vegetative Growth (Leaf Emergence): Appearance of new leaves and active vegetative development after germination or seasonal regeneration. Flower Bud Initiation Visible flower buds appear, signalling the beginning of reproductive growth. First Bloom: The first completely grown bloom to open on an individual plant. Full Flowering (50% Bloom) Stage, when about 50%

of the blooms on an individual plant are fully open and functional. Fruit Initiation: Development of developing fruits or pods as a result of successful pollination and fertilization. Pod Maturity: Development of fully ripe pods bearing viable seed. Seed dispersal and senescence Pod dehiscence, seed release and eventual senescence or desiccation of reproductive organs. The date of beginning, peak and completion of each phenophase was noted. The percentage of individuals with a given phenophase at each time of observation was also computed. Phenological length was estimated as the number of days between the start and end of each developmental stage. Periodic digital images were taken to confirm field findings and to provide a visual record of developmental changes. All observations were performed by the same investigator following similar methods for the whole study period to avoid observer bias. The phenological data acquired were later transformed into Julian days for statistical studies and associated with environmental characteristics including temperature, rainfall, relative humidity and photoperiod. This approach helped in identifying temporal patterns and species-specific responses of Crotalaria phenology to climate variability in the semi-arid regions of Andhra Pradesh.

### 2.4 Climatic Data 2.4.1

Daily meteorological data of maximum temperature (Tmax), minimum temperature (Tmin), relative humidity and total rainfall during the study period were obtained from the automatic weather station at the meteorological observatory of Sri Venkateswara University and were supplemented with data from the Tirupati International Airport (VOTP) weather station. monthly fluctuation 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 shows a definite seasonal trend characteristic of the tropical semi-arid climate of the region of Rayalaseema. There is a considerable variation in temperature and precipitation throughout the year. Mean maximum temperatures grew progressively from January, peaking in April and May when temperatures frequently topped 40°C. This time is the hottest phase of the year and is associated with high solar radiation, enhanced evapotranspiration and relatively low rainfall. After the arrival of the southwest monsoon, the maximum temperature gradually decreased from June to September due to increased cloud cover and precipitation. Mean minimum temperatures showed a similar seasonal tendency, rising from around 17-19°c during the winter months (December-January) to about 27-29°c during late summer (April-May), before dropping throughout the monsoon and post-monsoon seasons. Rainfall was highly seasonal in distribution. Precipitation during the winter and early summer months (January–April) was quite low, indicating protracted dry conditions. Rainfall began to build in May and June with pre-monsoon showers and rose dramatically throughout the southwest monsoon season (July-September). The maximum rainfall occurred during September and October, when the southwest monsoon and the northeast monsoon systems were in combination. October had the largest monthly rainfall and reflects the significance of post-monsoon precipitation in the Tirupati region. Rainfall then dropped in November and December, entering the dry season. The discovered climate pattern has important consequences for the phenology of Crotalaria species. more temperatures during pre-monsoon season appear to boost seed germination and vegetative growth, while more rainfall during monsoon season favours floral bud initiation, blooming and fruit development. In most of the species, the peak reproductive activity coincided with adequate soil moisture and moderate temperatures throughout the monsoon and post-monsoon months. By contrast, low precipitation and low temperature in winter were related to senescence and seed distribution of annual species, such as Crotalaria juncea. The constant reproductive activity of Crotalaria verrucosa shows greater tolerance to seasonal climatic change and less dependence on monsoon rainfall as compared to the other investigated species. In summary, the climate diagram shows that temperature and precipitation are the main environmental factors that influence the phenological development of Crotalaria species. The evident seasonal synchronization between climatic factors and plant developmental stages underscores the susceptibility of these species to environmental variability and underlines the prospective impacts of climate change on their growth, flowering behaviour, reproductive success and ecological adaptation in the semi-arid ecosystems of Andhra Pradesh. The climate diagram (Fig. 2) shows a clear negative link between temperature and rainfall throughout the year. The pre-monsoon period was marked by high temperatures and low rainfall.

