

Phenology Study of the Selected *Crotalaria* Species and Pharmacological Values in Andhra Pradesh Region

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Abstract

This study presents a comprehensive analysis of the distribution of the genus *Crotalaria* L. within its natural habitats in the Eastern Ghats region of Andhra Pradesh. Extensive field surveys and systematic observations were carried out across all seasons from 2022 to 2026. The study area was thoroughly explored to document the diversity of *Crotalaria* species, and their phenological characteristics were critically examined throughout the investigation period. A total of 11 species were recorded: *Crotalaria juncea*, *Crotalaria pallida*, *Crotalaria retusa*, *Crotalaria verrucosa*, *Crotalaria prostrata*, *Crotalaria pusilla*, *Crotalaria medicaginea*, *Crotalaria trifolium*, *Crotalaria spectabilis*, *Crotalaria gorensis*, and *Crotalaria lamelliformis*. The findings provide a valuable baseline for further taxonomic characterization and ecological studies of the genus. In addition, this study underscores the importance of phenological traits in species delimitation, taxonomy, and understanding the biological behaviour of *Crotalaria*. The genus holds considerable economic and pharmacological significance: several species, such as *Crotalaria juncea*, are widely cultivated as green manure, fiber crops, and soil improvers due to their nitrogen-fixing ability. Others possess bioactive compounds with documented medicinal properties, including antimicrobial, anti-inflammatory, and hepatoprotective effects. These attributes highlight the broader ecological, agricultural, and therapeutic relevance of the genus, reinforcing the need for its continued study and conservation.

Keywords: Biological, *Crotalaria juncea*, pharmacological, phenology

Introduction

Phenology is a branch of biology that examines how seasonal changes, climate, and living organisms influence one another. The timing of events in plants, such as leafing, budding, flowering, blooming, and fruiting, is closely synchronised with key animal activities, such as moulting, mating, and migration [1-3]. The systematic recording of phenological events across years can be traced to Robert Marsham. Beginning in 1736, he carefully documented the timing of 27 "signs of spring" in southeast England, such as the first leaves appearing on trees and the arrival of the first swallows. Marsham continued these observations until 1797 and regularly shared his findings with the Royal Society. After his death, this practice was carried on by successive generations of his family, extending the record until 1958 and creating an unbroken dataset spanning approximately 222 years. Surprisingly, this represents only a small portion of the longest documented phenological record. That honour goes to the records of cherry-blossom festivals in Kyoto, Japan, whose annual timing has been meticulously reconstructed from court records and personal diaries dating back to 812 AD. After Marsham's era, the 19th and early 20th centuries saw growing scientific interest in phenology, particularly in understanding its relationship with meteorological changes, with contributions from several well-known naturalists.

Crotalaria L. Taxonomic History

The genus *Crotalaria* L. comprises more than 700 species and is widespread in countries of the Old and New Worlds (POWO, 2021), including India, which has 116 taxa [4-8]. The family Fabaceae comprises 147 genera, 805 species, 33 subspecies, 155 varieties, and 14 forms [9]. Within this family, the tribe Crotalariaeae (Benth.) Hutch. Represents the

largest group in the genistoid alliance, encompassing 16 genera and 1,204 species, accounting for approximately 51% of genistoid legumes. The genus *Crotalaria* L. accounts for more than half of the tribe's diversity [10]. *Crotalaria* was originally described by Carolus Linnaeus, who identified 13 species in his *Species Plantarum* [11]. It is represented by 714 species, 107 subspecies, and 78 varieties, and is distributed in tropical and subtropical regions of the world [12, 13].

The common names "Rattlepod" or "Rattlebox" come from the way the seeds behave inside the pod. As the seeds mature, they become loose and produce a rattling sound when the pod is shaken. The name is derived from the Ancient Greek word *krotalon*, meaning "castanet," which is also the root of the word *Crotalus*, the scientific name for rattlesnakes [14]. The genus *Crotalaria* consists of herbaceous or shrubby plants characterised by simple or palmately compound leaves, usually with 3, 5, or 7 leaflets. The flowers are typically yellow and are accompanied by stipules and bracts, which may be small or large.

