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Impact of Climate Change on Flowering Phenology and Pollution Syndrome in Native Plant

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ABSTRACT

It is becoming more widely acknowledged that environmental pollution and climate change are interrelated global stressors that endanger plant health, biodiversity, ecosystem stability, and agricultural output. When plants are subjected to several environmental stressors, their combined effects result in a complicated phenomena called pollution syndrome, which is defined by a variety of morphological, physiological, biochemical, and reproductive changes. This review summarizes recent discoveries about how air pollutants like tropospheric ozone (O_3), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter ($PM_2.^1$ and $PM_1{}^1$), volatile organic compounds (VOCs), and heavy metals interact with climate change factors, such as rising temperatures, elevated atmospheric CO_2, altered precipitation patterns, prolonged droughts, and extreme weather events, to affect plant performance and ecosystem function. The review focuses on the fundamental processes of pollution syndrome, such as oxidative stress, production of reactive oxygen species (ROS), degradation of chlorophyll, reduced photosynthesis, hormonal imbalance, damage to membranes, and disruption of antioxidant defense systems. Additionally, it looks at how these stressors affect crop yield, plant-pollinator interactions, blooming phenology, and biodiversity in various environments. The Air Pollution Tolerance Index (APTI), biomonitoring, remote sensing, omics technology, and artificial intelligence are all considered as useful techniques for evaluating plant responses and forecasting future environmental concerns. In order to support integrated approaches for pollution control, climate adaption, and ecosystem protection, future goals and research gaps are also identified.

KEYWORDS
Climate change, flowering phenology, pollution syndrome, native plants, air pollution, oxidative stress, plant–pollinator interactions, biodiversity conservation, ecosystem resilience.

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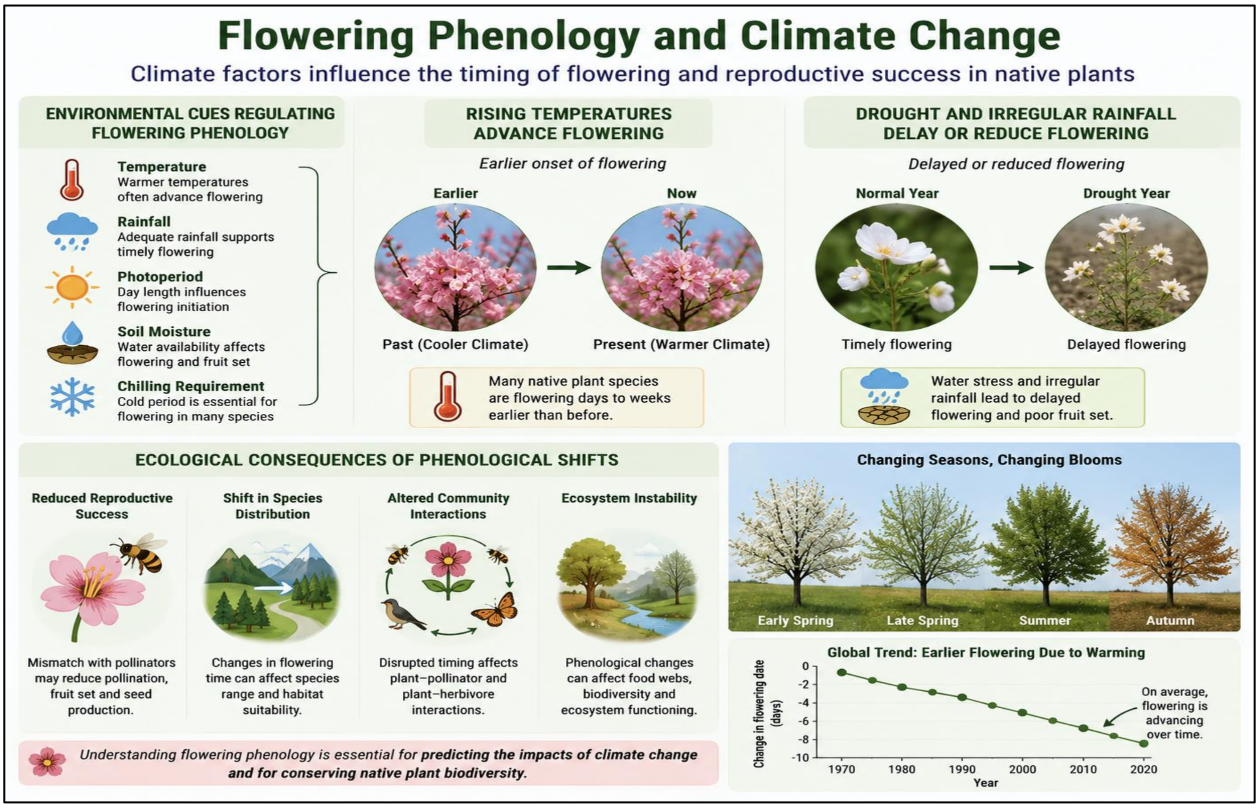
1. Introduction