The beginning of the monsoon was signified by a steady fall in temperature and increased moisture in the atmosphere. These climatic circumstances have a considerable impact on the phenological behaviour of the examined Crotalaria species. Vegetative growth and reproductive development were often began during periods of rising rainfall and mild temperatures, and seed maturation and dissemination occurred during the transition from monsoon to dry season. The observed climatic trends show that temperature and precipitation are important environmental variables controlling phenological events in tropical leguminous plants. The relatively warm temperatures of 2024 and 2025 also show continuous climate variability that may influence the timing and duration of flowering, fruiting, and seed distribution in future years.

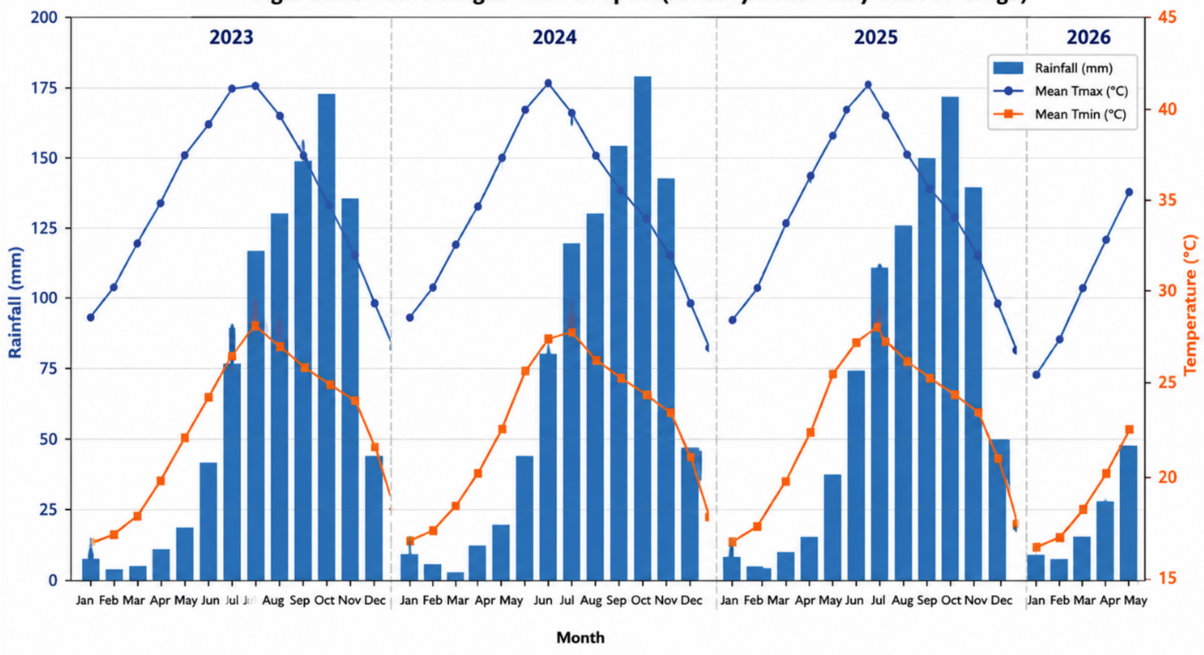



**Figure 2. Climate Diagram for Tirupati (January 2023–May 2026 Average)**

## III. Results

### 3.1 Climate Trends at 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 |

| Month | Mean Tmax (°C) | Mean Tmin (°C) | Mean Rainfall (mm) | Mean Relative Humidity (%) |
|---|---|---|---|---|
| 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 |

