

Impact of Rising Temperature and Erratic Rainfall on Phenology of Local Medicinal Plants in Haryana

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Abstract

Climate change is exerting profound effects on ecosystems worldwide, altering temperature patterns, precipitation regimes, and seasonal cycles. In Haryana, India, these changes are particularly consequential for medicinal plants such as *Withania somnifera* (Ashwagandha), *Aloe vera*, and *Ocimum sanctum* (Tulsi), which hold significant cultural, therapeutic, and economic value. Rising temperatures and erratic rainfall have been observed to disrupt the natural timing of critical phenological events, including flowering, fruiting, and seed dispersal. Such disruptions not only affect plant survival and reproductive success but also have cascading impacts on biodiversity, pollinator interactions, and ecological balance.

This study investigates the influence of climate variability on the phenology of selected medicinal plants in Haryana over the past decade. Data were collected from field observations, agricultural universities, local herbal farms, and meteorological records, focusing on changes in flowering onset, fruiting duration, and seed maturation. Statistical analyses were performed to correlate phenological shifts with climatic parameters such as temperature fluctuations and rainfall irregularities.

Findings indicate that *Withania somnifera* exhibits earlier flowering and shortened fruiting periods due to increased early-summer temperatures, while *Aloe vera* shows irregular reproductive cycles and dominance of vegetative growth under prolonged drought conditions. *Ocimum sanctum* demonstrates an extended flowering period but suffers from flower drop and reduced seed viability during extreme heat and erratic rainfall events. These phenological shifts have direct implications for the quality and quantity of bioactive compounds, affecting medicinal potency, yield, and economic returns for cultivators.

The study underscores the urgency of monitoring phenological responses in medicinal plants as indicators of ecological stress and climate adaptation. Understanding these shifts can inform climate-resilient agricultural practices, sustainable harvesting schedules, and conservation strategies for culturally and medicinally important plant species. By linking climate variability to plant phenology, this research provides critical insights into managing the impacts of global climate change on local biodiversity and livelihoods in Haryana.

Keywords: Phenology, Climate Change, Medicinal Plants, Haryana, *Withania somnifera*, *Aloe vera*, *Ocimum sanctum*, Flowering, Fruiting, Rainfall Variability

1. Introduction

Phenology—the study of cyclic events in plant life such as flowering, fruiting, and seed dispersal—is one of the most sensitive indicators of climate change. Shifts in temperature and rainfall influence plant growth, pollinator interactions, and seed viability. In Haryana, climate change has been marked by rising average temperatures, declining winter rainfall, and erratic monsoon distribution [1], [2]. These trends directly affect native and cultivated medicinal plants, many of which are integral to Ayurveda and local traditional medicine.

Medicinal plants like *Withania somnifera*, *Aloe vera*, and *Ocimum sanctum* are widely cultivated in Haryana's semi-arid to sub-humid regions. Changes in their phenology could impact not only ecological processes but also the yield and quality of bioactive compounds that are crucial for medicinal use [3], [4].

2. Climate Trends in Haryana

Haryana, located in northern India, has experienced significant climatic changes over the past few decades. The state has witnessed a rise in average temperatures, particularly during the summer months, leading to increased evapotranspiration and altered soil moisture regimes [1], [2]. Additionally, the region has experienced a decline in winter rainfall and erratic monsoon distribution, characterized by delayed onset, uneven intensity, and early withdrawal. These climatic shifts have profound implications for agricultural practices and the phenology of crops, including medicinal plants [2], [3].

3. Medicinal Plants in Haryana

Withania somnifera (Ashwagandha), *Aloe vera*, and *Ocimum sanctum* (Tulsi) are among the most widely cultivated medicinal plants in

Haryana. These species are integral to traditional medicine systems like Ayurveda and have significant economic value due to their therapeutic properties [4], [5].

- *Withania somnifera*: Known for its adaptogenic properties, Ashwagandha is used to enhance stamina, reduce stress, and improve overall health. It thrives in semi-arid climates and is sensitive to temperature variations and water availability [2], [5].

- *Aloe vera*: This succulent plant is renowned for its skin-healing properties and is widely used in cosmetics and pharmaceuticals. *Aloe vera*'s growth and bioactive compound production are influenced by temperature and water stress [1], [4].

