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Pollution Syndrome under Climate Change: A Global Review

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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, pollution syndrome, air pollution, oxidative stress, reactive oxygen species, plant physiology, flowering phenology, biodiversity, ecosystem resilience, biomonitoring, Air Pollution Tolerance Index (APTI), remote sensing, environmental sustainability.

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1. Introduction

Among the biggest environmental problems of the twenty-first century are pollution and climate change. Their combined effects have profoundly changed human health, agricultural output, biodiversity, and ecosystem functioning. The concentrations of greenhouse gases (GHGs) and air pollutants in the atmosphere have significantly increased due to anthropogenic activities such fast industrialization, urbanization, mining, intensive agriculture, burning fossil fuels, and land-use change. 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 factors like elevated atmospheric carbon dioxide (CO_2), rising temperatures, prolonged droughts, irregular precipitation, and extreme weather events to create complex environmental stress that threatens both natural and managed ecosystems (IPCC, 2023; Rai, 2016; Mills et al., 2016; Fuhrer et al., 2016).

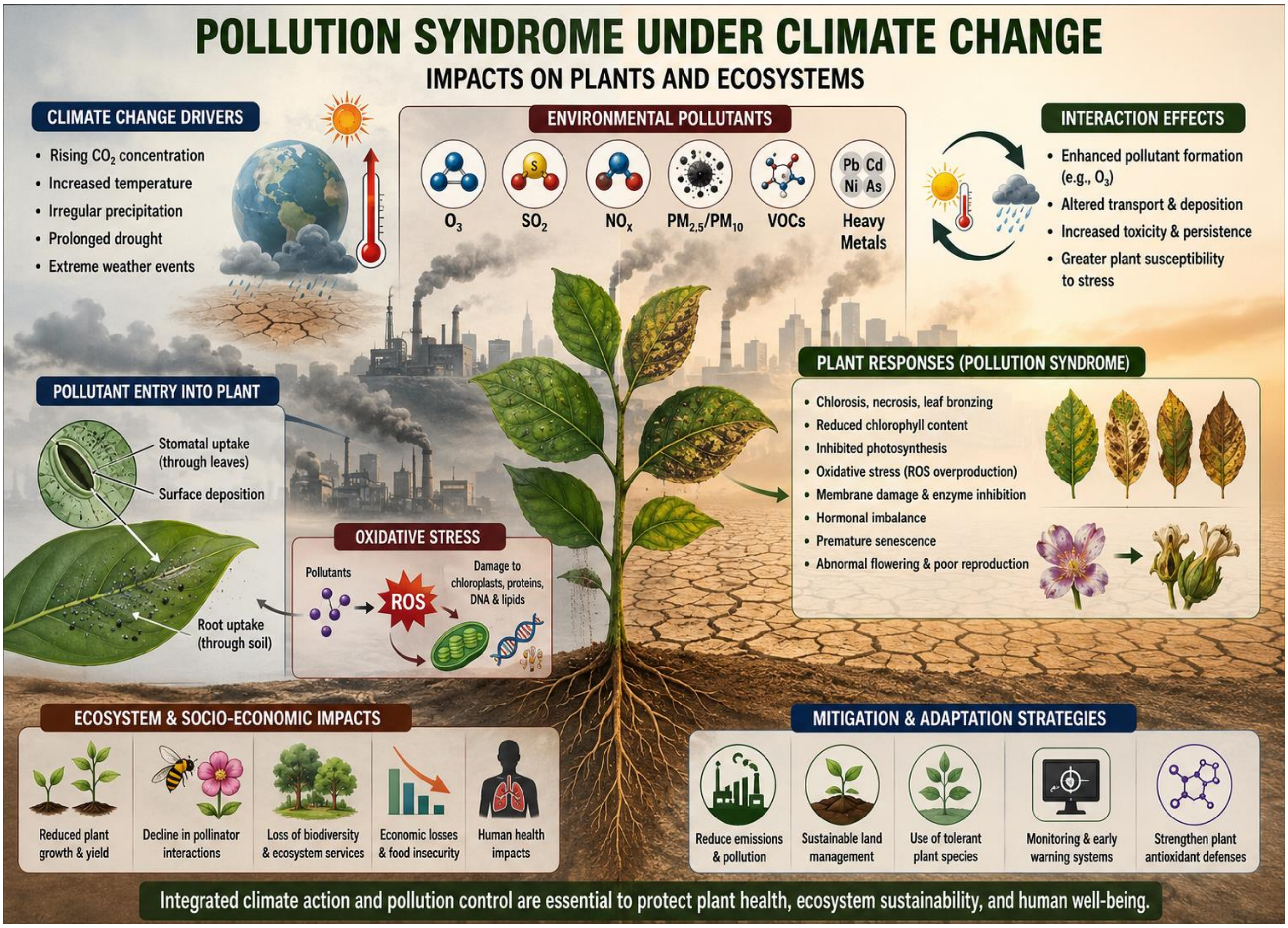
Because they are sessile, plants are constantly exposed to environmental stress, which makes them good markers of the health of ecosystems. Plant morphology, physiology, biochemistry, and molecular metabolism are all negatively impacted by air pollution. Chlorosis, necrosis, leaf bronzing, decreased leaf area, early senescence, aberrant flowering, and poor reproductive performance are common outward signs. Pollutants harm chloroplasts, reduce the amount of chlorophyll in the cell, prevent photosynthesis, change the permeability of membranes, and cause oxidative stress by producing too many reactive oxygen species (ROS). The term "pollution syndrome," which describes the distinctive morphological, physiological, biochemical, and reproductive changes in plants exposed to long-term environmental pollution, refers to these integrated responses taken together (Rai, 2016; Agathokleous et al., 2016; Ainsworth, 2016).