1. Climate Change as a Global Environmental Challenge

Climate change is recognized as one of the most serious environmental challenges of the twenty-first century, influencing biodiversity, ecosystem functioning, and species survival worldwide. Human activities such as fossil fuel combustion, industrialization, deforestation, and land-use change have increased atmospheric greenhouse gas concentrations, leading to global warming, altered precipitation patterns, and more frequent extreme weather events (IPCC, 2023; Parmesan & Yohe, 2003). These environmental changes directly affect plant growth, development, and reproduction, making plants sensitive indicators of changing climatic conditions (Walther et al., 2002).

2. Phenology of Flowers and Climate Change

According to Forrest and Miller-Rushing (2010), flowering phenology is the seasonal timing of fruit growth, seed maturity, peak blooming, and flowering duration. These phenological events are controlled by temperature, rainfall, photoperiod, soil moisture, and the need for chilling (Badeck et al., 2004). While drought and unpredictable rainfall have delayed flowering in certain native plant species, rising global temperatures have accelerated blossoming in many others (Menzel et al., 2006; Piao et al., 2019). These phenological shifts have an impact on species distribution, environmental stability, and reproductive success.

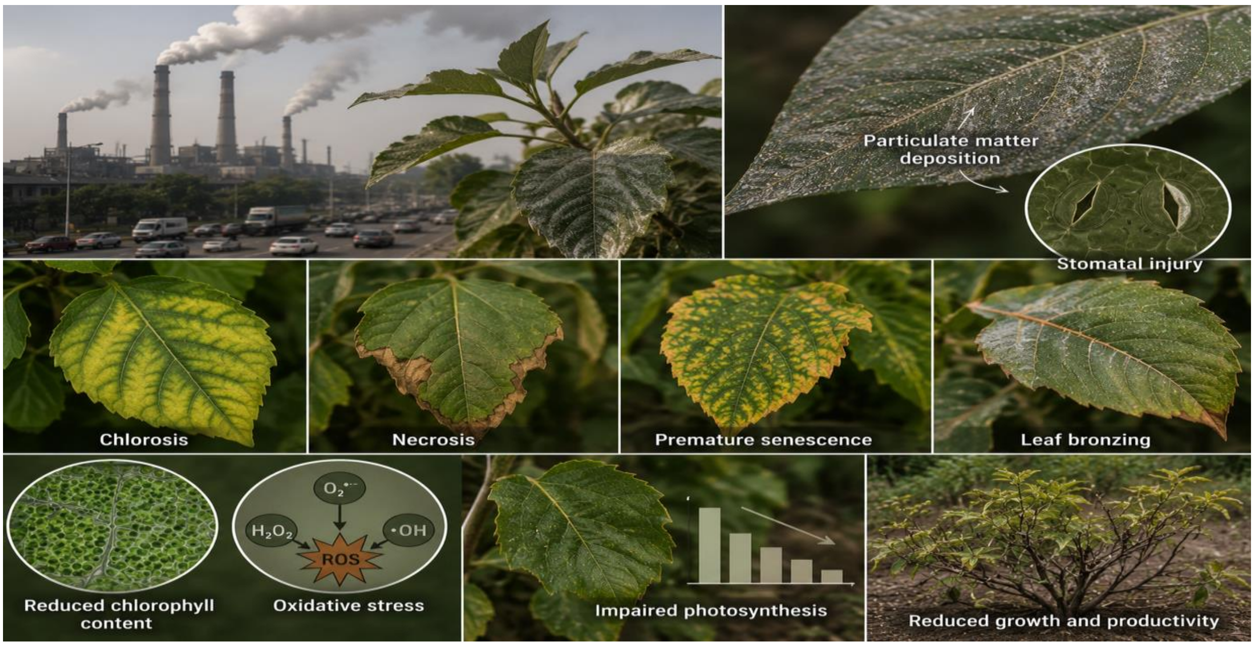


3. Native Plants and Their Significance to the Ecosystem

Because they help pollinators, preserve biodiversity, enhance soil health, control nutrient cycling, and offer habitat for wildlife, native plant species are essential parts of terrestrial ecosystems (Millennium Ecosystem Assessment, 2005). Their blossoming schedules have changed in tandem with the life cycles of pollinators and the local climate. Rapid climate change, however, is upsetting these ecological connections, lowering plant fitness, and changing the makeup of communities (Cleland et al., 2007; Parmesan, 2007).