- *Ocimum sanctum*: Commonly known as Tulsi or Holy Basil, this aromatic herb is revered for its medicinal properties, including anti-inflammatory and immunomodulatory effects. Its growth and chemical composition are affected by climatic factors [3], [6].

4. Phenological Shifts Due to Climate Variability

Climate variability has led to observable changes in the phenology of these medicinal plants in Haryana:

- *Withania somnifera*: Studies indicate that rising temperatures have led to earlier flowering and fruiting in Ashwagandha. However, erratic rainfall patterns have resulted in reduced seed yield and compromised root quality, affecting the plant's medicinal efficacy [2], [5].

- *Aloe vera*: Prolonged drought conditions and temperature fluctuations influence *Aloe vera* growth patterns, leading to reduced gel content and altered phytochemical profiles, impacting its therapeutic properties [1], [4].

- *Ocimum sanctum*: The extended flowering period observed in Tulsi due to rising temperatures has been associated with flower

drop and reduced seed viability. Additionally, erratic rainfall events have led to fluctuations in essential oil concentrations, affecting the plant's medicinal potency [3], [6].

5. Ecological and Economic Implications

The phenological changes in these medicinal plants have far-reaching ecological and economic implications:

- **Biodiversity:** Altered flowering and fruiting times can disrupt plant-pollinator interactions, reducing seed set and genetic diversity [2], [3].
- **Agricultural Productivity:** Farmers cultivating medicinal plants may experience inconsistent yields and quality due to climatic stresses, leading to economic losses and challenges in meeting market demands [4], [5].
- **Medicinal Quality:** The concentration of bioactive compounds in medicinal plants is regulated by environmental factors. Climate-induced stress can lead to variations in these compounds, affecting the therapeutic efficacy of the plants [1], [6].

6. Research Objectives

This study aims to:

- Assess the impact of rising temperatures and erratic rainfall on the phenology of *Withania somnifera*, *Aloe vera*, and *Ocimum sanctum* in Haryana [1], [2].
- Examine the correlation between climatic variables and changes in flowering, fruiting, and seed dispersal patterns [3], [4].
- Evaluate the implications of these phenological shifts on biodiversity, agricultural productivity, and medicinal quality [5], [6].

7. Literature Review

7.1 Biodiversity and Ecosystem Services

Climate change has significantly impacted plant-pollinator interactions, which are crucial for maintaining biodiversity and ecosystem services. Shifts in the phenology of plants and their pollinators due to climate change can lead to mismatches in their life cycles, disrupting mutualistic relationships. For example, earlier flowering times in plants may not coincide with the availability of pollinators, leading to reduced pollination success and lower seed production. Such disruptions can affect the stability and resilience of ecosystems that depend on these interactions [7].

High levels of biodiversity can buffer the negative effects of phenological shifts. Diverse plant communities may provide alternative resources for pollinators, helping to maintain pollination services even when specific plant-pollinator interactions are disrupted. This concept, known as the biodiversity insurance hypothesis, suggests that biodiversity enhances and stabilizes phenological synchrony between plants and their pollinators [8].

7.2 Medicinal Quality

The concentration of secondary metabolites in medicinal plants, such as withanolides in *Withania somnifera* and essential oils in *Ocimum sanctum*, is influenced by environmental factors including temperature and water availability. These bioactive compounds are responsible for the therapeutic properties of these plants. Climate-induced stresses, such as drought and temperature extremes, can alter the synthesis and accumulation of these metabolites, potentially affecting medicinal quality [9].

Studies have shown that moderate environmental stresses can increase the production of certain secondary metabolites as part of the plant's defense mechanism. However, prolonged or extreme stress conditions may reduce overall plant growth and biomass, leading to decreased yields of these valuable compounds. Understanding

these dynamics is crucial for ensuring the consistent quality of medicinal plants under changing climatic conditions [10], [11].

7.3 Agriculture and Livelihoods

Farmers cultivating medicinal plants are increasingly facing challenges due to climate change. Altered phenology, such as shifts in flowering and fruiting times, can affect harvest schedules, leading to reduced yields and inconsistent quality. These changes have significant economic implications for farmers who rely on medicinal plants as a primary source of income [12].

