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Air Pollution Alters Floral Scent Signals and Pollinator Behavior in Native Plant Species

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ABSTRACT

Essential cues that draw pollinators are provided by floral hydrocarbons. However, hydrocarbons are degraded by chemical reactions involving pollutants like ozone as soon as they are released into the atmosphere. Therefore, it is likely that pollinator-attracting hydrocarbon signals are disrupted by increased air pollution. The position of air parcels distant from hydrocarbon sources and the rate at which hydrocarbons were chemically destroyed as air parcels traveled across the landscape were determined using a Lagrangian diffusion model in order to test this theory. Since linalool, β-myrcene, and β-ocimene are hydrocarbon chemicals that are frequently emitted from flowers, they were selected. Increased regional concentrations of ozone, hydroxyl, and nitrate radicals were shown to be associated with decreased ambient abundances of volatile organic molecules. Floral hydrocarbons give vital signals that attract pollinators. However, as soon as hydrocarbons are released into the atmosphere, they are broken down by chemical processes involving pollutants like ozone. Therefore, it is likely that rising air pollution disrupts hydrocarbon signals that attract pollinators. This notion was tested by using a Lagrangian diffusion model to predict the location of air parcels far from hydrocarbon sources and the rate at which hydrocarbons were chemically degraded as air parcels moved across the terrain. Linalool, β-myrcene, and β-ocimene were chosen because they are hydrocarbon compounds that are commonly released from flowers. It has been demonstrated that lower ambient abundances of volatile organic molecules are linked to higher regional concentrations of ozone, hydroxyl, and nitrate radicals.

KEYWORDS
Air pollution; Floral scent; Pollinator behavior; Native plants; Plant–pollinator interactions; Volatile organic compounds (VOCs); Biodiversity conservation; Climate change

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1. Introduction

One of the biggest environmental issues of the twenty-first century is air pollution, which has an impact on global ecosystem functioning, agricultural output, biodiversity, and human health. The concentration of atmospheric pollutants, such as ground-level ozone (O_3), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), ammonia (NH_3), particulate matter ($PM_{2.}{}^{1}$ and $PM_{1}{}^{1}$), and volatile organic compounds (VOCs), has significantly increased due to anthropogenic activities like industrialization, rapid urbanization, fossil fuel combustion, vehicular emissions, mining, thermal power generation, and burning of biomass. These pollutants affect the physiological, biochemical, and ecological processes that control plant growth and ecosystem stability in addition to degrading the quality of the air.

Studies on air pollution have traditionally concentrated on obvious damage to plants, such as necrosis, chlorosis, early leaf senescence, decreased photosynthetic efficiency, poor carbon absorption, and lower agricultural output (Ainsworth, 2017; Feng et al., 2018). However, air pollution also interferes with plant-pollinator communication, one of the most crucial ecological interactions that sustain terrestrial biodiversity, according to recent developments in chemical ecology (Ryalls et al., 2022; Chan et al., 2024). Because flower aroma serves as a long-distance chemical signal that directs pollinating insects toward floral resources, it is one of the most important communication processes between plants and pollinators. According to Potts et al. (2016) and IPBES (2016), loss or change of floral fragrance by air pollutants may hence lower pollination efficiency and ultimately jeopardize both natural ecosystems and global food security.

One of the most important ecosystem services is pollination, which supports the reproduction of over 87% of flowering plant species and 75% of food crops and contributes between USD 235 and 577 billion to global agriculture each year (IPBES, 2016; Potts et al., 2016). Thus, a growing area of study in environmental science, plant biology, atmospheric chemistry, and conservation ecology is how air pollution affects flower smell chemistry and pollinator behavior.

1. The Chemical Communication System of Floral Scent

In order to promote interactions with pollinating animals, flowering plants have developed complex communication systems. These systems include chemical signals known as floral volatile organic compounds (VOCs) as well as visual signals such flower color, UV patterns, floral morphology, and nectar rewards. Because volatile molecules spread through the atmosphere and can be noticed before blooms become physically apparent, floral aroma is thought to be the most effective long-distance attractant among these cues (Raguso, 2016; Dudareva et al., 2013).