Since plants are rarely subjected to a single environmental stress, the idea of pollution syndrome has grown in significance. Pollutant transport, atmospheric chemistry, deposition patterns, persistence, and toxicity are all altered by climate change, which affects how vulnerable plants are to pollution. While changing precipitation influences pollution deposition and heavy metal mobility, elevated temperatures speed up photochemical reactions that produce ground-level ozone. Prolonged drought simultaneously lowers the water status and antioxidant capability of plants, making them more susceptible to oxidative damage. Increased climatic stress and ozone exposure frequently counteract the protective impact of elevated atmospheric CO2, which may decrease stomatal conductance in certain species and affect pollutant uptake (Mills et al., 2016; Fuhrer et al., 2016; Ainsworth, 2016).

Globally, air pollution continues to be one of the key factors causing ecological degradation. Because tropospheric ozone enters leaves through stomata and quickly produces reactive oxygen species that harm proteins, nucleic acids, membrane lipids, and chloroplast structures, it is regarded as one of the most phytotoxic atmospheric pollutants. By creating sulfite ions in leaf tissues, sulfur dioxide interferes with cellular activity, while nitrogen oxides cause acid buildup and nutrient imbalance. When particulate matter builds up on leaf surfaces, it reduces light interception, obstructs stomatal holes, hinders transpiration, and introduces hazardous heavy metals into plant tissues. According to Rai (2016), Mills et al. (2016), and Fuhrer et al. (2016), these contaminants dramatically lower photosynthetic efficiency, plant productivity, carbon sequestration, and ecosystem resilience.

Pollutant-induced harm is exacerbated by climate change in a number of ways. Heat waves speed up cellular metabolism and respiration, producing more ROS than antioxidant defense systems can detoxify. Flooding changes the soil's redox potential and increases the availability of heavy metals, whereas drought stress restricts nutrient delivery and reduces physiological resilience. Large amounts of particulate matter, black carbon, nitrogen oxides, and volatile organic compounds are released by wildfires, which are occurring more frequently as a result of climate change. This exposes vegetation to several pollutants at once. As a result, plants often undergo combinatorial stress responses that outweigh the impacts of other environmental stressors (IPCC, 2023; Mills et al., 2016; Fuhrer et al., 2016).

Oxidative stress is the primary metabolic process that underlies pollution syndrome. Lipid peroxidation, protein oxidation, DNA damage, and programmed cell death are all brought on by an excessive build-up of ROS, which include superoxide radicals, hydrogen peroxide, hydroxyl radicals, and singlet oxygen. In response, plants activate non-enzymatic antioxidants such ascorbic acid, glutathione, flavonoids, carotenoids, and phenolic substances as well as antioxidant enzymes like superoxide dismutase, catalase, peroxidase, glutathione reductase, and ascorbate peroxidase. Long-term exposure eventually overwhelms antioxidant capacity, leading to irreversible cellular damage and growth loss even though these defense mechanisms improve stress tolerance (Rai, 2016; Agathokleous et al., 2016).