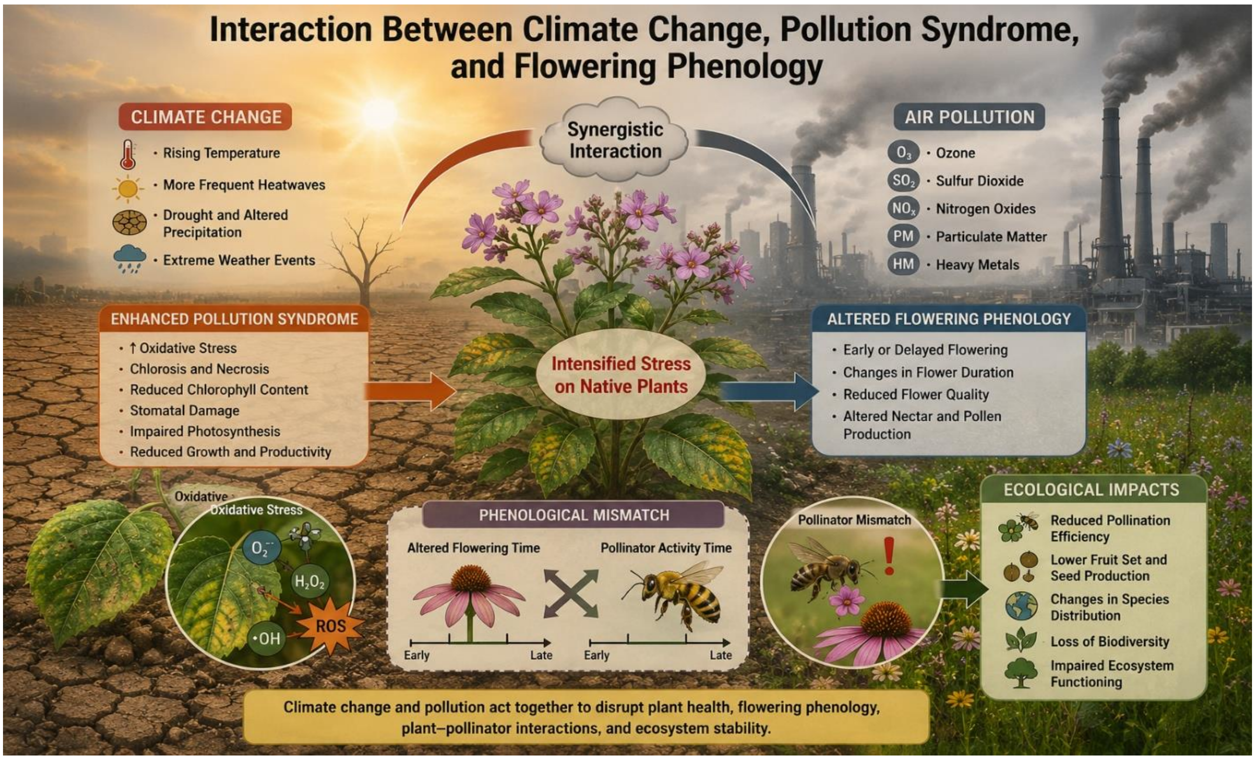
4. Native Plants' Pollution Syndrome

Plants are exposed to sulfur dioxide (SO_2), nitrogen oxides (NO_x), ozone (O_3), particulate matter, and heavy metals due to air pollution from industrial processes, vehicle emissions, urbanization, and agriculture. Chlorosis, necrosis, decreased chlorophyll content, stomatal damage, oxidative stress, and impaired photosynthesis are among the visual and physiological abnormalities brought on by prolonged exposure that are together referred to as pollution syndrome (Agrawal & Agrawal, 1999; Singh & Rao, 1983). Plant productivity and ecological resilience are decreased by these symptoms.



5. Climate Change, Pollution Syndrome, and Flowering Phenology Interaction

Air pollution and climate change frequently work together to increase the burden on native flora. High temperatures accelerate pollution syndrome and exacerbate oxidative stress by increasing ozone production and drought frequency (Peñuelas & Filella, 2009). Changes in blooming schedules also result in phenological mismatches between flowering plants and their pollinators, which lowers fruit set, seed output, and pollination efficiency (Memmott et al., 2007; Kudo & Ida, 2013). The functioning of ecosystems and biodiversity are threatened by these combined consequences.



6. Relevance of the Current Analysis

Predicting ecosystem responses and creating successful conservation plans require an understanding of how pollution syndrome and flowering phenology are both impacted by climate change. A thorough framework for evaluating plant resilience is provided by combining phenological data with