Monoterpenes, sesquiterpenes, benzenoids, phenylpropanoids, fatty acid derivatives, and nitrogen-containing chemicals are among the hundreds of low-molecular-weight substances that make up floral volatile organic compounds (VOCs) (Knudsen & Gershenzon, 2020). Pollinators are able to differentiate between different plant species because each flowering species releases a distinct combination of these molecules, creating a distinctive chemical fingerprint. According to Junker and Parachnowitsch (2015) and Schiestl (2015), these fragrance profiles are very species-specific and frequently change depending on flowering stage, time of day, ambient factors, and pollinator preferences.

Mevalonate, methylerythritol phosphate, shikimate, and fatty acid metabolic pathways are the primary processes used in the manufacture of floral volatile organic compounds. The amount and makeup of floral fragrance emissions are determined by the enzymatic control of these pathways. According to Dudareva et al. (2013) and Peñuelas & Staudt (2010), environmental stressors such drought, temperature changes, high atmospheric CO_2, and air pollution can modify these metabolic processes and change the composition and emission rates of floral scents.

2. Floral Fragrance's Significance in Pollinator Attraction

In order to locate nectar and pollen supplies, pollinators heavily rely on smell cues. The highly developed olfactory sensors of honey bees (Apis mellifera), bumblebees (Bombus spp.), butterflies, moths, hoverflies, beetles, wasps, and even some birds can detect floral volatile organic compounds (VOCs) at very low concentrations (Raguso, 2016; Kantsa et al., 2018).

Essential ecological information, such as flower identity, nectar availability, pollen quality, floral age, and reproductive status, can be obtained through floral aroma. Pollinators combine visual and olfactory cues to enhance learning behavior and maximize foraging efficiency. For instance, honey bees have a phenomena called floral constancy in which they visit flowers that produce recognizable volatile organic compound (VOC) blends on a regular basis and are able to retain complicated floral aroma mixtures.

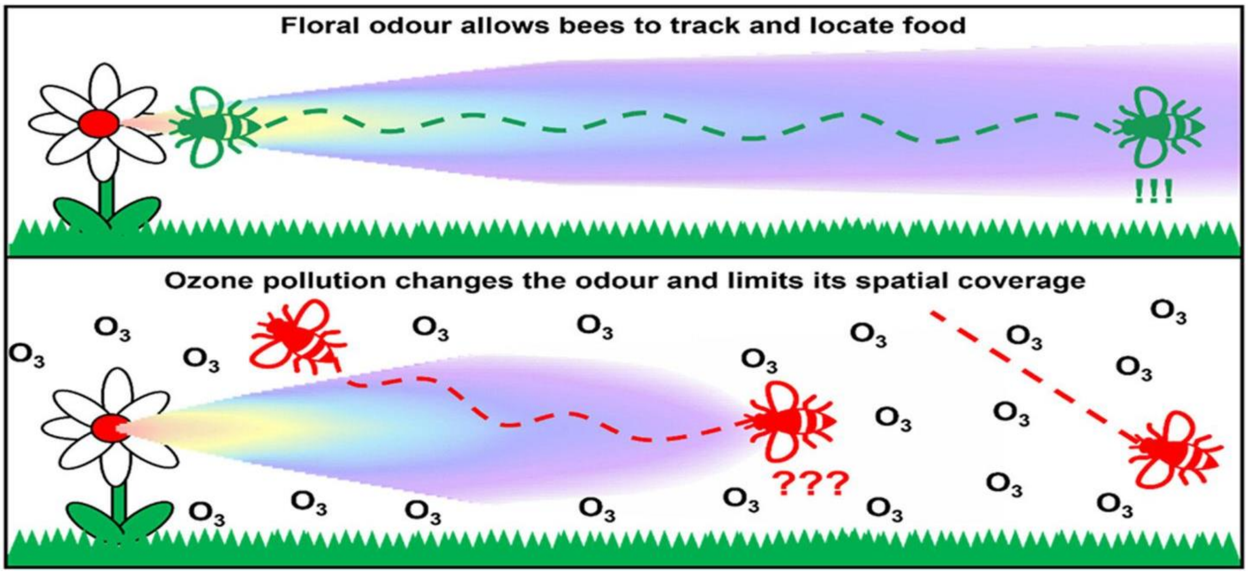
Floral volatile organic compounds (VOCs) not only draw pollinators but also mediate a number of ecological processes, such as defense against herbivores, attraction of pests' natural enemies, communication between nearby plants, and reproductive isolation between closely related plant species (Junker & Parachnowitsch, 2015). Therefore, altering the chemistry of floral scents has consequences that go beyond pollination and impact entire ecological networks.