Interactions between Climate Change and Pollution: A Multifactorial Stress Framework

In natural ecosystems, plants are increasingly subjected to several environmental stresses at once instead of one at a time. Recent study shows that climate change alters the intensity, duration, transport, and toxicity of environmental contaminants, causing synergistic, additive, or antagonistic impacts on plant health, in contrast to earlier studies that concentrated on individual pollutants. While extended dryness increases pollutant buildup by decreasing wet deposition, rising temperatures speed up atmospheric photochemical processes, boosting the generation of tropospheric ozone. severe metals and other pollutants are also mobilized from soils into aquatic and terrestrial ecosystems by severe rains and flooding. As a result, pollution has become a global ecological challenge due to climate change (IPCC, 2023; Agathokleous et al., 2021; Mills et al., 2018; Tai et al., 2021).

These interactions have a major impact on ecological functioning and plant metabolism. In certain plant species, elevated atmospheric CO2 may enhance photosynthetic carbon fixation; however, ozone-induced oxidative damage, nutritional limitation, heat stress, and water scarcity often offset this beneficial effect. In a similar vein, rising temperatures speed up metabolism and respiration, boosting the formation of reactive oxygen species (ROS) and decreasing the effectiveness of antioxidant defense mechanisms. Thus, rather than being separate environmental stressors, pollution and climate change should be viewed as interrelated causes of vegetation decrease (Ainsworth, 2017; Fuhrer & Booker, 2016; IPCC, 2023).

1. Principal Elements of Pollution Syndrome

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A wide spectrum of structural, physiological, biochemical, molecular, and ecological changes brought on by extended exposure to environmental pollutants under shifting climatic conditions are collectively referred to as pollution syndrome. Depending on their genetic traits, developmental stage, pollutant concentration, and environmental circumstances, different plant species have different reactions.

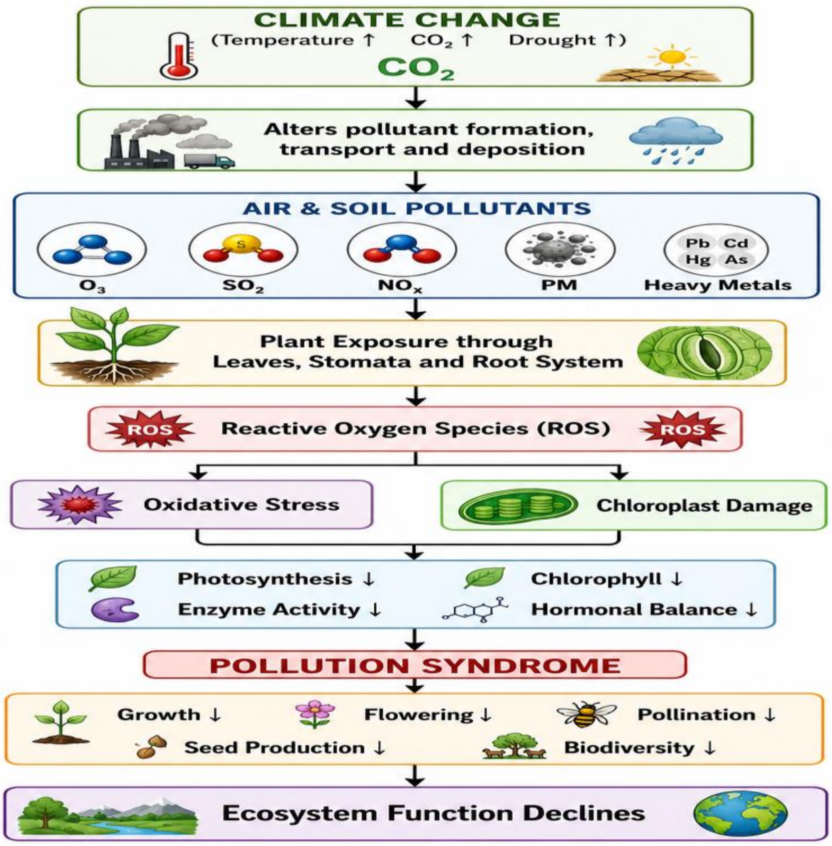
The main elements consist of:

- Damage to the morphology (chlorosis, necrosis, leaf bronzing, curling)
- A decrease in the amount of chlorophyll
- A reduction in photosynthesis
- ROS buildup and oxidative stress

An imbalance of hormones

- Modified metabolism of nutrients
- Decreased viability of pollen
- Flowering phenology disturbances
- A decrease in seed output
- Reduced crop production and biomass
- interactions between microbes and plants
- A reduction in the resilience of ecosystems

Together, these reactions lower ecosystem stability and plant production (Rai, 2016; Agathokleous et al., 2021; Sharma et al., 2020).