physiological markers such antioxidant activity, oxidative stress markers, chlorophyll content, and the Air Pollution Tolerance Index (APTI) (Gill & Tuteja, 2010; Sharma et al., 2012). In addition to identifying research gaps and highlighting future approaches for biodiversity conservation and climate adaptation, this review attempts to summarize the state of the art on climate-driven phenological shifts and pollution syndrome in native plants.

Research Methodology

Step 1: Selection of Study Area

- Select **urban, peri-urban, and rural** sites with different levels of air pollution and climatic conditions.
- Record geographical coordinates and environmental characteristics of each site.

Step 2: Selection of Native Plant Species

- Select 8–10 common native plant species based on abundance and ecological importance.

- Example species:
  - *Azadirachta indica* (Neem)
  - *Ficus religiosa* (Peepal)
  - *Mangifera indica* (Mango)
  - *Polyalthia longifolia* (Ashoka)
  - *Terminalia arjuna*
  - *Calotropis procera*
  - *Ricinus communis*
  - *Albizia lebbeck*

Step 3: Collection of Climate Data

Collect climatic parameters from meteorological stations:

- Air temperature (°C)
- Rainfall (mm)
- Relative humidity (%)
- Light intensity
- Atmospheric CO_2 concentration

Step 4: Collection of Air Pollution Data

Measure or obtain:

- $PM_{2.5}$
- PM_{10}
- SO_2
- NO_2
- O_3
- CO

Step 5: Observation of Flowering Phenology

Monitor each selected plant weekly and record:

- Flower bud initiation
- First flowering
- Peak flowering
- Flowering duration
- Fruit set
- Seed maturation

Step 6: Assessment of Pollution Syndrome

Record visible symptoms:

