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Application of Essential Oil-Based Organic Molecules in Chemical Sensor Development for Detection of Environmental Pollutants

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ABSTRACT

Environmental pollution has intensified the need for sensitive, selective, low-cost, and sustainable chemical sensors capable of detecting toxic substances in air, water, soil, and industrial surroundings. Conventional sensing materials often rely on synthetic reagents, expensive nanostructures, or environmentally burdensome fabrication routes. In this context, essential oil-based organic molecules have emerged as promising candidates for green sensor development because they are renewable, structurally diverse, chemically active, and capable of interacting with a wide range of analytes. Molecules such as eugenol, thymol, carvacrol, citral, cinnamaldehyde, menthol, limonene, linalool, geraniol, and vanillin contain functional groups including phenolic hydroxyl, aldehyde, alkene, ether, and alcohol moieties. These groups can participate in hydrogen bonding, redox reactions, coordination interactions, nucleophilic addition, fluorescence modulation, and surface adsorption processes that are useful in chemical sensing.

The present article examines the application of essential oil-based organic molecules in the development of chemical sensors for detecting environmental pollutants. It adopts a conceptual and analytical approach based on secondary sources from green chemistry, analytical chemistry, material science, environmental monitoring, and sensor technology. The discussion focuses on the chemical features of essential oil-derived molecules, their suitability as recognition elements or functional modifiers, and their possible integration with optical, electrochemical, colorimetric, and nanocomposite sensor platforms. Particular attention is given to pollutants such as heavy metal ions, volatile organic compounds, pesticides, nitroaromatic compounds, acidic/basic gases, and water contaminants.

The article argues that essential oil-derived molecules can support environmentally compatible sensing systems by improving selectivity, reducing dependence on hazardous reagents, and enabling biodegradable or low-toxicity sensor designs. However, challenges such as volatility, stability, reproducibility, interference, and standardization must be addressed before large-scale practical application. The study concludes that essential oil-based organic molecules represent an important bridge between natural product chemistry and sustainable sensor development.

Keywords: Essential oils; Organic molecules; Chemical sensors; Environmental pollutants; Green chemistry; Heavy metal detection; Volatile organic compounds; Sustainable sensing materials

1. INTRODUCTION

Environmental pollution has become one of the most serious scientific, social, and public health concerns of the present century. Industrialization, urban expansion, intensive agriculture, energy production, mining activities, transport emissions, and improper waste disposal have introduced numerous toxic substances into natural ecosystems. Water bodies are increasingly affected by heavy metals, pesticides, dyes, pharmaceuticals, petroleum residues, nitrates, and organic solvents. Air quality is deteriorating due to volatile organic compounds, nitrogen oxides, sulfur compounds, particulate matter, and toxic gases. Soil systems are similarly threatened by agrochemical residues, industrial effluents, and persistent organic pollutants. These contaminants do not remain confined to their original sources; they travel through environmental pathways, enter food chains, and pose long-term risks to human health, biodiversity, and ecological stability.

The accurate detection of environmental pollutants is therefore an essential requirement for pollution control, environmental governance, public safety, and sustainable development. Traditional analytical techniques such as atomic absorption spectroscopy, gas chromatography, liquid chromatography, inductively coupled plasma mass spectrometry, and spectrophotometry provide high precision and reliability. However, these methods often require sophisticated instruments, trained personnel, complex sample preparation, centralized laboratories, and relatively high operational cost. For routine monitoring, field-based detection, rapid screening, and decentralized environmental assessment, chemical sensors offer an attractive alternative. They can provide real-time or near-real-time responses, portability, miniaturization, low sample consumption, and rapid decision-making support.

A chemical sensor generally contains a recognition element that interacts with a target analyte and a transduction element that converts this interaction into a measurable signal. The signal may appear as a color change, fluorescence variation, electrical current, potential difference, resistance change, or optical response. The success of a chemical sensor depends largely on the chemical nature of the sensing material. Ideal sensing materials should be selective, stable, sensitive, reproducible, affordable, and environmentally safe. In recent years, sensor research has moved toward green and sustainable materials because many conventional synthetic receptors and nanomaterials may involve toxic solvents, expensive precursors, complicated synthesis, or ecological concerns.