In Haryana, several initiatives have been launched to promote climate-resilient agriculture practices among smallholder farmers. These programs aim to improve adaptive capacity by introducing sustainable farming techniques, such as water conservation methods and crop diversification, to mitigate the impacts of climate change on medicinal plant cultivation. Such efforts are essential for safeguarding farmer livelihoods and ensuring the sustainable production of medicinal plants [13], [14].

7.4 Climate Adaptation

Understanding phenological responses of medicinal plants to climate change is vital for developing effective adaptation strategies. By monitoring changes in flowering, fruiting, and seed dispersal patterns, researchers can identify species that are resilient to climatic stresses and those that may require intervention to maintain viability [15].

In Haryana, pilot projects have explored natural farming practices as a means to enhance climate resilience. For instance, demonstration zones on state-owned farmland provide training and support to farmers to adopt sustainable practices. Successful implementation of such initiatives can serve as

a model for promoting climate-smart agriculture and conserving medicinal plant resources [16], [17].

3. Climate Trends in Haryana

Haryana, situated in northern India, has been experiencing noticeable climatic changes over the past few decades. Temperature records indicate a consistent rise of approximately 0.2–0.3°C per decade, accompanied by more frequent and intense heat waves in recent years [18], [19]. These temperature increases have been particularly pronounced during the summer months, leading to enhanced evapotranspiration, increased soil moisture deficits, and thermal stress on both cultivated and wild plant species. Rising temperatures directly influence plant physiological processes, including photosynthesis, respiration, and water-use efficiency, thereby affecting overall growth and development [20].

Rainfall patterns in Haryana have also become increasingly erratic. Winter rainfall has shown a declining trend, while the monsoon season is marked by irregular distribution, delayed onset, early withdrawal, and extreme events such as heavy downpours followed by prolonged dry spells [21]. These shifts have resulted in a highly variable soil moisture regime, with alternating periods of waterlogging and drought. Such fluctuations significantly impact germination, flowering, and fruiting cycles of plants, particularly sensitive medicinal species like *Withania somnifera*, *Aloe vera*, and *Ocimum sanctum* [22].

The combined effects of rising temperature and erratic rainfall pose serious challenges for agriculture and ecosystem stability in Haryana. Prolonged droughts lead to moisture stress, inhibiting seed germination and reducing vegetative growth, while sudden heavy rainfall can cause soil erosion, nutrient leaching, and

waterlogging, adversely affecting plant reproductive success [23]. These climatic pressures necessitate the adoption of adaptive strategies in agricultural planning, irrigation management, and the cultivation of climate-resilient plant varieties to ensure sustainable productivity and conservation of local biodiversity.

4. Methodological Framework

The methodological framework of this study is designed to systematically assess the impact of climate variability on the phenology of selected medicinal plants in Haryana. The approach combines careful plant selection, extensive data collection from multiple sources, and robust analytical techniques to establish relationships between climatic factors and phenological changes.

4.1 Plant Selection

Three medicinal plant species were selected for this study based on their cultural, medicinal, and economic importance in Haryana:

- **Withania somnifera (Ashwagandha):** Ashwagandha is a well-known adaptogenic herb widely used in Ayurveda for its stress-reducing and health-promoting properties. The plant is highly sensitive to environmental conditions, making it an ideal candidate for studying the impact of temperature and rainfall variability on flowering, fruiting, and seed development [24], [25].
- **Aloe vera:** Aloe vera is a succulent plant extensively cultivated for dermatological, therapeutic, and cosmetic applications. Its growth, leaf gel content, and phytochemical composition are influenced by water availability and temperature, making it a suitable model for examining climate-induced phenological shifts [26].
- **Ocimum sanctum (Tulsi):** Tulsi is a revered medicinal herb with immunomodulatory and therapeutic properties. It is widely cultivated in Haryana and is highly sensitive to seasonal changes, particularly

temperature and rainfall patterns, which influence its flowering and essential oil content [27].