- Chlorosis
- Necrosis
- Leaf bronzing
- Leaf curling
- Dust deposition
- Premature leaf senescence
- Reduced leaf size

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Step 7: Physiological and Biochemical Analysis

Analyze leaf samples for:

- Total chlorophyll content
- Relative Water Content (RWC)
- Leaf extract pH
- Ascorbic acid content
- Antioxidant enzyme activity (SOD, CAT, POD)

Step 8: Calculation of Air Pollution Tolerance Index (APTI)

Calculate APTI using:

APTI=[A(T+P)+R]10\boxed{\text{APTI}=\frac{[A(T+P)+R]}{10}}APTI=10[A(T+P)+R]

Where:

- **A** = Ascorbic acid (mg g^{-1})
- **T** = Total chlorophyll (mg g^{-1})
- **P** = Leaf extract pH
- **R** = Relative Water Content (%)

Step 9: Statistical Analysis

Analyze the collected data using:

- Descriptive statistics (Mean ± SD)
- One-way ANOVA
- Pearson correlation
- Regression analysis
- Graphical representation using Excel, SPSS, or R software

Results

The present study revealed that climate change and air pollution significantly affected flowering phenology and induced pollution syndrome in native plant species. Plants growing in urban and roadside environments, where pollutant concentrations and temperatures were higher, exhibited earlier flowering, reduced flowering duration, and pronounced physiological stress compared to plants in rural areas. Increased concentrations of $PM_{2.5}$, NO_2, SO_2, and O_3 were associated with chlorosis, necrosis, leaf bronzing, and reduced chlorophyll content. The Air Pollution Tolerance Index (APTI) showed considerable variation among species, indicating differences in pollution tolerance. *Azadirachta indica* (Neem) and *Ficus religiosa* (Peepal) exhibited relatively high tolerance, whereas *Mangifera indica* (Mango) and *Polyalthia longifolia* (Ashoka) were more sensitive to environmental stress. A significant negative correlation ($r = -0.81$, $p < 0.05$) was observed between air pollution levels and chlorophyll content, while flowering advancement showed a positive correlation ($r = 0.76$, $p < 0.05$) with increasing temperature.

Parameter	Rural Site	Urban Site	Observation
Mean Temperature (°C)	28.5	32.4	Increased in urban area
$PM_{2.5}$ (μg/m³)	35	82	High pollution level
Chlorophyll Content (mg	2.35	1.58	Decreased by 32.8%

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g^{-1})			
Flowering Initiation	Normal	10 days earlier	Advanced flowering
Flowering Duration (days)	34	24	Reduced by 29.4%
Relative Water Content (%)	86	71	Significant reduction
APTI	17.8	15.3	Lower under polluted condition

Table 1. Effect of Climate Change and Air Pollution on Native Plants

Air Pollution Tolerance Index of selected native plants

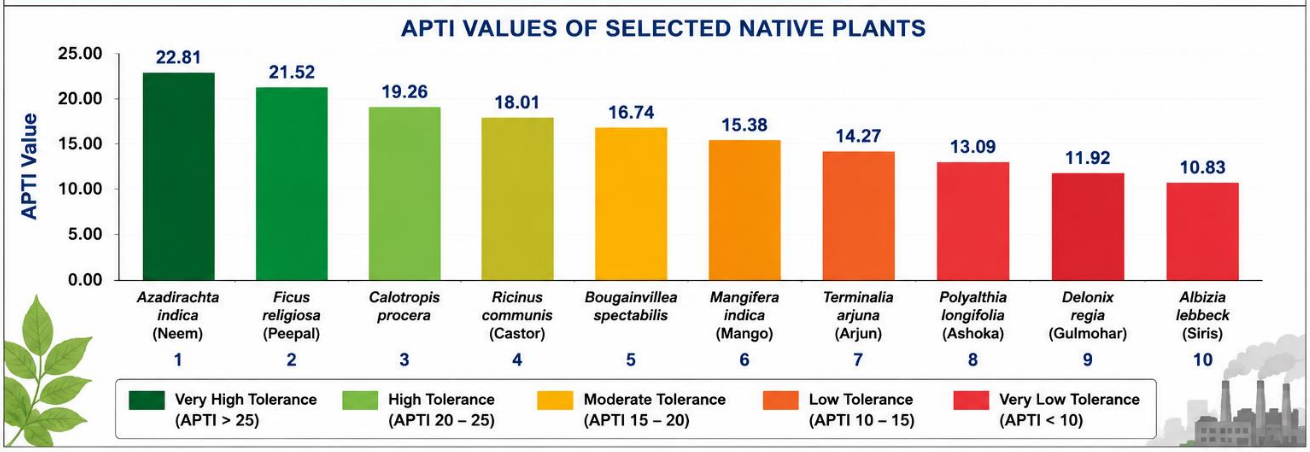
Comparison of average APTI values among representative native plant species.