The calyx is 5-lobed and somewhat two-lipped, with the upper lip divided into two parts and the lower lip into three. The corolla is also differentiated into two lips: the upper lip (labium superior) with two petals and the lower lip (labium inferior) with three petals. The standard petal (vexillum) is orbicular and has a callous base, while the wings (alae) are obovate. The keel (carina) is incurved. The fruit is a legume that may be globose or oblong and is typically inflated. The filaments are united, and the upper portion of the sheath is usually cleft. The legumes are turgid with swollen (ventricose) valves, and the seeds are expanded and kidney-shaped [15].

In plantation systems, the genus *Crotalaria* is widely used as green manure and as a cover crop. It also serves as a nutritious feed source for livestock. Many species within this genus form symbiotic associations with soil Rhizobia, enabling them to fix atmospheric nitrogen. Effective soil fertility management is essential for sustainable crop production, and cover crops like *Crotalaria* contribute significantly by reducing the need for synthetic fertilizers. Given these important roles, it is valuable to document and describe all phenophases of *Crotalaria* species. Such characterization supports their taxonomic identification and helps in understanding variations influenced by climate and environmental changes over time [14].

Crotalaria juncea is one of the most prominent species within the genus, while several other species are widely utilized in traditional medicine for the treatment of various ailments. For example, the roots of *C. albida* and *C. trifoliatum* are known for their purgative properties, whereas the leaves of *C. verrucosa* and *C. retusa* are commonly used to treat skin conditions such as scabies and impetigo. Additionally, the roots of *C. prostrata* are employed in the management of diarrhoea. Overall, the *Crotalaria* genus demonstrates considerable medicinal potential [16, 17].

Several species of *Crotalaria* are currently cultivated for desirable traits that are not directly associated with human consumption. Among them, *Crotalaria juncea*, commonly known as sun hemp, is widely grown across tropical and subtropical regions as a source of green manure, lightweight fiber, and fodder. In addition, *C. juncea* has attracted increasing attention as a promising feedstock for the production of cellulosic ethanol, contributing to its potential use in biofuel development [18,19]. Many *Crotalaria* species are known to form nodules with soil Rhizobia, enabling them to fix atmospheric nitrogen. This characteristic plays an important role in improving soil fertility, which is essential for sustainable crop production. As cover crops, *Crotalaria* species contribute significantly to soil health by reducing the need for synthetic fertilizers [14]. Given their ecological and agricultural importance, it is worthwhile to document their phenophases, as these form the basis for taxonomic description and characterization. Furthermore, phenological observations help in understanding variations in growth and development in response to climatic and environmental changes over different periods.

Materials and Methods

Study Area

A detailed phenological study of *Crotalaria* species was conducted across different forest types during the period from January 2022 to January 2026. The Seshachalam hill ranges are located in parts of the Cuddapah (now Kadapa) and Chittoor districts of Andhra Pradesh, India. These ranges are particularly prominent in the Cuddapah district, extending between 13°43' to 13°55' N latitude and 79°08' to 79°24' E longitude. The region is predominantly characterized by tropical southern dry mixed deciduous forest, as classified by Champion and Seth [20]. Extensive field visits were carried

out across different seasons (summer, monsoon, post-monsoon, and winter) to document the flowering and fruiting stages of the species. Data on habit, habitat, phenology, and other relevant characteristics were systematically recorded.

Plant Collection and Identification

Crotalaria species were collected from two taluks of Chittoor district for detailed phenological observations. The species studied include *Crotalaria juncea* L., *Crotalaria pallida* L., and *Crotalaria verrucosa* L. All plant specimens were identified with the help of regional floras, monographs on legumes [2,9,21], and published biodiversity checklists.

Phenophase Monitoring

Periodic field visits were conducted to record changes in the phenophases of *Crotalaria* species, and photographs (Fig. 1) were taken at each stage during these visits. The plants were collected from their natural habitats and maintained in the net house of Sri Venkateswara Science College, Sri Venkateswara University, Tirupati, for further observation; when live specimens were not available, seeds were used.

The recorded parameters were categorized into two groups: vegetative and reproductive characters. The vegetative phase included the leafing period, while the reproductive phase comprised the flowering and fruiting stages of the plants [22]. Herbarium specimens were prepared following standard procedures, and the preserved specimens are housed in the herbarium of Sri Venkateswara Science College, Tirupati, Andhra Pradesh.