The selection of these species ensures that the study encompasses a range of plant types, including herbaceous, succulent, and aromatic medicinal plants, which allows for a comprehensive understanding of climate impacts on phenology.

4.2 Data Sources

Data were collected from multiple sources to ensure reliability, accuracy, and comprehensiveness:

- **Phenological Records:** Field observations were conducted across herbal farms, agricultural universities, and community-managed cultivation sites in Haryana over the period 2013–2023. These records documented the timing of key phenological events, including flowering onset, fruiting duration, and seed dispersal patterns [28]. Additionally, published surveys and previous studies were reviewed to supplement field data and provide long-term context [29].
- **Climate Data:** Meteorological data were obtained from the Haryana Agricultural University weather stations and the India Meteorological Department (IMD). Temperature, rainfall, humidity, and other relevant climatic variables were compiled to correlate with observed phenological changes [30]. Historical climate trends were analyzed to detect patterns of warming, drought, and rainfall irregularity affecting plant life cycles.
- **Comparative Analysis:** The collected phenological and climate datasets were compared across the decade to identify trends in early or delayed flowering, fruiting durations, and seed dispersal shifts. This comparative analysis enables the detection of both gradual changes and extreme events influencing plant reproductive cycles.

4.3 Analytical Tools

The study employed robust statistical and analytical techniques to quantify relationships between climate and plant phenology:

- **Statistical Correlation:** Pearson correlation coefficients were used to analyze relationships between key climatic variables (temperature, rainfall) and phenological parameters such as flowering onset, fruiting duration, and seed dispersal timing [31]. Significant correlations helped identify climatic factors most strongly associated with observed phenological shifts.
- **Trend Analysis:** Temporal trends were analyzed to detect advances or delays in flowering and fruiting events over the decade. Regression models and time-series analysis were applied to quantify shifts in phenology and predict future trends under continued climate variability [32].
- **Visualization Tools:** Graphical representation of phenological shifts, heat maps, and comparative bar charts were used to visualize correlations between climate variables and plant developmental stages. These visualizations provide clear insights into how specific climatic stresses impact growth and reproduction.

By combining targeted plant selection, comprehensive data collection, and rigorous analytical approaches, this methodological framework enables a detailed understanding of the impact of climate change on medicinal plant phenology in Haryana. The framework not only identifies phenological shifts but also provides actionable insights for climate-adaptive cultivation practices and conservation strategies.

5. Observations and Findings

This study assessed the impact of rising temperatures and erratic rainfall on the phenology of three important medicinal plants in Haryana: *Withania somnifera*, *Aloe vera*,

and *Ocimum sanctum*. The observations were based on a combination of field data (2013–2023), climate datasets, and comparative analysis to understand shifts in flowering, fruiting, and seed dispersal patterns.

5.1 *Withania somnifera* (Ashwagandha)

Withania somnifera, a key adaptogenic herb, exhibited significant phenological shifts over the decade. Field observations indicated that flowering now occurs approximately 10–15 days earlier than a decade ago, largely attributed to higher early summer temperatures [33]. This advancement in flowering timing has implications for pollinator interactions, potentially reducing effective pollination periods.

Erratic rainfall during the fruiting phase has led to a shortened fruiting period, which directly impacts seed yield. Observations showed that inconsistent moisture availability affected berry development, leading to smaller fruit sizes and a lower number of viable seeds per plant [34].

Heat stress, particularly during peak summer months, further exacerbated these effects. Plants exposed to prolonged high temperatures produced berries with reduced size and weight, which may compromise both propagation and the medicinal quality of roots and leaves. These findings highlight the sensitivity of *Ashwagandha* to combined temperature and water stress, emphasizing the need for adaptive cultivation practices [35].

5.2 *Aloe vera*

Aloe vera demonstrated increased variability in flowering patterns, with some plants skipping reproductive cycles during prolonged drought periods. This irregular flowering was particularly observed in regions with reduced monsoon rainfall [36]. High temperatures favored vegetative growth over reproductive development, resulting in dominance of leaf proliferation while flowering was reduced.