Essential oils provide a valuable natural source for the development of sustainable sensing materials. They are complex mixtures of volatile organic compounds extracted from plants through distillation, expression, or solvent-free techniques. Their major constituents include terpenes, terpenoids, phenylpropanoids, aldehydes, alcohols, ketones, esters, ethers, and phenolic compounds. These molecules are not chemically passive. They possess reactive functional groups, pi-electron systems, redox-active centers, hydrophobic domains, and metal-binding possibilities. Such structural features make them suitable for interaction with environmental pollutants through coordination, charge transfer, hydrogen bonding, protonation-deprotonation, oxidation-reduction, adsorption, and fluorescence quenching or enhancement.

The use of essential oil-derived molecules in chemical sensing is also consistent with the principles of green chemistry. These molecules are renewable, plant-based, often biodegradable, and generally less hazardous than many synthetic reagents. Their incorporation into sensor platforms can reduce reliance on toxic chemical modifiers and support the design of eco-friendly analytical devices. They may be used directly as sensing agents, as functional groups attached to polymer matrices, as reducing or stabilizing agents in nanoparticle synthesis, or as surface modifiers that improve selectivity toward specific pollutants. Therefore, essential oil-based organic molecules occupy an important interdisciplinary position connecting natural product chemistry, analytical science, material chemistry, and environmental monitoring.

The present article explores how essential oil-based organic molecules can be applied in chemical sensor development for the detection of environmental pollutants. It focuses on the chemical logic behind their sensing behavior, the types of pollutants that can be detected, the major sensor platforms in which they may be used, and the challenges that need to be overcome for practical application. The discussion is particularly relevant because future environmental sensing systems must not only be accurate and efficient but also sustainable in their materials, fabrication processes, and end-of-life impact.

2. REVIEW OF LITERATURE

Research on chemical sensors has expanded rapidly due to growing environmental monitoring needs. Early sensor studies focused mainly on synthetic ionophores, inorganic semiconductors, conducting polymers, and metal-based complexes. These materials provided useful sensitivity and selectivity, but many of them required complex preparation or involved non-renewable resources. As the demand for sustainable analytical tools increased, researchers began examining natural compounds, bio-derived materials, and green synthetic routes for sensor fabrication.

A major stream of literature deals with plant-derived molecules as sensing agents. Natural phenolics, flavonoids, alkaloids, terpenoids, and essential oil constituents have been studied because they contain electron-rich groups capable of interacting with metal ions and organic pollutants. Phenolic compounds such as eugenol, thymol, and carvacrol are especially significant because their hydroxyl groups and aromatic systems can participate in redox reactions, hydrogen bonding, and metal coordination. Aldehydic compounds such as citral and cinnamaldehyde have been examined for their reactivity toward amines and nucleophilic species, while terpenes and alcohols have been considered for volatile compound sensing and surface functionalization.

Literature on green nanotechnology also supports the use of essential oil-derived molecules in sensor development. Several plant extracts and essential oil components have been used as reducing, capping, or stabilizing agents for metal nanoparticles. These nanoparticles can then act as optical or electrochemical sensing platforms. For example, changes in nanoparticle aggregation or surface plasmon resonance can produce visible color shifts in the presence of metal ions or toxic analytes. Essential oil molecules can improve the environmental profile of such synthesis by reducing the use of harsh reducing agents.

Electrochemical sensor research has also considered natural molecules as electrode modifiers. Carbon paste electrodes, glassy carbon electrodes, screen-printed electrodes, and nanocomposite electrodes can be modified with organic functional groups to improve analyte recognition. Essential oil-derived phenolics can contribute to electron transfer processes and may enhance detection of pollutants such as nitro compounds, phenolic contaminants, pesticides, and heavy metal ions. Their antioxidant and redox-active behavior makes them useful in signal amplification and selective interaction.

Optical and colorimetric sensor studies show that natural organic molecules may generate visible or fluorescence-based responses when exposed to target analytes. Many environmental pollutants alter the electronic environment of organic molecules through quenching, complex formation, proton transfer, or oxidation. Essential oil-derived molecules with conjugated systems or reactive aldehyde groups may therefore be incorporated into colorimetric strips, polymer films, hydrogel matrices, or nanoparticle systems for simple

visual detection. Such approaches are valuable for low-resource environmental monitoring because they do not always require expensive instrumentation.
The literature also identifies several limitations. Essential oil constituents may be volatile, chemically unstable under light or heat, and variable in composition depending on plant source, extraction method, and storage conditions. Their selectivity may be affected by interfering ions or mixed pollutant matrices. Reproducible sensor fabrication requires purified compounds, standardized immobilization methods, and careful calibration. Despite these limitations, the literature suggests that essential oil-derived organic molecules are promising candidates for future green chemical sensors, especially when combined with stable supports such as polymers, silica, carbon materials, metal-organic frameworks, or nanocomposites.