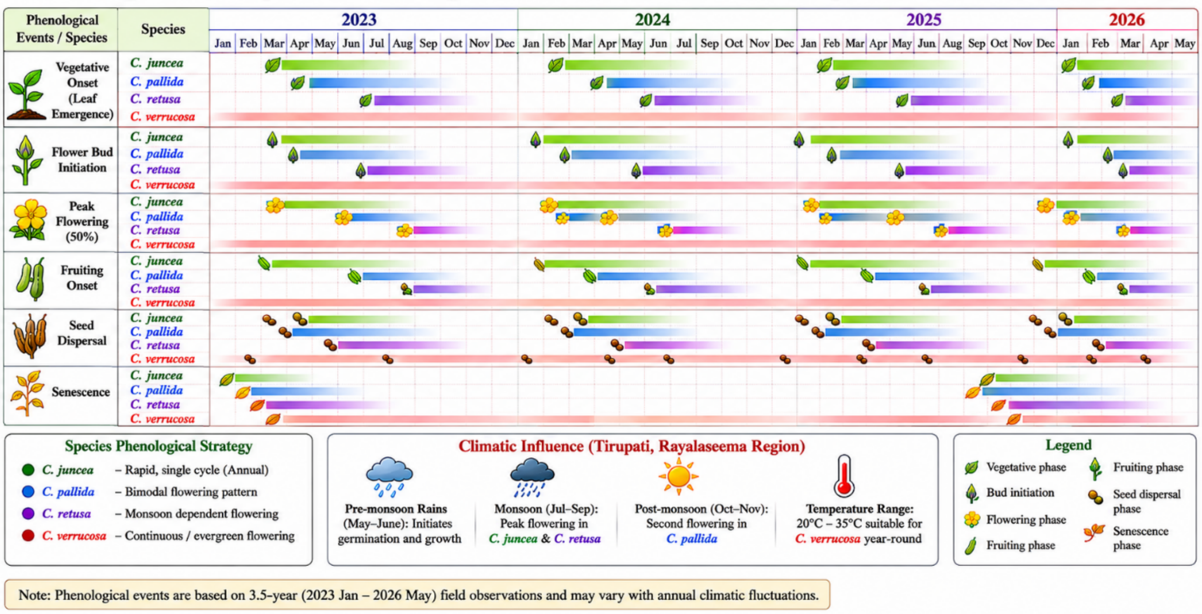
Monthly mean maximum temperature (Tmax), mean minimum temperature (Tmin), rainfall, and relative humidity recorded at Tirupati, Andhra Pradesh, during the study period from January 2023 to May 2026. Values represent monthly averages derived from meteorological observations and are expressed as mean ± 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*

Fig. 3. Interpretation of Comparative Phenological Calendar of Four Crotalaria Species (January 2023-May 2026). The phenological pattern of four Crotalaria species (Crotalaria juncea, C. pallida, C. retusa and C. verrucosa) observed throughout the period of January 2023 to May 2026 in the Tirupati region of Andhra Pradesh is presented in Figure 3. Interspecific differences were found in timing, duration and seasonal occurrence of main phenophases: vegetative growth, flower bud initiation, blooming, fruiting, seed distribution and senescence. These variations seem to be directly related to the seasonal climate variations, especially the distribution of rainfall, temperature and relative humidity. Among the examined species, C. juncea has a fast yearly cycle with vegetative growth initiated in pre-monsoon (April–May), flower bud formation in June and peak flowering in July–September. Fruiting began soon after flowering, with ripe pods being formed from September to October, with seed distribution and senescence from November to December. This species was an univoltine, and its life cycle was completed within a growing season, suggesting a high dependence on monsoon rains for successful growth and reproduction. Bimodal flowering was noted in Crotalaria pallida. Vegetative growth was began in the early monsoon period, and flowering occurred in two separate peaks, one in the southwest monsoon season (July-September) and the other in the post-monsoon period (October-November). Therefore, fruiting and seed production likewise took place in two periods. The prolonged reproductive cycle indicates higher ecological flexibility and adaptation to