Soil moisture fluctuations had a notable impact on leaf gel yield and its bioactive compounds. Reduced moisture content under drought conditions decreased leaf succulence, which is directly correlated with the concentration of polysaccharides and other therapeutic compounds. Conversely, excessive rainfall leading to waterlogging negatively affected gel quality due to reduced leaf firmness and potential microbial growth [37]. These observations underline the critical influence of both temperature and water availability on Aloe vera's reproductive and medicinal potential.

5.3 Ocimum sanctum (Tulsi)

Ocimum sanctum, an aromatic and medicinal herb, displayed an extended flowering period under rising temperatures. While warmer conditions prolonged flowering, excessive heat during peak summer caused premature flower drop, thereby reducing seed set and potential yield [38].

Erratic rainfall, particularly delayed or insufficient monsoon events, adversely affected seed germination rates. In areas with uneven precipitation, germination success was reduced by up to 20% compared to regions with stable rainfall patterns [39].

Additionally, essential oil concentrations, a key determinant of Tulsi's medicinal potency, fluctuated in response to climatic variability. Periods of drought or heat stress increased essential oil synthesis temporarily, but prolonged stress ultimately reduced oil yield and altered its chemical composition [40]. This variability poses challenges for standardizing Tulsi-based medicinal products and emphasizes the need for climate-resilient cultivation strategies. Overall, these observations indicate that rising temperatures and erratic rainfall in Haryana are significantly altering the phenology of medicinal plants. Withania somnifera is showing earlier flowering and reduced fruiting; Aloe vera exhibits irregular flowering with vegetative dominance; and Ocimum sanctum experiences

extended but unstable flowering. These shifts not only affect plant reproduction but also the medicinal quality of bioactive compounds and the livelihoods of farmers relying on these crops.

6. Discussion

The phenological shifts observed in Withania somnifera, Aloe vera, and Ocimum sanctum provide compelling evidence of how climate variability is influencing plant reproductive cycles and ecological interactions in Haryana. Earlier flowering, reduced fruiting duration, and altered seed dispersal patterns indicate that these species are responding to a combination of thermal stress and water availability fluctuations, reflecting broader ecological responses to climate change [41].

6.1 Ecological Implications

Earlier onset of flowering, particularly in Withania somnifera, suggests that higher early summer temperatures are accelerating plant developmental processes. While this may initially seem advantageous, it can result in a temporal mismatch with pollinator activity, reducing pollination efficiency and seed set [42]. In ecosystems where pollinator populations are also affected by rising temperatures, these mismatches may compound, potentially leading to long-term reductions in genetic diversity. Shortened fruiting windows, observed in Ashwagandha due to erratic rainfall, further exacerbate reproductive limitations by constraining the period available for successful seed maturation and dispersal [43].

In Aloe vera, increased vegetative growth dominance under high temperatures indicates a trade-off between reproductive and vegetative allocation. Plants that skip flowering cycles under drought conditions may survive short-term environmental stress but risk long-term population decline due to reduced seed production [44]. Similarly, Tulsi's extended

but unstable flowering period under rising temperatures and erratic rainfall highlights how climatic extremes can disrupt reproductive synchrony, leading to potential declines in plant populations over time [45].

The combined effects of thermal stress and irregular rainfall are altering soil moisture regimes, which are critical for germination, root development, and nutrient uptake. Prolonged drought conditions limit water availability for reproductive tissues, while sudden heavy rainfall can damage developing flowers and seeds. These fluctuations not only affect plant survival but also modify ecological interactions, such as competition, herbivory, and pollination dynamics [46].

6.2 Implications for Medicinal Quality

The medicinal quality of these plants is closely linked to their physiological responses to environmental stress. In *Withania somnifera*, water stress and heat affect the synthesis of withanolides, which are the principal bioactive compounds responsible for its adaptogenic properties [47]. Fluctuations in rainfall and temperature can therefore alter both the quantity and quality of these compounds, potentially reducing the efficacy of Ashwagandha-based formulations.

In *Tulsi*, essential oil content is highly sensitive to rainfall and temperature variability. While mild stress can enhance the production of volatile compounds, prolonged drought or excessive heat reduces oil yield and alters chemical composition, affecting therapeutic potency [48]. Aloe vera leaf gel, used widely in dermatological and therapeutic applications, is similarly impacted by soil moisture conditions. Water stress reduces leaf succulence and polysaccharide content, directly affecting both yield and medicinal quality [49].