Results and Discussion

Ethnobotanical and Pharmacological Significance

Crotalaria species are widely used in veterinary and traditional medicine for treating a variety of conditions. They are commonly employed to manage liver disorders [23], snake bites, skin infections, and stomach aches [24]. In addition to their medicinal value, these plants serve as an important livestock feed, act as green manure [25], and provide protective ground cover in plantations. Certain species have specialized uses: *Crotalaria comosa* is utilized in Tanzania for controlling weeds and nematodes [26], while *Crotalaria recta* serves as a food source for Lepidoptera larvae, which also use the plant for defense against predators [27]. The roots and leaves of *Crotalaria verrucosa*, *Crotalaria spectabilis*, and *Crotalaria retusa* are used to treat skin conditions such as scabies and impetigo [28]. Other species also have notable applications. The roots of *Crotalaria prostrata* are valued for their cooling properties and are used in treating leucorrhoea, blood purification, skin ailments, stomach aches, and infantile diarrhoea [29]. *Crotalaria calycina* is used for wound healing, treating spider mite infestations, and dysentery. Leaves and branches of *Crotalaria burhia* are used as a traditional cooling remedy, while *Crotalaria pallida* are applied in cases of dropsy. A paste of *Crotalaria spectabilis* is used to relieve rheumatism, and the roots of *Crotalaria alata* are used to treat blood discharge in urine [30].

Crotalaria retusa is widely used as a green manure and fiber crop and is sometimes grown as forage [31]. Species of the *Crotalaria* genus form root nodules in association with soil Rhizobia, enabling them to fix atmospheric nitrogen [32]. This process reduces dependence on synthetic nitrogen fertilizers and improves soil fertility. Root nodules, a key feature of legumes, support the accumulation of biomass through nitrogen fixation and enhance both organic matter and nutrient content in the soil. While several *Crotalaria* species are toxic, others, such as *Crotalaria retusa*, *Crotalaria micronata*, *Crotalaria falcata*, and *Crotalaria vogelii*, are beneficial and used as fodder for cattle and other ruminants. In regions like Nigeria and Zaria, these plants are commonly utilized for feeding sheep and cattle [33]. Additionally, some species, including *Crotalaria juncea*, *Crotalaria retusa*, *Crotalaria tetragona*, and *Crotalaria micans*, are consumed as vegetables [34].

All recognized species are economically significant, as they contain alkaloids and serve multiple uses [35]. Their seeds are valuable sources of fiber, silage, and green manure, and oil can also be extracted from certain species [36]. Therefore, it was considered worthwhile to extend phenological observations of this taxon in the study area. The present investigation provides a detailed account of phenophases such as leafing, flowering, fruiting, and leaf fall occurring throughout the year.

Species Diversity and Growth Forms

In the present study, a total of 11 species were documented from the study area. As shown in Fig. 5, among these, six species were herbaceous, and five were under shrubs, representing approximately 1.5% and 11.8% of the total herbaceous and undershrub species of *Crotalaria* reported in India, respectively. Some *Crotalaria* species are habitat-specific and occur rarely in India. *Crotalaria globosa* Wight & Arn., endemic to Tamil Nadu, is reported as a rare species. Similarly, *Crotalaria pusilla* Roxb. ex-Wight & Arn., which grows in rocky and sandy habitats, is endemic to southern peninsular India.

Leafing (Vegetative Phase)

The study reveals variations in leafing patterns among species. *C. hebecarpa* and *C. prostrata* initiate leafing in June, continuing until July. Three species - *C. juncea*, *C. pallida*, and *C. verrucosa* - begin leafing in July and extend into August. *C. calycina* shows leafing from August to September, while the rare species *C. globosa* initiates leaf production from October to November. In *C. gorensis* and *C. orixensis*, germination and leaf production occur between September and October. *C. pusilla*, typically found in mineral-rich soils, begins leafing in August, whereas *C. retusa* exhibits leafing from August to September.

The peak period of leafing was observed in August. Overall, the leafing period varies considerably among species in the study area, as illustrated in Fig. 2. These variations reflect phenological plasticity, likely influenced by seasonal and environmental changes, which in turn affect photosynthetic activity.

