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The Science behind the Scent: The Role of Biogenic Volatile Organic Compounds in the Atmosphere

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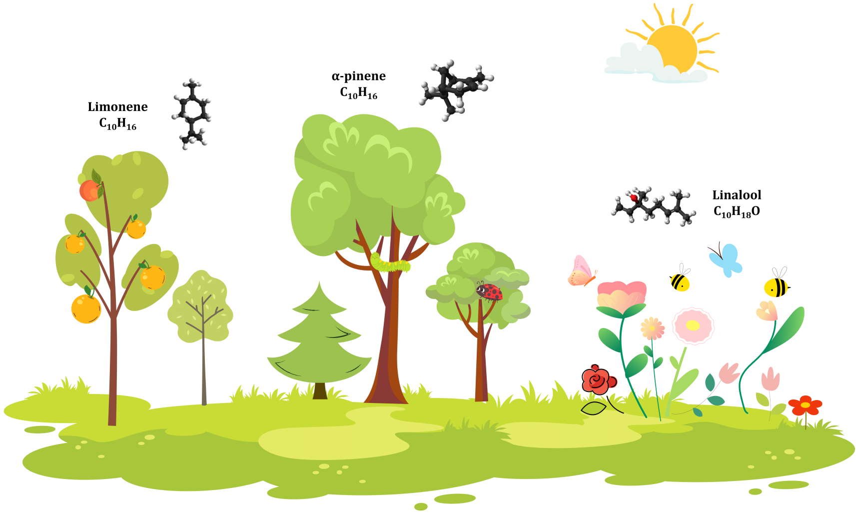
Highlights

- Chemically diverse BVOCs play key roles in plant defense.
- BVOC emissions strongly influence atmospheric chemistry and climate.
- Improved measurements and high-resolution models are needed to better understand BVOCs.



1. Introduction

The crisp scent of pine in a morning forest, the earthy aroma that rises after rain, and the burst of citrus fragrance when an orange is peeled; all these familiar moments are linked to the same invisible actors: biogenic volatile organic compounds (BVOCs). Emitted by plants as part of normal metabolism, BVOCs come in dazzling variety and are remarkably reactive. Systematic documentation began in the 1960s–1970s [1], and the scientific story has only grown richer since.

BVOCs are much more than nature's perfumes. In the atmosphere, they assume powerful roles: they help drive the formation of secondary pollutants such as ozone (O_3) and secondary organic aerosols (SOA), modulate the availability of cloud condensation nuclei, and influence the surface radiation balance. Through these intertwined processes, BVOCs link terrestrial ecosystems (e.g., forests, grasslands) to the atmosphere, integrating air quality and climate into a unified Earth system (Figure 1).

This article examines a deceptively simple yet fundamental question: How do BVOCs connect the "scents" we perceive with the "atmosphere" by shaping ecosystems, air pollution, and climate change? To answer this, we summarize the fundamental characteristics of BVOCs, describe the physiological pathways that govern their emissions, and explain their impact on air pollution and climate. In short, BVOCs influence not only the odors around us but also, quietly and persistently, the composition of the air we breathe.

2. Perspective

2.1. "Nature's Scent Envoys": An Introduction to BVOCs

BVOCs are organic gases released into the atmosphere by plants and microorganisms as part of routine metabolism. The crisp scent of pine in a forest, the sweetness of blooming flowers, and the zesty burst when an orange is peeled all trace back to these compounds. Forest ecosystems are the dominant terrestrial source of BVOC emissions, contributing on the order of 60–70% of global terrestrial emissions, with substantial methodological and interannual uncertainty arising from emission algorithms, driving meteorology, and land-cover datasets [2].

BVOCs are not a single molecule but a large family of related chemicals, whose diversity is remarkable. Scientists have identified over ten thousand distinct compounds, a breadth that rivals the variety of the plant kingdom [3]. Broadly, BVOCs are grouped into four categories: isoprene, monoterpenes (e.g., α-pinene, β-pinene, trans-β-ocimene, limonene), sesquiterpenes (e.g., β-caryophyllene, α-humulene), and oxygenated BVOCs (e.g., alcohols, aldehydes, ketones, and esters). Globally, the Model of Emissions of Gases and Aerosols from Nature (MEGAN v2.10) indicates that isoprene contributes roughly 50% of total BVOC emissions, while monoterpenes together with oxygenated BVOCs add about another 30%. The remaining 17% is supplied by a further set of about 20 compounds, predominantly terpenoids [2].