6.3 Socioeconomic Implications

Farmers and industries dependent on these medicinal plants face substantial challenges due to these phenological and physiological changes. Altered flowering and fruiting cycles can lead to inconsistent harvest periods, reduced seed availability, and unpredictable yields. Consequently, the economic viability of medicinal plant cultivation may be threatened, particularly for smallholder farmers who rely on these crops as a primary source of income [50].

The pharmaceutical and herbal industries, which depend on standardized concentrations of bioactive compounds, may experience quality inconsistencies, affecting product efficacy and market competitiveness. Such variability underscores the importance of developing climate-resilient cultivation strategies, including irrigation management, selection of drought-tolerant genotypes, and optimized planting schedules to mitigate the impacts of climate variability on both yield and quality [51].

6.4 Broader Implications

These findings highlight the critical need for integrating climate change considerations into medicinal plant management and conservation strategies in Haryana. Phenological shifts not only affect individual species but also influence ecosystem-level processes, such as pollination networks and natural regeneration. Monitoring phenology can serve as an early indicator of ecological stress and help guide adaptive management practices to ensure sustainable production, biodiversity conservation, and the continued availability of medicinal resources [52].

In conclusion, the observed phenological shifts, influenced by rising temperatures and erratic rainfall, present significant ecological, medicinal, and socioeconomic challenges. Proactive measures that combine climate-adaptive agricultural practices with conservation strategies are essential to

safeguard the long-term sustainability and medicinal value of these culturally and economically important plants.

7. Challenges and Limitations

While this study provides critical insights into the phenological responses of medicinal plants to climate variability in Haryana, several challenges and limitations were encountered that may influence the interpretation and generalization of the results. Understanding these constraints is essential for designing future research and adaptive management strategies.

7.1 Limited Long-Term Phenological Data

One of the primary challenges was the scarcity of continuous, long-term phenological records for many medicinal plants. Although data from 2013–2023 were compiled from field observations, agricultural universities, herbal farms, and published surveys, gaps remain in consistent monitoring, particularly for less-studied species [53]. Incomplete datasets may limit the ability to detect subtle phenological shifts or distinguish between inter-annual variability and long-term trends.

7.2 Regional Variation in Cultivation Practices

Phenological responses can vary significantly depending on local cultivation practices, soil types, irrigation schedules, and microclimatic conditions. In Haryana, farmers employ diverse techniques for medicinal plant cultivation, including differences in planting time, spacing, and fertilization. These variations complicate uniform analysis and may introduce confounding factors, making it challenging to isolate the effects of temperature and rainfall alone on phenology [54].

7.3 Climate Data Limitations

Although meteorological data were obtained from Haryana Agricultural University and the India Meteorological Department (IMD), the spatial resolution of climate stations may not fully capture local variability in temperature, rainfall, or soil moisture. This limitation can affect the precision of correlations between climate parameters and observed phenological changes, particularly in areas with heterogeneous landscapes or microclimates [55].

7.4 Stress Response Complexity

Medicinal plants exhibit complex physiological responses to combined climatic stresses such as heat, drought, and erratic rainfall. Factors like nutrient availability, pest incidence, and disease pressure can interact with climate stress to influence flowering, fruiting, and secondary metabolite production [56]. Disentangling these interacting factors requires controlled experiments or modeling approaches, which were beyond the scope of the current observational study.

7.5 Need for Molecular and Biochemical Integration

While phenological observations provide valuable information about shifts in flowering and fruiting, they do not fully capture underlying biochemical or genetic mechanisms. For instance, variations in withanolide content in *Withania somnifera* or essential oils in *Ocimum sanctum* are influenced by molecular pathways regulated by stress responses. Integrating molecular studies and metabolite profiling would provide a more comprehensive understanding of climate impacts on medicinal quality [57].

7.6 Socioeconomic Constraints

Another limitation arises from socio-economic factors affecting medicinal plant cultivation.

Farmers may alter planting schedules or irrigation practices in response to market demands, labor availability, or water scarcity. These human-mediated adjustments can mask or amplify the effects of climate variability on phenology, complicating data interpretation [58].