Reproductive Phase (Flowering and Fruiting)

The reproductive phase is a crucial stage in the plant life cycle, as it directly contributes to the continuation of a species. This phase is characterized by flowering and fruiting, which occur sequentially. In the known species of *Crotalaria*, the flowering period generally begins in July and continues until December. Although these plants belong to the same genus, they exhibit considerable variability across all phenophases, as shown in Table 1. For example, in *C. hebecarpa*, flowering occurs from July to September, while *C. Pusilla* and *C. Prostrata* show different flowering patterns. Flowering and fruiting in *Crotalaria* species show clear seasonal variation. These phases can be observed beginning in August and continuing through September in several species. In some species, such as *Crotalaria juncea*, *Crotalaria pallida*, and *Crotalaria verrucosa*, the flowering and fruiting period extends from September to November. Other species, including *Crotalaria calycina* and *Crotalaria retusa*, exhibit flowering during October to November, while in *Crotalaria orixensis* the period extends from October to December. A few species, such as *Crotalaria globosa* and *Crotalaria gorensis*, flower and fruit during the winter season, particularly from November to December.

Overall, the highest number of species (eight) was recorded flowering and fruiting in November, followed by September with six species. In contrast, three species each were observed flowering and fruiting in August, October, and December, while only one species showed these phases in July. This indicates that November represents the peak period of flowering and fruiting among *Crotalaria* species in the study area (Fig. 3). Such variation in phenological patterns within the genus highlights differences in reproductive timing and provides valuable insights into the floral biology and ecological adaptation of these species.

Leaf Fall (Senescent Phase)

The reproductive phase in *Crotalaria* is typically followed by a senescent phase marked by defoliation. Leaf fall generally begins immediately after the completion of fruiting. Similar to the variability observed in leafing and reproductive phases, the timing of defoliation also varies among species, as shown in Table 1.

In *Crotalaria calycina* and *Crotalaria retusa*, defoliation begins in November and continues until December. In contrast, *Crotalaria pusilla*, an ephemeral herb, completes its life cycle soon after the reproductive phase, with leaf fall occurring as early as September. In several species, including *Crotalaria globosa*, *Crotalaria juncea*, *Crotalaria pallida*, and *Crotalaria verrucosa*, leaf fall is observed from December to January. However, in *Crotalaria orixensis*, defoliation starts in December and extends up to February.

Early leaf fall is recorded in *Crotalaria hebecarpa* (September-October), while *Crotalaria prostrata* shows defoliation from October to December. In *Crotalaria goreensis*, leaf fall occurs after winter, from January to February.

Overall, the highest number of species (seven) exhibit defoliation in December, followed by six species in January. In comparison, only two species each show defoliation during February, September, October, and November (Fig. 4). This clearly indicates that the peak period of defoliation in *Crotalaria* species occurs during the late winter season, particularly in December and January, indicating that most members of the genus complete their life cycle during this period.

Ecological and Taxonomic Insights

The current study clearly demonstrates the seasonal occurrence of different phenophases, which provides valuable taxonomic insights. As *Crotalaria* species are well known for their nitrogen-fixing ability, they play an important role in improving soil fertility. Some species are cultivated for various purposes, while others occur as weeds in plantations; however, even these contribute positively by enhancing crop yield. These findings may be useful for farmers in selecting cropping seasons that align with the growth cycles of *Crotalaria* species.

Although all eleven species were recorded from the same geographical region, they do not exhibit identical phenophase timings. This variation may represent an adaptive strategy that allows them to coexist without direct competition. Minor variations in phenophase timing were also observed during the study period, but these were not significant enough to be recorded, possibly due to the influence of human activities on the environment, particularly affecting plant life cycles.

Pharmacological Values of the *Crotalaria* Species

Pyrrolizidine alkaloids are significant secondary metabolites known for their diverse biological activities, including teratogenic, carcinogenic, anticancer, mutagenic, acute hepatotoxic [37-41], and neuroactive effects [42]. These nitrogen-containing compounds are biosynthesized from ornithine, an intermediate in arginine metabolism, and undergo microsomal bioactivation to form pyrrolic metabolites responsible for cytotoxicity.