3. OBJECTIVES OF THE STUDY

The study is guided by the following objectives:
1. To examine the relevance of essential oil-based organic molecules in sustainable chemical sensor development.
2. To analyze the structural and functional properties of essential oil-derived molecules that support pollutant detection.
3. To discuss the use of these molecules in optical, electrochemical, colorimetric, and nanocomposite sensor platforms.
4. To evaluate their application in the detection of major environmental pollutants such as heavy metals, pesticides, volatile organic compounds, gases, and organic contaminants.
5. To identify the major challenges associated with stability, selectivity, reproducibility, and practical deployment of essential oil-based sensors.
6. To suggest future directions for developing eco-friendly, low-cost, and field-applicable chemical sensors based on natural organic molecules.

4. RESEARCH METHODOLOGY

The present article is conceptual and analytical in nature. It is based on secondary data collected from books, peer-reviewed research articles, review papers, environmental reports, and scientific literature related to essential oils, organic molecules, chemical sensors, green chemistry, nanomaterials, and environmental pollutant detection. The study does not involve laboratory experimentation or primary data collection. Instead, it synthesizes available scientific knowledge to develop a structured understanding of how essential oil-based organic molecules can be applied in chemical sensor development.
A qualitative review approach has been adopted. Relevant literature has been examined from the fields of analytical chemistry, natural product chemistry, environmental chemistry, material science, and sensor technology. The review focuses on the chemical characteristics of essential oil constituents, their interaction mechanisms with pollutants, their role in sensor platforms, and their advantages and limitations. Special attention has been given to compounds such as eugenol, thymol, carvacrol, citral, cinnamaldehyde, limonene, linalool, menthol, geraniol, and vanillin because these molecules are widely discussed in relation to antimicrobial activity, antioxidant behavior, chemical reactivity, and functional material development.
The method of analysis is descriptive, interpretive, and comparative. The descriptive component explains the nature of essential oil-derived molecules and the basic concept of chemical sensors. The interpretive component examines how molecular structure influences sensing behavior. The comparative component evaluates different sensing platforms and pollutant categories in terms of their suitability for essential oil-based sensor development. The study is limited by its dependence on secondary sources and by the fact that practical sensor performance may vary according to experimental design, purity of compounds, immobilization method, environmental conditions, and analyte concentration. Nevertheless, the article provides a useful conceptual base for future experimental research.

Essential Oil-Based Organic Molecules: Chemical Features and Sensor Relevance

Essential oils are natural volatile mixtures obtained from aromatic plants. Their composition varies according to plant species, climate, geographical origin, harvesting stage, extraction method, and storage conditions. Despite this variation, many essential oils contain recurring classes of organic molecules that are chemically relevant for sensor design. These include monoterpenes, sesquiterpenes, phenylpropanoids, alcohols, aldehydes, ketones, esters, ethers, and phenolic compounds. The value of these molecules in sensing lies in their functional groups and interaction potential.
Phenolic molecules such as eugenol, thymol, and carvacrol are especially important because they contain hydroxyl groups attached to aromatic rings. These structures can donate electrons, form hydrogen bonds, undergo oxidation, and interact with metal ions. Their electron-rich aromatic systems can also participate in pi interactions with organic pollutants. Such features may be used in electrochemical sensors, colorimetric

systems, or nanocomposite materials. For example, a phenolic molecule immobilized on an electrode surface may facilitate electron transfer when a pollutant is oxidized or reduced.

Aldehydic essential oil constituents such as citral and cinnamaldehyde possess carbonyl groups that can react with amines, hydrazines, and other nucleophilic pollutants. This reactivity can support selective detection through changes in optical absorption, fluorescence, or chemical structure. Alcoholic compounds such as linalool, geraniol, and menthol may contribute to hydrogen bonding and surface interactions, while terpene hydrocarbons such as limonene may be useful in hydrophobic sensing environments and volatile analyte interactions.