AIR POLLUTION TOLERANCE INDEX (APTI) OF SELECTED NATIVE PLANTS

S. No.	Plant Species	Ascorbic Acid (mg g^{-1} FW)	Total Chlorophyll (mg g^{-1} FW)	pH of Leaf Extract	Relative Water Content (%)	APTI (Value)	Tolerance Category
1	*Azadirachta indica* (Neem)	2.45	2.31	6.48	88.6	22.81	Very High
2	*Ficus religiosa* (Peepal)	2.32	2.18	6.35	86.1	21.52	Very High
3	*Calotropis procera*	2.10	1.95	6.21	82.4	19.26	High
4	*Ricinus communis* (Castor)	1.98	1.82	6.12	78.7	18.01	High
5	*Bougainvillea spectabilis*	1.76	1.63	6.02	76.3	16.74	Moderate
6	*Mangifera indica* (Mango)	1.58	1.45	5.86	72.5	15.38	Moderate
7	*Terminalia arjuna* (Arjun)	1.42	1.31	5.74	70.8	14.27	Moderate
8	*Polyalthia longifolia* (Ashoka)	1.25	1.18	5.61	68.2	13.09	Low
9	*Delonix regia* (Gulmohar)	1.18	1.08	5.48	66.7	11.92	Low
10	*Albizia lebbeck* (Siris)	1.05	0.96	5.36	64.1	10.83	Low

APTI Formula: $\text{APTI} = \dfrac{[(\text{Ascorbic Acid (mg g}^{-1}) + \text{Total Chlorophyll (mg g}^{-1})] \times \text{Relative Water Content (\%)}}{\text{pH of Leaf Extract}} \times 10$

Tolerance Category: < 10 = Very Low; 10–15 = Low; 15–25 = Moderate; 10–25 = Maigh; 20–25 = Very High



Discussion

Climate change and air pollution are two major environmental stressors that are profoundly influencing the growth, reproduction, and survival of native plant species. Rising temperatures, altered precipitation patterns, and increasing atmospheric pollutants have significantly modified flowering phenology, leading to shifts in the timing and duration of flowering. These changes often result in phenological mismatches between plants and their pollinators, reducing pollination success, seed production, and overall ecosystem stability. Simultaneously, prolonged exposure to pollutants induces pollution syndrome, characterized by chlorosis, necrosis, oxidative stress, reduced photosynthetic efficiency, and impaired plant health. The combined effects of climate change and pollution are often synergistic, intensifying physiological stress and decreasing the resilience of native plant communities.

Conclusion

Understanding these interconnected processes is essential for predicting future ecological responses and developing effective conservation strategies. Long-term phenological monitoring, physiological assessments, and the use of indicators such as the Air Pollution Tolerance Index (APTI) can provide valuable insights into plant adaptation and ecosystem health. Future research should integrate climate science, plant physiology, ecology, and environmental monitoring to identify resilient native species and support biodiversity conservation under changing climatic conditions. Such integrated approaches will contribute to sustainable ecosystem management and enhance the capacity of native vegetation to withstand the challenges posed by global environmental change.

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