altering environmental conditions compared to the other species. Crotalaria retusa displayed a phenological approach mostly dependent on the monsoon. Vegetative growth commenced with the arrival of seasonal rains, flower bud initiation in June and peak flowering in August and September. Fruiting and pod development were seen throughout September to November, and seed dissemination was concentrated in the late post-monsoon months. The synchrony of reproductive episodes with periods of maximum rainfall suggests that moisture availability is a key factor regulating the phenology of this species. In contrast, Crotalaria verrucosa had a long and almost continuous phenological cycle throughout the research period. Vegetative growth, blooming, fruiting and seed production were recorded most months of the year, with only minimal seasonal changes. This evergreen reproductive activity mirrors a reduced dependency on specific climatic cues and an increased tolerance to environmental fluctuation. Continuous flowering and fruiting may provide a reproductive benefit by optimizing opportunities for pollination and seed dissemination under variable environmental circumstances. In conclusion, the phenological calendar shows that rainfall and temperature are the main climatic factors affecting the time and duration of developmental phases in Crotalaria species. Monsoon rains were conducive to vegetative development and reproduction start of C. juncea and C. retusa, whereas C. pallida responded to monsoon and post monsoon conditions. The current phenological activity of C. verrucosa exhibits a greater ecological plasticity. These results emphasize species-specific responses to climatic variability and provide important insights on the possible consequences of future climate change on reproductive ecology and seasonal dynamics of tropical leguminous plants in semi-arid parts of Andhra Pradesh. Crotalaria juncea: This species exhibited a short and condensed phenological cycle (ca. 180–210 days). It came up with the premonsoon rains (May-June) and blossomed profusely in the late monsoon (August-September). Its life cycle was entirely completed by December, and there was no overlap between generations. Crotalaria pallida: Exhibiting a bimodal flowering pattern. The first large flowering pulse occurred during the dry summer (May–June), helped by residual soil moisture and long day length, whereas a second, less powerful pulse was recorded in the postmonsoon period (October–November). Crotalaria retusa: Flowering phenology was strongly associated with the beginning of the monsoon. It was vegetal in the dry pre-monsoon season. Within 15–20 days of the first heavy rain (>50 mm), it produced a simultaneous flush of flowers lasting 6–8 weeks, a classic "monsoon flowering" technique. Crotalaria verrucosa: Demonstrated a perennial or 'evergreen' flowering technique in the Tirupati climate. In suitable microhabitats, vegetative growth, blooming and fruiting periods of individuals overlapped during the year. This was ascribed to its tolerance of a broad temperature range (20-38 °C).

**Figure 3. Comparative Phenological Calendar of Four *Crotalaria* Species (2023 January – 2026 May)**



## IV. Discussion

The results of this three-year and five-month study reveal that climate conditions have a strong and species-specific effect on the phenology of tropical legumes even within the same genus and habitat. The results provide further evidence that increasing global temperatures are already causing detectable changes in reproductive timing in tropical species, a process extensively established in temperate systems. The substantial negative relationship between temperature and days to flowering in C. pallida and C. juncea suggests that these animals have heightened sensitivity to temperature stimuli. This is compatible with their employment as summer cover crops in agriculture, where the accumulation of heat accelerates their life cycle. In comparison, C. has poor sensitivity. verrucosa to changes in temperature is an important adaptation that permits it to maintain a competitive edge in a changing climate through constant reproduction. C. retusa is an example of a “monsoon specialist,” with all reproductive effort concentrated in the rainy season. This technique reduces water stress during flowering, but renders the plant extremely vulnerable to delayed monsoons or midseason droughts, which can cause a severe reduction in seed set. On the other hand, C. The ability of pallida to flower throughout the hard summer dry season, perhaps due to a taproot system and adaptation to high temperatures, suggests a more robust response to the growing interannual variability of rainfall. C. " Verrucosa demonstrated a clear “bet-hedging” phenological strategy blooming throughout the year. In a climatically unpredictable environment, this continuous reproduction ensures that certain cohorts of seeds are created under favourable conditions, whatever the timing. This may be a crucial component in its effective naturalization in a wide range of tropical and subtropical areas. 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 by 15–25 days. Such a change could misalign these plants from their effective pollinators or seed dispersers. Moreover, the high dependency of C. retusa on monsoon rainfall is extremely vulnerable to the projected rise in extreme rainfall events (heavy rain followed by protracted dry periods).

## V. Conclusions

This extensive field study offers the first detailed documentation of the phenological responses of four key Crotalaria species to climate determinants in the Eastern Ghats region of Andhra Pradesh. Main findings: Species-specific responses are the rule, not the exception: even closely related, co-occurring Crotalaria species exhibit dramatically diverse (condensed, bimodal, monsoon-dependent, and continuous) phenological strategies in response to the same environmental signals. Temperature is the main factor: Increasing temperatures are driving the blossoming of C. juncea and C. pallida, consistent with the reported global patterns in phenological transitions. Rainfall cues still matter: The timing and intensity of the monsoon remain the single most essential element triggering reproduction in C. retusa, due to its sensitivity to changes in rainfall associated with climate. Continuous flowering may be an adaptive strategy: The year-round phenology of C. Verrucosa could be an evolutionary triumph, and an insurance policy against climate uncertainty. These results have important implications for managing Crotalaria spp. as cover crops or possible invasive weeds. Future work should investigate the molecular mechanisms driving these divergent phenological responses and the cascading effects on associated insect pollinators and herbivores in a rapidly warming future.

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