In nature, BVOC emission rates are not constant; they behave more like a highly sensitive biospheric "sensors" of environmental forcing. Light and temperature act as primary "accelerators": as irradiance increases and leaf temperature approaches a species-specific optimum, BVOC emissions typically intensify, whereas heat waves or drought rapidly depress emissions via stomatal closure and substrate limitation. The optimum temperature is not fixed. It varies with climate zones and plant species. Tropical vegetation generally has a higher optimum temperature, often above 40 °C, whereas temperate vegetation peaks around 35–40 °C. Consequently, tropical plants can sustain relatively active BVOC emissions under warmer conditions. Beyond light and temperature, water status and atmospheric dryness further regulate stomatal conductance, while carbon dioxide (CO_2) levels, nutrient availability, and phenological stage redistribute carbon and reshape metabolic pathways, thereby altering BVOC composition and flux. Biotic and abiotic stresses, including herbivory and O_3, can trigger defensive bursts of certain terpenoids. Finally, meteorological transport and mixing, such as wind speed and boundary-layer depth, further modulate the fate of these compounds above the canopy.

Consequently, BVOC emissions display pronounced spatiotemporal heterogeneity, with emission speciation and magnitude differing substantially across climates and plant functional types. For example, isoprene emission rates among different plant species range widely from 0.1 to 100 μg g^{-1} h^{-1}. Owing to diverse environmental conditions, species with very low to very high emission capacities are found across many plant families and even within key genera such as *Quercus* (oaks), *Picea* (spruce), *Abies* (firs), and *Acacia* [4]. On a global scale, trees emit BVOCs at rates approximately eight times those of shrubs, herbaceous plants, and crops [2]. Broad-leaved trees (e.g., *Populus*, *Quercus*, *Salix*), especially in tropical and warm-temperate regions, show the highest potential for releasing short-chain BVOCs such as isoprene. By contrast, needle-leaved trees (e.g., *Abies*, *Picea*, *Pinus*) in temperate and boreal zones tend to emit more monoterpenes [2]. Although tropical trees occupy only about 18% of global forest area [5], they account for nearly 70% of total BVOC emissions and approximately 80% of global isoprene and monoterpene fluxes [2].

2.2. "Plants' Hidden Arsenal": The Role of BVOCs in Plant Defense

BVOCs are far more than the hidden source of forest freshness or floral fragrance. They form a plant's "secret arsenal". Together, these molecules constitute a finely tuned chemical language that enables plants to communicate, coordinate, and rapidly mount defenses against environmental fluctuations and biotic threats [6].

When leaves are chewed, pathogens invade, or heat and drought intensify, plants quietly activate a biochemical "factory". For example, green leaf volatiles (GLVs) emerge within seconds of injury. These six-carbon (C_6) compounds, responsible for the familiar "fresh-cut grass" scent, not only inhibit pathogens but also signal neighboring tissues to prepare for damage. In addition, plants may emit terpenoids (e.g., monoterpenes and sesquiterpenes) and phenylpropanoids, which together create a chemical "smokescreen". These compounds deposit protective layers on leaf surfaces and interfere with herbivore feeding and host finding [7]. In addition to direct defenses, plants also deploy indirect defenses mediated by BVOCs. They release volatile scent cues that attract the natural enemies of herbivores, including predators and parasitoids such as wasps. It is as if the plant were shouting into the air: "Dinner is served, come and take care of these intruders!" These allies prey on or parasitize the attackers, thereby reducing damage and improving plant survival. Beyond within-plant signaling, neighboring plants can "eavesdrop" on these volatile signals and prepare their own defenses. This "neighborhood watch effect" transforms a patch of vegetation into a coordinated defense network, standing united against threats. Recent research even suggests that BVOCs may help plants store memories of past stress, so that individuals that have already endured herbivore attacks can respond faster and more strongly the next time danger strikes [8].

Beyond defense, BVOCs help steer growth and reproduction, subtly reshaping plant–ecosystem interactions [9]. They function like "traffic lights" for carbon allocation among leaves, flowers, and fruits. Floral scent bouquets precisely target pollinators, boosting pollination efficiency and seed set, while terpene- and carbonyl-rich aromas during fruit maturation modulate color and scent to attract dispersers and promote seed dispersal. At leaf and root interfaces, BVOCs can recruit microbial partners, strengthening mutualisms with mycorrhizal fungi and endophytes, and exert allelopathic effects that suppress competitors. In this way, from individual growth rhythms to community structure and the connectivity of species interaction networks, this invisible chemical language quietly shapes the living tapestry of ecosystems.