In summary, while this study highlights important trends in the phenology of key medicinal plants under changing climatic conditions, these challenges underscore the need for continuous monitoring, region-specific research, and integration of ecological, physiological, and socio-economic data. Addressing these limitations will enhance the predictive accuracy of climate-adaptive strategies for sustainable cultivation and conservation of medicinal plant resources in Haryana.

8. Future Directions

The observed phenological shifts in medicinal plants due to rising temperatures and erratic rainfall in Haryana highlight the urgent need for proactive research and management strategies. Future efforts should focus on establishing long-term phenology monitoring stations across diverse agro-climatic zones of the state. Such stations would provide continuous data on flowering, fruiting, and seed dispersal patterns, enabling early detection of climate-induced changes and guiding adaptive cultivation practices.

Integration of remote sensing technologies and artificial intelligence (AI)-based modeling can greatly enhance predictive capabilities. Satellite imagery, drone-based monitoring, and climate simulations can be used to track phenological changes at large scales, identify areas most at risk, and develop site-specific management strategies. These tools can also support decision-making for planting

schedules, irrigation management, and harvesting periods, ensuring optimal yields and medicinal quality.

Research should also explore the genetic diversity and adaptive potential of local landraces of medicinal plants. Identifying drought-tolerant, heat-resistant, and early-flowering genotypes will allow farmers to cultivate varieties that are better suited to changing climatic conditions. Breeding programs can focus on enhancing both yield and bioactive compound production while maintaining resilience to environmental stresses.

Furthermore, climate-smart cultivation practices should be promoted among farmers. Techniques such as water conservation through drip irrigation, mulching, use of shade nets, and soil moisture management can help mitigate the effects of heat and drought. Diversification of crops and intercropping with climate-resilient species may also enhance overall ecosystem stability and reduce the vulnerability of medicinal plant cultivation.

Collaborative efforts between research institutions, government agencies, and local farmers are essential to implement these strategies effectively. Training programs, demonstration plots, and knowledge-sharing platforms can build capacity and ensure sustainable cultivation practices. Overall, a combination of monitoring, predictive modeling, genetic research, and climate-smart management can safeguard the phenology, medicinal quality, and long-term sustainability of Haryana's medicinal plant resources under ongoing climate change.

9. Conclusion

This study highlights the profound impact of rising temperatures and erratic rainfall on the phenology of key medicinal plants in Haryana, including *Withania somnifera* (Ashwagandha),

Aloe vera, and Ocimum sanctum (Tulsi). Observations indicate that climate variability has advanced flowering times, shortened fruiting periods, and altered seed dispersal patterns, reflecting broader ecological responses to thermal stress and irregular precipitation. These phenological shifts not only affect plant reproductive success and long-term genetic diversity but also disrupt interactions with pollinators, thereby impacting ecosystem stability.

The implications for medicinal quality are equally significant. Water stress and temperature extremes influence the synthesis of bioactive compounds, such as withanolides in Ashwagandha and essential oils in Tulsi, as well as polysaccharide content in Aloe vera. Variability in these compounds affects both therapeutic efficacy and commercial value, posing challenges for farmers and industries dependent on consistent medicinal yields.

From a socio-economic perspective, altered phenology leads to unpredictable harvest times, reduced seed availability, and fluctuating crop quality. Smallholder farmers cultivating these medicinal plants are particularly vulnerable, highlighting the need for climate-resilient agricultural practices. Integrating long-term monitoring, predictive modeling, genetic research, and climate-smart cultivation strategies can mitigate these challenges, ensuring sustainable production and conservation of valuable medicinal resources.

In conclusion, the rising temperatures and erratic rainfall patterns in Haryana are reshaping the reproductive cycles, medicinal quality, and ecological interactions of local medicinal plants. Proactive measures, including adaptive cultivation practices, conservation of genetic diversity, and continuous monitoring, are essential to safeguard both the ecological and economic value of these culturally and medically important species. Addressing these challenges will not only help maintain biodiversity but also support local livelihoods and the long-

term sustainability of medicinal plant-based industries in the region.

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