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REVIEW ARTICLE BENEFIT OF VOLATILE ORGANIC COMPOUNDS IN CITRUS SPECIES

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Abstrak

Senyawa organik mudah menguap dalam spesies Citrus, seperti jeruk, jeruk nipis, dan lemon, sangat penting bagi ekologi tanaman dan berbagai aplikasi manusia. Artikel tinjauan ini mengeksplorasi beragam manfaat senyawa organik mudah menguap Citrus, menyoroti perannya dalam mekanisme pertahanan tanaman, daya tarik penyerbuk, dan komunikasi intraspesies. Komposisi kimia senyawa organik mudah menguap Citrus mencakup senyawa utama seperti limonene, β-linalool, trans-citral, β-myrcene, α-Pinene, β-Pinene, γ-Terpinene, dan Terpineol, yang menunjukkan sifat anti-mikroba, anti-inflamasi, anti-oksidan, dan potensi anti-kanker yang signifikan. Senyawa-senyawa ini merupakan bagian integral dari kesehatan manusia, digunakan dalam aromaterapi, dan meningkatkan suasana hati serta mengurangi kecemasan. Secara industri, senyawa organik mudah menguap Citrus sangat diperlukan dalam industri makanan dan minuman sebagai bahan penyedap, dalam kosmetik dan produk perawatan pribadi karena aromanya yang menyegarkan dan manfaatnya bagi kulit, dan dalam produk pembersih karena sifat antimikrobanya. Lebih jauh lagi, potensi terapeutiknya telah menyebabkannya dimasukkan dalam produk farmasi dan nutraseutika1. Ulasan ini menggarisbawahi peran multifaset dan signifikansi ekonomi senyawa organik mudah menguap Citrus, yang menganjurkan penelitian berkelanjutan dan kemajuan teknologi untuk sepenuhnya memanfaatkan manfaatnya dalam kesehatan, industri, dan keberlanjutan.

Kata kunci: Senyawa Organik Mudah Menguap, Citrus, Jeruk Manis, Jeruk Lemon, Jeruk Nipis

Abstract

The volatile organic compounds in Citrus species, such as oranges, limes, and lemons, are crucial for both plant ecology and various human applications. This review article explores the diverse benefits of Citrus volatile organic compounds, highlighting their roles in plant defense mechanisms, pollinator attraction, and intraspecies communication. The chemical composition of Citrus volatile organic compounds includes key compounds like limonene, β-linalool, trans-citral, β-myrcene, α-Pinene, β-Pinene, γ-Terpinene, and Terpineol, which exhibit significant anti-microbial, anti-inflammatory, anti-oxidant, and potential anti-cancer properties. These compounds are integral to human health, utilized in aromatherapy, and enhancing mood and reducing anxiety. Industrially, Citrus volatile organic compounds are indispensable in the food and beverage industry as flavoring agents, in cosmetics and personal care products for their refreshing scents and skin benefits, and in cleaning products for their anti-microbial properties. Furthermore, their therapeutic potential has led to their inclusion in pharmaceutical and nutraceutical products. This review underscores the multifaceted role and economic significance of Citrus volatile organic compounds, advocating for continued research and technological advances to fully harness their benefits in health, industry, and sustainability.

Keywords: *Volatile Organic Compound, Citrus, Orange, Lemon, Lime*

INTRODUCTION

The volatile organic compounds (VOCs) are a diverse group of organic chemicals characterized by their high vapor pressure at room temperature. This high vapor pressure results in their easy evaporation into the atmosphere, making them detectable by smell even at low concentrations. The volatile organic compounds include a wide variety of chemical compounds such as aldehydes, ketones, esters, and terpenes, each with unique chemical properties and functions (Paolin & Strlič, 2024).

Plants are prolific producers of volatile organic compounds, emitting these compounds as part of their metabolic processes. The production and release of volatile organic compounds by plants are influenced by several factors, including the species of the plant, environmental conditions, developmental stage, and biotic interactions. These volatile organic compounds are synthesized in various parts of the plant, including leaves, flowers, fruits, and roots, and can be emitted into the atmosphere or released into the soil (Clavijo McCormick et al., 2023).