2.3. "The Shadow behind the Fragrance": BVOCs as Behind-the-Scenes Drivers of Air Pollution

When we breathe the freshness of a forest, we seldom realize that the same molecules are "busy" in the air, reshaping atmospheric chemistry. Each year, plants and microbes emit roughly 1 Pg C of BVOCs into the atmosphere. These emissions account for over 90% of the global VOC emissions and far exceed anthropogenic sources [2,10]. Although most BVOCs are not "pollutants" in the classical sense, their high reactivity and short atmospheric lifetimes (from seconds for isoprene to days for methanol) enable rapid conversion into two familiar "troublemakers": O_3 and SOA, making BVOCs behind-the-scenes drivers of air pollution [11].

On bright days, the atmosphere behaves like a sunlit "chemical reactor". Plant-emitted BVOCs act as the ingredients. Sunlight energizes them and they rapidly form highly reactive "helpers", notably peroxy radicals (RO_2). These "helpers" react with nitrogen oxides (NO_x) in a chain of steps that assemble oxygen into O_3 and cause near-surface O_3 to accumulate. In parallel, low-volatility oxidation products condense or partition into the particle phase to form SOA, a major component of fine particulate matter ($PM_{2.5}$) [12]. Chemistry continues after sunset: nitrate radicals (NO_3) oxidize specific BVOCs, sustaining SOA production in darkness. BVOC emissions are estimated to account for about 10–30% of urban surface O_3 levels [13], while contributing up to 90% of global SOA formation [14].

The same molecule can therefore yield very different consequences depending on altitude and chemical context. In the stratosphere, O_3 acts as the planet's "sunscreen" by absorbing biologically harmful ultraviolet radiation; near the surface, however, it becomes an unwelcome "guest" that irritates the respiratory tract, reduces lung function, and aggravates asthma. In 2019, long-term O_3 exposure was associated with around 365,000 premature deaths worldwide [15]. $PM_{2.5}$ is small enough to penetrate deep into the alveolar region and is linked to well-documented long-term cardiovascular and respiratory risks [16]. According to data from the 2019 "Global Air Status Report", an estimated 54% of the global population lived in areas with $PM_{2.5}$ concentrations above 35 μg m^{-3}, which contributed to about 2.9 million premature deaths attributable to $PM_{2.5}$ exposure [15].

Even at relatively low concentrations, BVOCs serve as critical precursors to both O_3 and $PM_{2.5}$. In NO_x-rich urban environments, the "green fragrance molecules" emitted by plants can team up with anthropogenic emissions, amplifying the complexity of secondary pollution [17]. Under these conditions, human pollution can shift the chemistry so that nature's perfume turns from "green" to "gray" [18]. To mitigate urban O_3 and SOA pollution, greening plans should prioritize low-BVOC-emitting species and cultivars and avoid known high emitters in O_3-prone corridors [17]. For example, maples (*Acer*) and lindens (*Tilia*) are often comparatively low isoprene emitters, whereas poplars (*Populus*), oaks (*Quercus*), eucalypts (*Eucalyptus*), and willows (*Salix*) typically emit more. Final choices should be guided by region-specific emission factors and co-benefits (e.g., shade, drought tolerance, allergenicity) and coordinated with local NO_x control.

2.4. "The Invisible Climate Tuner": How BVOCs Shape Earth's Climate

When climate change enters the conversation, we tend to think first of headline greenhouse gases such as CO_2 and methane (CH_4). Yet nature also deploys a quieter cast of climate shapers: BVOCs. Think of every plant in a forest, grassland, or backyard as a pocket-sized "natural air conditioner." When sunlight strikes a leaf, BVOCs are released. Beyond lending forests their piney freshness and fruit their perfume, these molecules enter a web of atmospheric chemistry that subtly tunes the climate system [6]. Although their net climate impact is smaller than that of major greenhouse gases and remains uncertain in sign and magnitude, BVOCs can exert regionally meaningful effects through SOA formation, aerosol–cloud interactions, and O_3 chemistry [19].

As mentioned above, BVOCs react with NO_x and contribute to the formation of SOA. These tiny particles act like Earth's sunglasses because they can scatter and absorb sunlight. Many SOA-containing particles also serve as cloud condensation nuclei (CCN). CCN are particles 10 to 100 nanometers in diameter, roughly one-thousandth the width of a human hair. They act as "seeds" to help water vapor condense into cloud droplets. As a result, thicker, more reflective clouds then return additional sunlight to space, enhancing surface cooling [12,20]. According to global model simulations, SOA produced from BVOC emissions causes a global-mean reduction of 0.03% in total surface shortwave radiation, corresponding to an annual mean radiative effect of −0.08 W m^{-2} [21]. In this sense, BVOCs are not just fragrance makers; they are architects of clouds, a role that is especially pronounced in tropical rainforests and other humid regions where such processes can influence local rainfall patterns and energy balance.