3. Air Pollution and Chemistry of the Atmosphere

Through oxidation, photochemical reactions, and secondary aerosol generation, air contaminants and atmospheric chemicals are constantly interacting. When flower volatile organic compounds (VOCs) are released into the atmosphere, they quickly react with reactive pollutants like ozone (O_3), nitrate radicals (NO_3), and hydroxyl radicals (OH). According to Fuentes et al. (2016) and McFrederick et al. (2008), these oxidation reactions transform physiologically active fragrance molecules into secondary oxidation products that are chemically different from the original chemicals and are frequently unrecognizable to pollinating insects.

According to atmospheric chemistry models, floral scent plumes can travel 800–1000 meters in relatively clean environments, but in polluted urban areas, this distance is reduced to less than 200–300 meters due to the rapid degradation of volatile molecules by reactive pollutants (Fuentes et al., 2016). Pollinators are less likely to find flowers as a result of the fragmented, weaker, and chemically distorted floral scent trails.

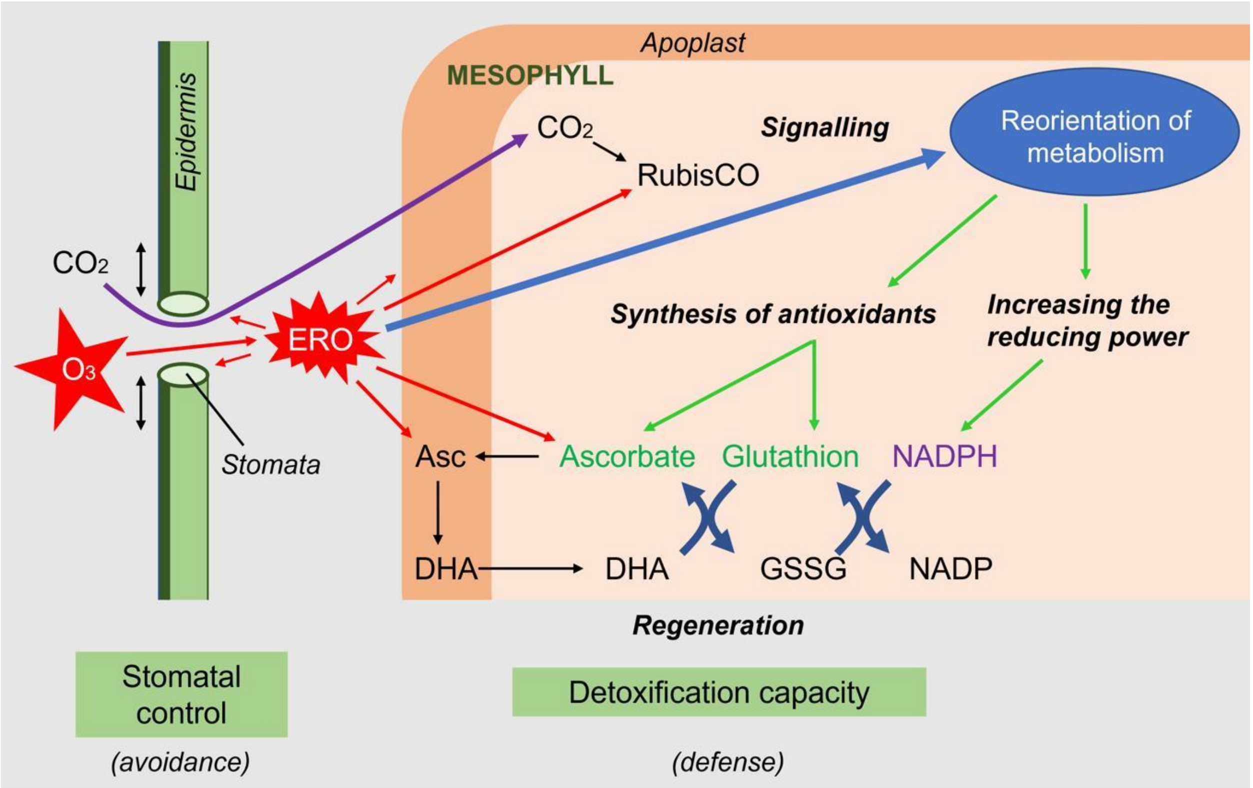
Because of its potent oxidizing potential, ground-level ozone is regarded as one of the most harmful pollutants. Terpenes, benzenoids, and unsaturated hydrocarbons included in floral VOC combinations react easily with ozone, thus shortening the scent's duration (Agathokleous et al., 2020). According to Girling et al. (2013), vehicle exhaust pollutants that contain nitrogen oxides and particulate matter deteriorate the floral scents that honey bees employ, which lowers blossom recognition and foraging efficiency.