The structural diversity of essential oil molecules allows them to serve multiple roles in sensor systems. They may act as recognition elements, signal mediators, electrode modifiers, polymer additives, nanoparticle stabilizers, or green reducing agents. Their low toxicity and renewable origin make them attractive for environmentally responsible sensor fabrication. However, their volatility and sensitivity to oxidation require careful immobilization within stable matrices such as polymers, sol-gels, cellulose films, silica particles, graphene-based materials, or metal-organic frameworks.

Chemical Sensor Development and Sensing Mechanisms

Chemical sensor development involves the purposeful design of a material system that can recognize a target analyte and convert that recognition into an observable signal. Essential oil-based organic molecules can contribute to both recognition and signal generation. Their molecular interactions with pollutants may involve coordination bonding, hydrogen bonding, acid-base reactions, redox processes, hydrophobic interactions, nucleophilic addition, adsorption, or changes in molecular conformation. These interactions influence optical or electrical properties and thereby generate a measurable response.

In optical sensors, essential oil-derived molecules may cause or support changes in color, absorbance, fluorescence, or light scattering. A colorimetric sensor may show a visible change when a molecule forms a complex with a metal ion or reacts with a gaseous pollutant. Fluorescence-based systems may show quenching or enhancement when pollutant molecules disturb the excited state of the sensing material. Cinnamaldehyde-based structures, for example, may interact with amines, while phenolic compounds may participate in metal coordination or oxidation-dependent optical changes.

In electrochemical sensors, the sensing response is commonly measured through current, potential, impedance, or conductance. Essential oil-derived phenolics can be useful because many of them are electroactive. When incorporated into electrode materials, they may improve electron transfer, increase surface activity, or provide selective binding sites. They can be combined with carbon nanotubes, graphene oxide, metal nanoparticles, conducting polymers, or screen-printed electrodes to improve sensitivity and lower detection limits.

Nanocomposite sensors provide another important route. Essential oil molecules can be used to functionalize nanoparticles or support green synthesis of metal nanoparticles. The interaction of pollutants with such nanostructures may produce measurable optical or electrochemical changes. For example, aggregation of functionalized metal nanoparticles can create color shifts, while nanoparticle-modified electrodes can improve catalytic detection of pesticides or heavy metals. Thus, essential oil-derived molecules can help create hybrid systems that combine natural molecular recognition with the high surface area and signal amplification of nanomaterials.

Detection of Environmental Pollutants

Environmental pollutants are chemically diverse, and sensor development must therefore address different classes of contaminants. Heavy metal ions such as lead, mercury, cadmium, chromium, arsenic, copper, and nickel are among the most significant water and soil pollutants. They are persistent, non-biodegradable, and capable of bioaccumulation. Essential oil-derived molecules containing hydroxyl, methoxy, aldehyde, or aromatic groups may interact with metal ions through coordination or complexation. When these interactions alter optical or electrochemical signals, they can be used for detection.

Volatile organic compounds are another major pollutant category. They arise from paints, fuels, solvents, adhesives, industrial emissions, cleaning agents, and petrochemical processes. Compounds such as benzene, toluene, xylene, formaldehyde, acetone, and chlorinated solvents affect air quality and human health. Because essential oils themselves contain volatile organic constituents, their molecules may be useful in designing selective vapor-sensitive films. Hydrophobic terpenes and oxygenated terpenoids can interact with VOCs through absorption, swelling, polarity changes, or vapor-phase partitioning in polymer matrices.

Pesticides and agrochemical residues are particularly important in agricultural regions. Organophosphates, carbamates, organochlorines, and synthetic pyrethroids can contaminate water, soil, and food products. Essential oil-based sensor materials may support pesticide detection through electrochemical oxidation-reduction responses, enzyme-mimicking activity, or interaction with nanomaterial surfaces. Natural phenolic compounds can also contribute to antioxidant or redox-mediated sensing processes. Such sensors may be useful for rapid field screening of agricultural contamination.

Toxic gases and acid-base pollutants also represent important targets. Ammonia, hydrogen sulfide, nitrogen dioxide, sulfur dioxide, and acidic vapors can be monitored through sensors that respond to protonation, deprotonation, oxidation, or surface adsorption. Essential oil-derived aldehydes and phenolics may be incorporated into polymer films or colorimetric strips that respond to vapors through visible changes. This approach may be useful for low-cost indoor air monitoring, industrial safety, and storage environment assessment.