At the same time, BVOCs participate in O_3 formation. O_3 is not only protective in the stratosphere; in the lower atmosphere it acts like a thin extra "blanket" that absorbs Earth's outgoing longwave radiation, increases radiative forcing, and raises temperature. O_3 also consumes hydroxyl radicals (OH), the atmosphere's primary "cleanup agents". With fewer OH radicals, CH_4 breaks down more slowly and persists longer, which subtly turns up the planet's warming dial. In sum, BVOCs can amplify warming by fostering O_3 production and reducing OH, thereby extending the lifetime of CH_4.

3. Conclusions

In nature's "palette of scents", BVOCs are subtle yet indispensable. The piney drift of a conifer forest, the honeyed breath over a blooming field, the zesty snap of an orchard, all bear their signature. Beyond fragrance, BVOCs serve both as a "chemical language" among plants and as "active agents" in the atmosphere.

Over the past few decades, understanding of BVOC emissions, atmospheric transformations, and climate impacts has advanced steadily. Nevertheless, substantial uncertainties persist. Emission fluxes exhibit strong spatial and temporal variability, reaction pathways are highly nonlinear, and interactions with anthropogenic pollutants create complex feedbacks. Moving forward, progress can be accelerated on several fronts:

(1) Advance high-precision measurement technologies

BVOCs are remarkably diverse, and their emissions vary with plant species, climate, season, and even between day and night. Moreover, because the chain reactions involving BVOCs, NO_x, and oxidants evolve rapidly and cannot be directly controlled in the atmosphere, accurately characterizing BVOC composition and capturing these fast-evolving chemical processes requires instruments with higher spatial and temporal resolution and enhanced sensitivity across multiple platforms.

In practice, this entails deploying state-of-the-art mass spectrometry (e.g., PTR-MS/CIMS/HR-ToF-MS) and gas chromatography–mass spectrometry (GC–MS) for speciation, co-located with real-time analyzers for NO_x, O_3, and total OH reactivity. Eddy-covariance flux towers, aircraft and UAV transects, and satellite or imaging-spectrometer retrievals should be integrated to resolve leaf-to-landscape gradients. Standardized calibrations and intercomparisons will ensure traceability across sites and seasons. Together, these advances will reduce measurement uncertainty, reveal the true composition of BVOCs, and provide the spatiotemporal detail needed to test and improve emission inventories and atmospheric chemistry models.

(2) Develop AI-based emission prediction models

With the rapid rise of artificial intelligence (AI), research on BVOC emissions is increasingly integrating intelligent modeling. Machine-learning methods now capture the nonlinear responses of emissions to temperature, light, and phenology. In parallel, multi-source datasets, including satellite observations, eddy-covariance flux towers, and urban tree registries, are being assimilated and inverted to update emission inventories dynamically.

Looking ahead, coupling physics-constrained AI models with traditional emission frameworks can lower computational costs, provide rigorous uncertainty quantification, and improve the accuracy and timeliness of BVOC emission estimates.

(3) Refine high-resolution atmospheric chemistry models

Although BVOC levels are often low in cities, they readily interact with NO_x from vehicles and industry, promoting O_3 and $PM_{2.5}$ and complicating urban air chemistry. Small shifts in NO_x or sunlight can flip the fate of peroxy radicals, steering reactions toward O_3 production or toward low-volatility products that form SOA. Daytime OH oxidation, nighttime NO_3 chemistry, autoxidation, and multiphase pathways (e.g., gas–particle partitioning, aqueous processing, oligomerization) interact on timescales of seconds to hours. Yields depend on temperature, humidity, oxidant levels, and the composition and mixing state of pre-existing organic aerosol, which makes simple linear scaling unreliable. This natural–anthropogenic "chemical alliance" introduces substantial uncertainty into air quality forecasts.

To capture these production and loss processes, models need finer spatial grids (tens to a few hundred meters) that resolve street canyons, canopy shading, and subgrid turbulence, together with updated chemical mechanisms and dynamic partitioning schemes.