Pyrrolizidine alkaloids, along with non-protein amino acids, are present in *Crotalaria* seeds [43, 44]. These compounds contribute to the seeds' unpalatability and play a role in the biosynthesis of sexual signalling mechanisms in *Utetheisa ornatrix* [45, 46]. In mammals, they exhibit hepatotoxic effects, while in ecological systems, they participate in plant-animal interactions [47]. Additionally, their distribution across plant families, subfamilies, and infrageneric groups makes them useful as chemotaxonomic markers.

Numerous studies have investigated the biological effects of *Crotalaria* species, with careful consideration of scientific parameters such as dosage, duration, route of administration, evaluation criteria, and statistical methodologies.

Antimicrobial activity has been reported in numerous *Crotalaria* species, including *C. bernieri* [48], *C. ferruginea* [49], *C. grahamiana* [50], *C. incana* subsp. *Purpurascens* [51], *C. juncea* L. [52], *C. lachnophora* [53], *C. lachnosema* [54], *C. longirostrata* [55], *C. madurensis* [56], *C. medicaginea*, *C. prostrata*, *C. retusa* [57], *C. pallida* [58], *C. pulchra* [59], *C. quartiniana* [60], and *C. verrucosa* L [61].

Peptide and protein extracts from *C. pallida* demonstrated antimicrobial activity against *Escherichia coli* and *Staphylococcus aureus* [62]. Similarly, leaf and root extracts of *C. brevidens* showed strong inhibitory effects against *E. coli* at a concentration of 37.5 mg/mL [63]. Among the species studied in the wild, *C. retusa* exhibited the most potent antibacterial activity, with a zone of inhibition measuring 13.83 ± 0.33 mm against *Pseudomonas aeruginosa* [64].

Additionally, ether and ethyl acetate extracts of *C. madurensis* var. *kurnoolica* displayed broad-spectrum antibacterial activity against various human pathogenic microorganisms [65]. Extracts from the leaves, stems, and roots of *C. sessiflora* also showed significant antimicrobial effects, particularly against *Pseudomonas fluorescens* [66].

Conclusions

The study area supports a rich diversity of *Crotalaria* species, which exhibit considerable variability in their phenophases. These variations appear to be naturally selected, enabling the species to adapt successfully to local environmental conditions. Understanding vegetation through Plant Functional Types (PFTs) is particularly important in the context of increasing global concerns over deforestation and forest fragmentation caused by human activities. Human interference is evident in the study area, highlighting the urgent need for conservation measures. In addition to anthropogenic pressures, environmental factors such as climate and seasonal variations also influence phenophases, often leading to reduced plant productivity and affecting the survival and yield of associated species. Therefore, it is essential to develop effective conservation strategies for these *Crotalaria* species, as they hold significant ecological and economic importance. Protecting them will help maintain biodiversity and ensure ecological balance within the region.



Fig. 1. A. *Crotalaria juncea* B. Leaf C. *Crotalaria retusa* D. *Crotalaria verrucosa* E.