Organic contaminants such as phenols, nitroaromatic compounds, dyes, and pharmaceutical residues are also relevant. These pollutants often possess electron-withdrawing or redox-active groups. Essential oil-derived molecules may interact with them through pi-pi interactions, hydrogen bonding, or electron transfer. When supported on conductive or optical platforms, such interactions can produce measurable signals. Therefore, essential oil-based molecules have potential across multiple pollutant classes rather than being limited to a single environmental application.

Sensor Platforms Using Essential Oil-Derived Molecules

Several sensor platforms can incorporate essential oil-derived organic molecules. Colorimetric sensors are among the simplest and most practical. They produce visible color changes that can be detected by the naked eye or analyzed through a smartphone camera. Essential oil molecules can be immobilized on paper strips, polymer films, hydrogels, or nanoparticle suspensions. Their reaction or complexation with pollutants can generate color variation. Such systems are useful for rapid screening where advanced instruments are not available.

Fluorescence sensors provide higher sensitivity and can detect low concentrations of pollutants. Essential oil-derived molecules may be used directly if they possess fluorescence-active structures, or they may be coupled with fluorescent nanomaterials such as quantum dots, carbon dots, or metal-organic frameworks. Pollutants can quench or enhance fluorescence through energy transfer, electron transfer, or binding-induced changes. Natural molecule-functionalized fluorescent systems are promising for water pollutant detection, though photostability and interference control remain important considerations.

Electrochemical sensors are highly suitable for portable and quantitative environmental monitoring. Essential oil-derived molecules can modify electrode surfaces or act as mediators. They may improve selectivity toward metal ions, pesticides, phenolic pollutants, or nitro compounds. When integrated with screen-printed electrodes, such sensors can become disposable, low-cost, and field-applicable. The combination of essential oil molecules with graphene, carbon nanotubes, metal nanoparticles, or conducting polymers may further enhance performance.

Gas and vapor sensors may also benefit from essential oil-based molecules. Terpenes and terpenoids can be embedded in polymeric sensing layers that respond to volatile pollutants by swelling, resistance change, mass change, or optical variation. Such systems may be integrated with quartz crystal microbalance sensors, chemiresistive devices, or optical fiber sensors. Because air pollution monitoring increasingly requires small and distributed devices, natural molecule-based vapor sensors may have practical value.

Hybrid nanocomposite sensors represent a particularly promising direction. Essential oil molecules can provide selective organic functionality, while nanomaterials provide high surface area and signal amplification. This combination may produce sensors with better sensitivity than natural molecules alone and better sustainability than entirely synthetic systems. Future sensor design may therefore focus on stable immobilization of essential oil molecules within robust nanostructured matrices.

Advantages of Essential Oil-Based Sensor Materials

The most important advantage of essential oil-based organic molecules is their renewable and natural origin. Since they are obtained from plant sources, they align with sustainable material development and reduce dependence on petroleum-derived or highly hazardous chemicals. Their use supports green chemistry principles such as safer chemicals, renewable feedstocks, reduced toxicity, and environmentally conscious design. This is particularly important because sensor materials themselves should not contribute to the pollution they are intended to detect.

Another advantage is chemical diversity. Essential oils contain a wide range of molecular structures, each with distinct functional groups and reactivity. This diversity allows researchers to select molecules according to the target pollutant. Phenolic compounds may be useful for electrochemical and metal-ion sensing, aldehydes for amine or nucleophile detection, alcohols for hydrogen bonding interactions, and terpenes for hydrophobic vapor sensing. Such diversity enables flexible sensor design.

Essential oil-derived molecules are also relatively accessible and can often be obtained from widely available plant materials. In regions with strong medicinal, aromatic, and agricultural plant resources, these molecules may support locally relevant sensing technologies. Their incorporation into low-cost sensor platforms such as paper strips, polymer films, and disposable electrodes can improve environmental monitoring in rural, agricultural, and resource-limited settings.

The biological and chemical activities of essential oil molecules provide additional benefits. Many are antimicrobial, antioxidant, and chemically reactive. In some cases, a sensor surface containing these molecules may resist microbial contamination or fouling, which is useful for environmental samples. Their antioxidant behavior may also support redox-based sensing. Moreover, their pleasant odors and natural identity may improve acceptability in consumer-oriented or indoor monitoring devices.