(4) Integrate BVOCs–climate dynamic feedback modeling

BVOC emissions not only influence climate change directly but are also shaped by it in turn. In other words, the interaction between BVOCs and climate is bidirectional, forming a tightly coupled feedback system. Climate change regulates both the magnitude and composition of BVOC emissions through multiple pathways. As global warming intensifies, more frequent and prolonged heat waves and droughts alter plant physiology and metabolic activity, thereby modulating BVOC release. For example, rising temperatures generally stimulate the emission of short-chain BVOCs such as isoprene, whereas extreme heat or water stress can suppress emissions through stomatal closure and substrate limitation [22]. At the same time, the continuous rise in atmospheric CO_2 concentration exerts a dual influence. Elevated CO_2 tends to reduce BVOC emissions by limiting the availability of photosynthetic substrates, yet its "fertilization effect" enhances vegetation growth and leaf area, indirectly increasing BVOC emission potential on larger spatial scales [23]. Over longer timescales, climate-driven changes in land cover and vegetation community composition, including species turnover, urban and rural greening, afforestation, and ecosystem restoration, will further reshape regional BVOC emission patterns [24]. Because these factors often act in opposite directions and interact nonlinearly, the magnitude and even the sign of climate impacts on BVOC emissions remain uncertain. This intricate feedback makes BVOCs a critical yet uncertain component in predicting future biosphere–atmosphere–climate interactions [23].

To meet this challenge, assessments should move beyond single drivers and adopt a multifactor perspective that integrates climatic, ecological, and anthropogenic influences. There is an urgent need to develop a dynamic feedback framework that links BVOC emissions, atmospheric chemistry, and climate effects, supported by high-resolution observations and intelligent data assimilation. This approach will improve the dynamic simulation and prediction of feedbacks between BVOCs and climate.

(5) Mobilize public participation and community action

This "smellable yet invisible" chemistry of BVOCs extends beyond the laboratory and calls for public participation.

For residents and communities: Use illustrated guides and QR-coded tree tags to communicate the BVOC emission profiles and seasonal patterns of common species. Following a simple, standardized protocol, community members can use mobile apps or low-cost sensors to record species identity, phenological stage, leaf condition, perceived scent intensity, and on-site weather. Each entry should be time-stamped and geotagged (latitude and longitude) to map and track neighborhood-scale spatiotemporal variability in BVOCs.

For natural resources, planning, and urban forestry departments: Strengthen routine maintenance of urban plantings through appropriate irrigation, timely pruning, and integrated pest management. During high-risk periods (e.g., heat waves and drought), implement emergency care and cooling measures to mitigate plant stress and reduce abnormal, stress-induced BVOC emissions.

For environmental regulators: Use monitoring and modeling to delineate "O_3 high-risk corridors," and share the results with parks or forestry and housing or urban construction agencies. In high-risk areas, prioritize low-emitting species (e.g., maples, lindens, zelkovas, and ginkgo) and avoid large monocultures of high-emitting trees. Apply time-of-day restrictions on solvent-based painting, cleaning, and pesticide application during hot afternoons (shifting work to morning or evening windows), and tighten NO_x-emission controls for construction and maintenance equipment. These activities do not replace professional monitoring, but they densify the observation network and provide actionable information for scientists and city managers.

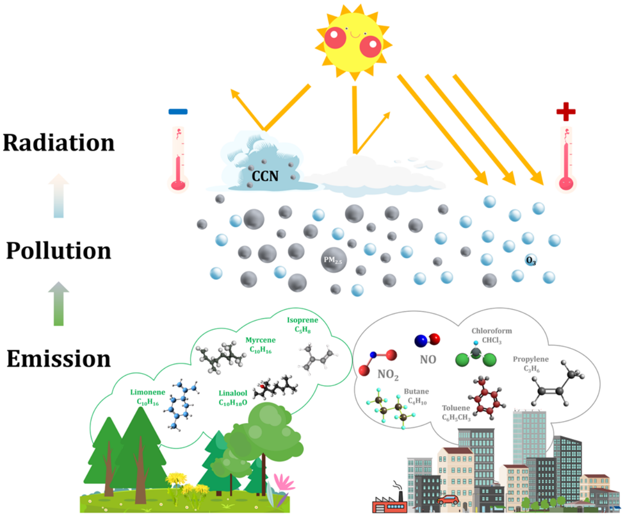


Figure 1. Conceptual diagram of BVOC processes from "Scent" to "Atmosphere": (1) Emission: leaves and fruits release BVOCs (e.g., pinene, limonene); (2) Pollution: BVOCs + NO_x + sunlight produce O_3 and SOA (a major component of $PM_{2.5}$); (3) Radiation: SOA acts as CCN and exerts a cooling effect, whereas O_3 exerts a warming effect.

Author Contributions

W.C. and M.S. designed the study. W.C. performed the research and wrote the initial draft of the paper. L.Z., P.D. and X.W. reviewed and revised the paper. All authors contributed to the discussion and interpretation of the results. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable for studies not involving humans or animals.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-assisted Technologies

During the preparation of this work, the authors used ChatGPT to polish the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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