4. Floral Fragrance Deterioration: New Information

There is strong evidence from recent experiments that air pollution directly hinders the conveyance of flower scents. Fuentes et al. (2016) showed that ozone dramatically reduced the atmospheric lifespan of floral volatile organic compounds (VOCs), decreasing pollinator attraction across vast distances, using atmospheric simulation chambers. Similarly, Girling et al. (2013) demonstrated that diesel exhaust quickly deteriorated important floral aroma molecules, making it impossible for honey bees to identify profitable blooms.

More recently, Chan et al. (2024) found that under environmentally realistic settings, nitrate radicals produced by anthropogenic air pollution inhibited nocturnal moth pollination by degrading floral smells based on monoterpenes. These results are among the best examples of how air pollution can directly impede plant-pollinator communication and lower ecosystem performance.



5. Oxidative Stress and Modification of Floral Volatile Organic Compounds Caused by Air Pollution

Air pollutants affect flowering plants by interfering with the physiological and biochemical processes that produce floral smell molecules, as well as by breaking them down after they are released into the atmosphere. Superoxide radicals ($O_2{\bullet}-$), hydrogen peroxide (H2O_2), hydroxyl radicals (•OH), and singlet oxygen ($^1O_2$) are among the reactive oxygen species (ROS) that are excessively produced when gaseous pollutants like ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter enter plant tissues through stomata. ROS homeostasis is normally maintained by antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR), and peroxidase (POD). According to Agathokleous et al. (2020), Hasanuzzaman et al. (2020), and Sharma et al. (2022), continuous exposure to air pollution overwhelms these antioxidant defense systems, resulting in oxidative stress.

Enzymes involved in the formation of secondary metabolites, proteins, lipids, nucleic acids, and chloroplast membranes are all harmed by oxidative stress. Oxidative damage modifies the quantity, composition, and timing of floral scent emissions because floral volatile organic compounds (VOCs) are produced via the mevalonate (MVA), methylerythritol phosphate (MEP), shikimate, and fatty acid pathways (Dudareva et al., 2013; Knudsen & Gershenzon, 2020; Pichersky & Raguso, 2018). According to Feng et al. (2018) and Agathokleous et al. (2020), flowers grown in contaminated environments

frequently produce reduced quantities of desirable monoterpenes, sesquiterpenes, benzenoids, and phenylpropanoids while simultaneously boosting the emission of stress-related volatiles.
According to a number of studies, exposure to ozone decreases photosynthetic efficiency, chlorophyll concentration, carbon absorption, nectar production, pollen viability, and floral lifetime. As a result, pollinating insects find flowers less appealing (Ainsworth, 2017; Feng et al., 2022). Long-term exposure to nitrogen oxides and particle matter has been shown to cause similar physiological reactions, suggesting that air pollution affects both floral chemistry and reproductive development.