5. CHALLENGES AND BARRIERS

Despite their promise, essential oil-based organic molecules face several challenges in sensor development. The first challenge is volatility. Many essential oil constituents evaporate easily, which may reduce sensor stability and reproducibility over time. If the sensing molecule is lost from the sensor surface, response intensity declines and calibration becomes unreliable. Immobilization in polymer matrices, encapsulation, or covalent attachment may be necessary to overcome this limitation.

A second challenge is chemical stability. Essential oil molecules can be sensitive to oxygen, light, heat, and moisture. Oxidation or degradation may alter their sensing behavior. For example, phenolic compounds may oxidize, aldehydes may undergo secondary reactions, and terpenes may form oxidation products during storage. This creates difficulty in producing sensors with long shelf life. Protective packaging and stabilizing matrices are therefore important.

A third challenge is selectivity. Environmental samples are complex and may contain several ions, organic compounds, salts, suspended solids, and pH variations. A molecule that responds well to one pollutant in pure solution may show interference in real samples. Selectivity must therefore be improved through molecular design, material engineering, masking agents, sensor arrays, or pattern-recognition approaches. Without selectivity, field application remains limited.

Standardization is another issue. Essential oil composition varies depending on plant source and extraction method. For reliable sensor fabrication, purified compounds or chemically characterized oils must be used. Batch-to-batch variation can otherwise affect sensor response. In addition, performance parameters such as detection limit, response time, recovery, repeatability, and stability must be validated under real environmental conditions.

Finally, scaling up essential oil-based sensors requires integration with practical devices. A promising material in the laboratory must be converted into a stable, user-friendly, portable, and affordable sensor. This requires interdisciplinary collaboration among chemists, material scientists, engineers, environmental scientists, and industry partners.

Suggestions and Future Implications

Future research should focus on stabilizing essential oil-derived molecules within durable sensor matrices. Polymer films, cellulose membranes, sol-gel networks, silica supports, hydrogels, carbon materials, and metal-organic frameworks can help reduce volatility and improve operational stability. Covalent immobilization may be especially useful when long-term sensor performance is required. Encapsulation techniques can also protect sensitive molecules from degradation while allowing analyte diffusion.

There is a need to design sensor arrays rather than relying only on single-molecule sensors. Since environmental pollutants often occur in mixtures, arrays containing different essential oil-derived molecules may generate response patterns that can be analyzed through chemometric or machine-learning methods. This approach can improve selectivity and allow detection of complex pollutant profiles. Smartphone-based color analysis and portable electrochemical readers may further improve field usability.

Researchers should also prioritize real-sample validation. Sensors should be tested in river water, groundwater, industrial wastewater, agricultural runoff, indoor air, and soil extracts rather than only in laboratory solutions. Such validation will reveal matrix effects and practical limitations. Long-term storage studies, repeatability tests, and interference studies are also necessary.

From a broader perspective, essential oil-based sensors may contribute to low-cost environmental monitoring in developing regions. They can support community-level water testing, agricultural safety, industrial compliance screening, and indoor air quality assessment. Their use may also encourage local value addition to aromatic and medicinal plants. Thus, the field has scientific, environmental, and socio-economic relevance.

6. CONCLUSION

The application of essential oil-based organic molecules in chemical sensor development represents a meaningful step toward sustainable environmental monitoring. These molecules possess functional groups, structural diversity, and chemical reactivity that can support the detection of heavy metals, volatile organic compounds, pesticides, toxic gases, and organic contaminants. Their renewable origin and relatively low toxicity make them attractive alternatives or complements to conventional synthetic sensing materials.

The discussion shows that essential oil-derived compounds can function as recognition elements, signal mediators, electrode modifiers, nanoparticle stabilizers, and polymer film additives. Their integration into colorimetric, optical, electrochemical, gas, and nanocomposite sensors opens several possibilities for rapid and low-cost pollutant detection. At the same time, practical application requires careful attention to volatility, stability, selectivity, reproducibility, and real-sample performance.

In conclusion, essential oil-based organic molecules should not be viewed only as fragrance or antimicrobial agents. They also offer significant potential in analytical and environmental chemistry. By combining natural product chemistry with modern sensor platforms, future research can develop greener, safer, and more accessible tools for detecting environmental pollutants. Such work can contribute to pollution control, public health protection, and the broader goal of sustainable technological development.

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