2. Oxidative Stress: The Main Process

The main physiological process causing pollution syndrome is oxidative stress. Reactive oxygen species (ROS), such as superoxide radicals ($O_2^{\bullet-}$), hydrogen peroxide (H_2O_2), hydroxyl radicals ($\bullet OH$), and singlet oxygen ($^1O_2$), are produced in excess when environmental contaminants are present. ROS are formed naturally during respiration and photosynthesis, but when they build up too much, they injure cellular components beyond what antioxidant mechanisms can detoxify (Gill & Tuteja, 2010; Sharma et al., 2012; Rai, 2016).

ROS cause lipid peroxidation, DNA damage, protein denaturation, enzyme inhibition, and disruption of membrane integrity by attacking membrane lipids, proteins, nucleic acids, and chloroplast structures. Because photosynthetic electron transport continuously produces ROS under environmental stress, chloroplasts are especially vulnerable. As a result, pollution syndrome symptoms include lower photosynthetic efficiency, decreased Rubisco activity, impaired carbon absorption, and chlorophyll degradation (Ainsworth, 2017; Agathokleous et al., 2021).

In addition to non-enzymatic antioxidants like ascorbic acid, glutathione, carotenoids, flavonoids, tocopherols, and phenolic compounds, plants also activate enzymatic antioxidants like superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), glutathione reductase (GR), and ascorbate peroxidase (APX). Long-term exposure to combined climatic and pollution stress eventually overwhelms cellular defense mechanisms, resulting in irreversible physiological damage, even if these antioxidant systems aid in the neutralization of ROS (Sharma et al., 2020; Rai, 2016).

3. Impact on Flowering Phenology

Both climate factors and air pollution have a significant impact on flowering phenology. While air pollution affect flower shape, pollen development, nectar secretion, and floral volatile organic compounds (VOCs), rising temperatures have caused many temperate and tropical species to flower earlier. Ecosystem stability is threatened by these changes, which lower pollinator attractiveness and reproductive success (Fitter & Fitter, 2002; IPCC, 2023; Agathokleous et al., 2021).

By causing oxidative damage to reproductive organs, tropospheric ozone reduces pollen viability. Pollinator visitation is restricted by particulate matter deposited on floral surfaces, and heavy metals impede pollen germination and tube elongation. Communication between flowers and insect pollinators is further disrupted by changes in floral fragrance composition brought on by pollutants. Therefore, in many ecosystems, falling pollination efficiency and seed production are caused by both pollution exposure and climate-driven phenological changes (Fuhrer & Booker, 2016; Tai et al., 2021).