6. Pollinator Behaviour and Air Pollution

To recognize desirable flowers, pollinators rely on a variety of sensory cues, including as eyesight, smell, learning capacity, and spatial memory. Because they enable insects to identify floral resources from a great distance before blossoms are visible, olfactory signals are especially significant among these cues. Butterflies, moths, hoverflies, beetles, bumblebees, and honey bees all have extremely sensitive antennal sensors that can identify floral volatile organic compounds (VOCs) at concentrations as low as a few parts per billion (Raguso, 2016; Schiestl, 2015).

Pollinators obtain inaccurate or partial information about the location and quality of flowers when air contaminants chemically change floral fragrance plumes.
Bees exposed to ozone-polluted environments exhibit irregular flight paths, take much longer to find flowers, visit fewer flowers per foraging trip, and gather less nectar and pollen, according to laboratory and field experiments (Fuentes et al., 2016; Girling et al., 2013). These behavioral changes lower colony productivity and pollination efficiency, which ultimately hinders plant reproductive success. Nitrate radicals produced by anthropogenic pollution have been shown in recent field studies to interfere with nocturnal pollination by destroying the monoterpene-rich floral fragrance mixes that hawkmoths employ.
These results show that air pollution impacts both nocturnal pollination systems and diurnal pollinators like bees, increasing the ecological effects of air pollution (Chan et al., 2024). Additionally, pollutants disrupt pollinator cognition. To remember flower scents and link them to nectar rewards, honey bees use associative learning. Bees' capacity to identify previously visited flowers is diminished by pollution-induced changes in floral fragrance composition, which increases energy expenditure and reduces foraging efficiency (Leonard et al., 2011; Riffell et al., 2014). Butterflies, hoverflies, and solitary bees have all shown similar reactions, indicating that olfactory disturbance is a common ecological phenomena.

Methodology

In order to assess how air pollution affects pollinator behavior and floral fragrance cues in native plant species, this study uses a systematic review methodology. Internationally renowned scientific databases, such as Web of Science, Scopus, PubMed, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, Google Scholar, and JSTOR, were used to do a thorough literature search. A small number of groundbreaking studies published prior to 2015 were taken into consideration to provide fundamental knowledge on floral volatile organic compounds (VOCs), plant–pollinator interactions, and atmospheric chemistry. Peer-reviewed research articles published between 2015 and 2025 were mostly included.

Combinations of keywords like "air pollution," "floral scent," "volatile organic compounds (VOCs)," "pollinator behavior," "native plants," "ozone," "nitrogen oxides," "particulate matter," "oxidative stress," "plant–pollinator interactions," and "climate change" were used to find pertinent studies. The inclusion of articles pertaining to atmospheric pollution and floral smell ecology was limited to English-language publications that reported original research, field surveys, laboratory experiments, or review findings. Excluded were editorials, conference abstracts, duplicate publications, and research with insufficient methodological details.

The principal air pollutants (O_3, SO_2, NO_x, $PM_{2.}{}^{1}$, and $PM_{1}{}^{1}$), their impacts on floral VOC generation and degradation, native plant physiological responses, pollinator behavioral changes, and ecological repercussions were all extracted from the chosen literature through a rigorous analysis. Key findings, study species, analytical methods (e.g., Solid-Phase Microextraction (SPME), Gas Chromatography–Mass Spectrometry (GC–MS), and field pollinator observations), and experimental design were all methodically assembled. In order to determine common patterns, knowledge gaps, and future research directions regarding the impact of air pollution on plant–pollinator interactions, the gathered data were qualitatively summarized. This methodical approach facilitates the creation of successful conservation and air quality management plans by offering a thorough grasp of the most recent scientific findings.

Conclusion

By changing and breaking down volatile organic compounds, air pollution severely alters floral fragrance cues, which lowers pollinator attractiveness and pollination efficiency in native plant species. These modifications reduce biodiversity, hinder plant reproduction, and jeopardize the stability of ecosystems. Developing successful conservation strategies, enhancing air quality management, and protecting pollination services that sustain both natural ecosystems and global agricultural productivity all depend on an understanding of the relationships between atmospheric pollutants, floral scent chemistry, and pollinator behavior.

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