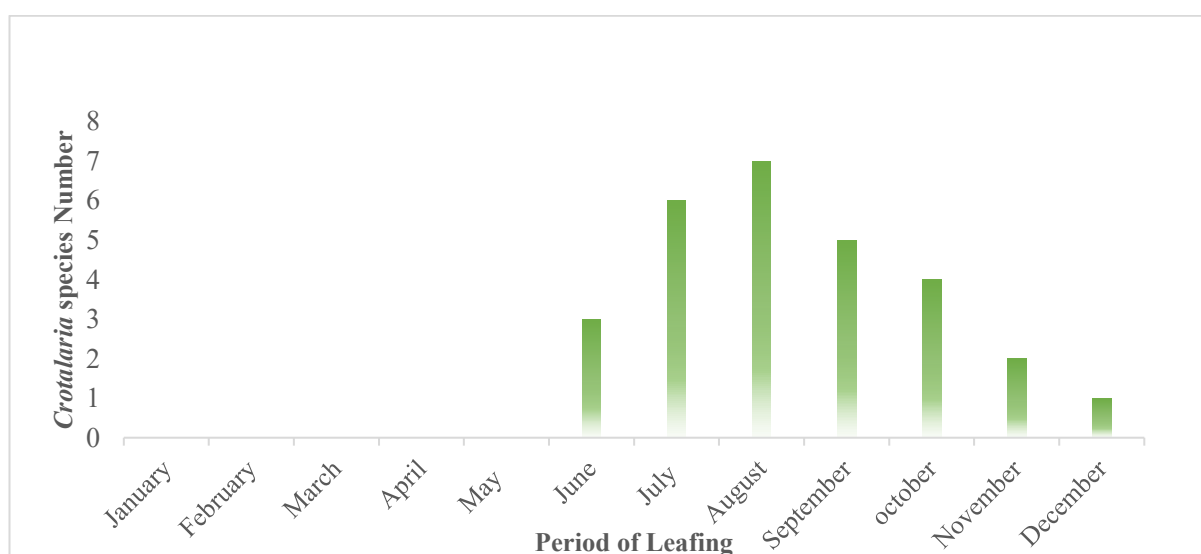


Fig.2 *Crotalaria* L Leafing Period

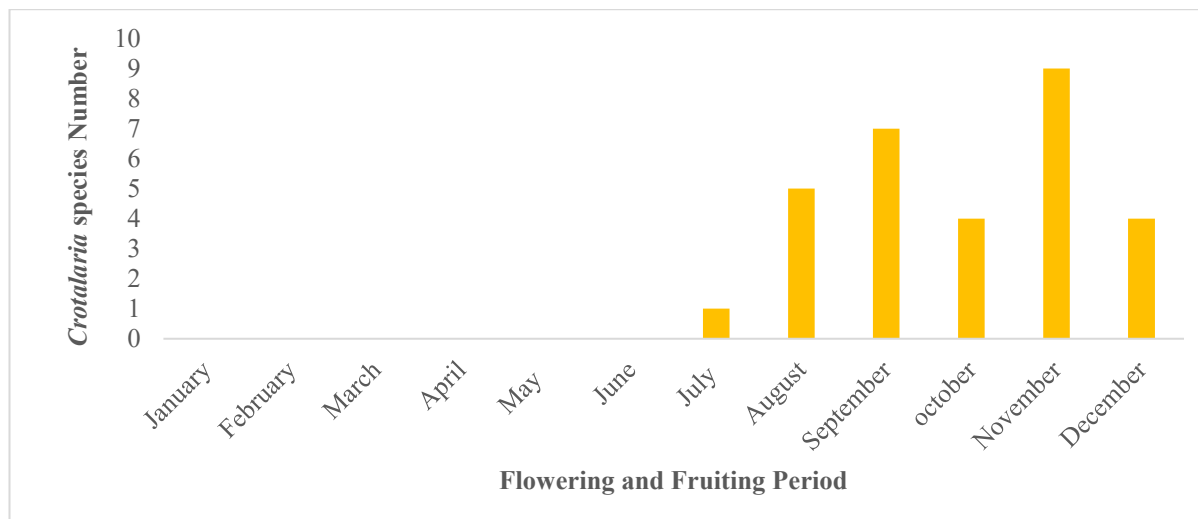


Fig.3 Crotalaria L Flowering and Fruiting Period

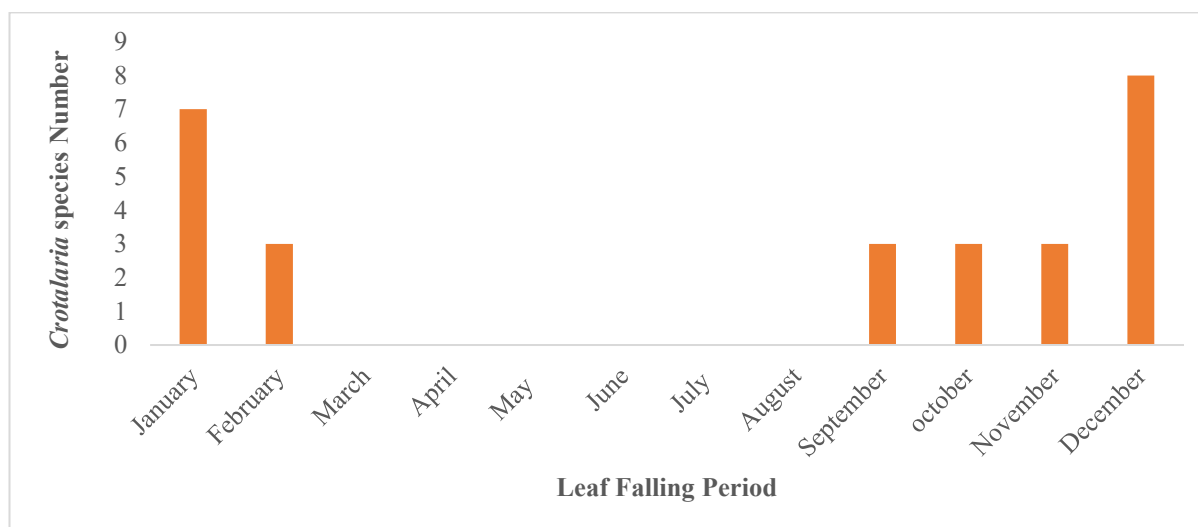


Fig 4. Crotalaria L Leaf Falling Period

Table No. 1 Phenology, Economic and Pharmacological Importance of Crotalaria Species (Andhra Pradesh Region)								
S. No	Species	Native / Distribution (A.P. context)	Habit	Flower ing	Fruit ing	Leaf Fall	Economic Value	Pharmacolo gical Value
1	Crotalaria juncea	Native to India; widely cultivated in Andhra Pradesh	Erect herb	Jul-Oct	Aug-Nov	Nov-Dec	Fiber (sunn hemp), green manure, soil fertility	Antimicrobia l, anti-inflammatory

2	<i>Crotalaria pallida</i>	Naturalized in India, common in the A.P. plains	Shrub	Aug-Nov	Sep-Dec	Dec-Jan	Green manure, fodder	Anti-inflammatory, antimicrobial, antifungal, antioxidant
3	<i>Crotalaria retusa</i>	Tropical regions are common in South India	Herb	Jul-Nov	Aug-Dec	Dec-Jan	Fodder, soil improvement	Used for skin diseases, antibacterial
4	<i>Crotalaria verrucosa</i>	Native to tropical Asia; found in the Eastern Ghats	Shrub	Aug-Dec	Sep-Jan	Jan-Feb	Ornamental, medicinal	Anti-inflammatory, cytotoxic, antioxidant
5	<i>Crotalaria prostrata</i>	Peninsular India (including A.P.)	Prostrate herb	Aug-Nov	Sep-Dec	Dec-Jan	Soil binder, erosion control	Antidiarrheal (root use)