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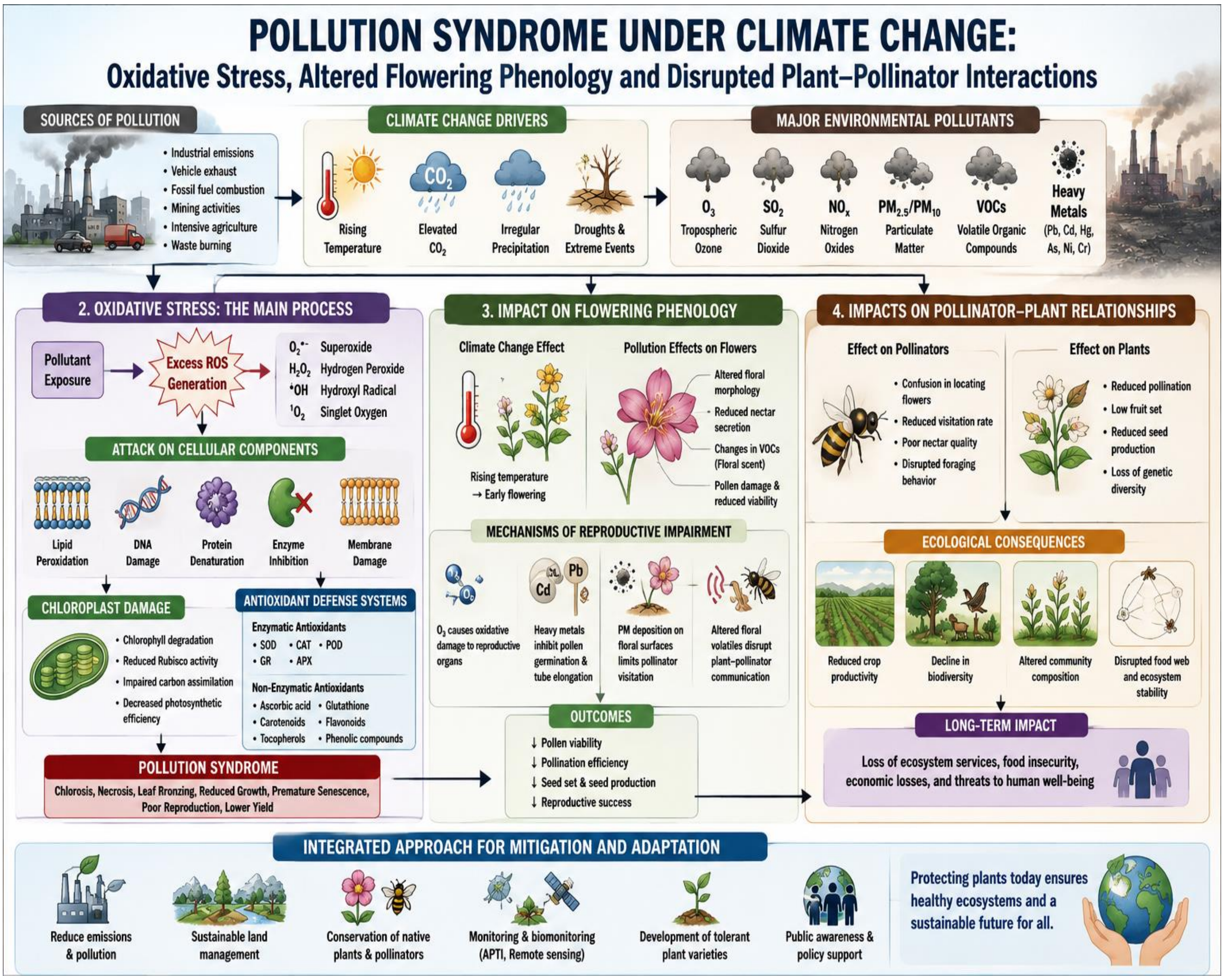

4. Impacts on Pollinator-Plant Relationships

One of the biological processes most at risk from pollution syndrome is pollination. To find suitable plants, pollinators use visual clues, floral scent, nectar rewards, and flowering synchronization. While pollutants degrade volatile floral chemicals and affect nectar quality, causing pollinator confusion and lower visiting rates, climate change alters flowering seasons (Agathokleous et al., 2021). Fruit output, seed set, and genetic diversity within plant populations are all negatively impacted by reduced pollination. In biodiversity hotspots with specific pollination systems, these effects are very severe. Long-term disturbance of plant-pollinator interactions may eventually change the stability of the food web, ecological productivity, and community composition (IPBES, 2019; Potts et al., 2016).

Conclusion

Chlorosis, necrosis, decreased chlorophyll content, poor photosynthesis, early leaf senescence, and disrupted blooming phenology are all symptoms of pollution syndrome in plants that have been exacerbated by climate change and air pollution. In addition to upsetting plant-pollinator relationships and ecological balance, these modifications have a detrimental impact on plant growth, reproduction, biodiversity, and ecosystem services. Increasing environmental stress frequently surpasses the tolerance limits of many plant species, despite the fact that they have adaptive mechanisms including antioxidant defenses and physiological adaptations. Remote sensing, physiological indicators, and the Air Pollution Tolerance Index (APTI) are useful tools for tracking plant health and finding species that can withstand pollution. To further understand plant responses, future study should incorporate molecular biology, artificial intelligence, climate modeling, and long-term ecological monitoring. Climate-resilient management techniques, native vegetation conservation, and efficient pollution control are crucial for maintaining

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