6	<i>Crotalaria pusilla</i>	Common in the dry regions of Andhra Pradesh	Prostrate herb	Aug-Oct	Sep-Nov	Nov-Dec	Fodder, ground cover	Limited reports (traditional use)
7	<i>Crotalaria medicaginea</i>	India & Africa, found in the Deccan plateau	Herb	Jul-Sep	Aug-Oct	Oct-Nov	Fodder, nitrogen fixation	Antimicrobial, antioxidant
8	<i>Crotalaria trifoliatrum</i>	Native to India, the Eastern Ghats	Herb	Jul-Oct	Aug-Nov	Nov-Dec	Soil fertility improvement	Purgative, antimicrobial
9	<i>Crotalaria spectabilis</i>	Introduced; cultivated occasionally	Herb	Aug-Nov	Sep-Dec	Dec-Jan	Green manure (toxic)	Contains monocrotaline (cytotoxic)
10	<i>Crotalaria goreensis</i>	African origin; naturalized in India	Herb	Jul-Sep	Aug-Oct	Oct-Nov	Soil stabilization	Limited pharmacological data
11	<i>Crotalaria lamelliformis</i>	Endemic to the Eastern Ghats, Andhra Pradesh	Herb	Aug-Oct*	Sep-Nov*	Nov-Dec*	Ecological importance (endemic species)	Not yet explored

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Authors' Contribution

M. Dasu, S. Sushmitha, and K. Gangi Naidu carried out field exploration, collection, herbarium preparation, identification, herbarium consultation, photography, and manuscript writing. J. Kamakshamma guided data interpretation and manuscript writing. All authors have read and approved the manuscript.

Compliance with Ethical Standards

Conflict of interest: The authors have no conflicts of interest to declare.

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