The volatile organic compounds are found in many natural and anthropogenic sources, but plants are among the most significant producers of these compounds. Within the plant kingdom, the genus Citrus has encompassing species such as orange (*Citrus sinensis*), lime (*Citrus auratiifolia*), lemon (*Citrus limon*), kaffier lime (*Citrus hystrix*), rough lemon (*Citrus jambhiri*), calamansi (*Citrus macrocarpa*), limau (*Citrus amblycarpa*), and pomelo (*Citrus maxima*). Citrus fruits are particularly notable for its rich and diverse production of volatile organic compounds (Wang et al., 2023).

The volatile organic compounds emitted by Citrus species play critical roles in plant physiology and ecology, as well as offering substantial benefits for human health and industry. These compounds contribute to the distinct aroma and flavor profiles of Citrus fruits, which are highly valued in culinary applications (Abbas et al., 2023). Furthermore, Citrus volatile organic compounds have demonstrated various biological activities, including anti-microbial, anti-inflammatory, anti-oxidant, and even anti-cancer properties. This article aims to review the significant benefits of volatile organic compounds in Citrus species, exploring their roles in plant biology, their impact on human health, and their industrial applications (Munir et al., 2024).

Importance of Volatile Organic Compounds in Plant Biology

The volatile organic compounds play essential roles in plant biology, serving as key mediators in plant-environment interactions. In Citrus species, these compounds are involved in various physiological processes:

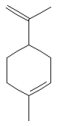
1. Defense Mechanisms: Citrus plants produce volatile organic compounds as a defensive strategy against herbivores and pathogens. When the plant tissues are damaged, such as by insect feeding, volatile organic compounds are released to deter herbivores and attract predators or parasitoids of the herbivores, thereby providing indirect defense (Razo-Belman & Ozuna, 2023).
2. Pollinator Attraction: The volatile organic compounds emitted from Citrus flowers serve to attract pollinators, ensuring successful reproduction. These fragrant compounds are highly specific and can attract a variety of pollinators, including bees, butterflies, and other insects (Jakubska-Busse et al., 2022).
3. Intraspecies Communication: The volatile organic compounds are used by Citrus plants for communication with other plants, often as a response to stress conditions. These chemical signals can trigger defensive responses in neighboring plants, creating a communal defense strategy against environmental threats (Pérez-Hedo et al., 2024).
4. Allelopathy: Some plants release volatile organic compounds into the soil that inhibit the growth of competing plant species, a strategy known as allelopathy. This chemical warfare helps the emitting plant reduce competition for resources such as light, water, and nutrients (Shan et al., 2023).
5. Environmental Adaptation: The volatile organic compounds also help plants adapt to their environment by responding to abiotic stresses such as drought, high temperatures, and ultra-violet radiation. The

emission of certain volatile organic compounds can help protect plant tissues from damage and aid in stress tolerance (Midzi et al., 2022).

Chemical Composition of Citrus Volatile Organic Compounds

The chemical profile of Citrus volatile organic compounds is highly complex and includes various terpenes, alcohols, aldehydes, ketones, and esters. The composition can vary significantly among different Citrus species and even among different cultivars within a species. Some of the primary volatile organic compounds found in Citrus include:

1. Limonene: is a major component in the peels of citrus fruits, especially oranges, lemons, and limes. It is a monocyclic monoterpene with a characteristic citrus aroma.

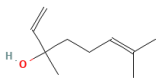


IUPAC: 1-Methyl-4-(1-methylethenyl)-cyclohexene
Molecular Formula & Weight: $C_{10}H_{16}$ and 136.24 g/mol
Boiling Point & Density: 176 °C (349 °F) and 0.841 g/cm³

Figure 1. Molecular Structure of Limonene

Anti-oxidant: Limonene exhibits strong anti-oxidant properties, helping to neutralize free radicals and reduce oxidative stress in the body.
Anti-inflammatory: Limonene has been shown to modulate inflammatory pathways, thereby reducing inflammation.
Anti-cancer: Limonene has demonstrated potential anti-cancer effects, including the ability to inhibit the proliferation of cancer cells and induce apoptosis, particularly in breast and colon cancer cells.
Gastro-protective: Limonene can help in the treatment of gastrointestinal conditions, including acid reflux and gastric ulcers, by protecting the stomach lining (Anandakumar et al., 2021).

2. β-Linalool: is a terpene alcohol found in the peels of citrus fruits, particularly in lemons and limes. It has a pleasant floral scent with hints of citrus.

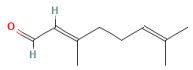


IUPAC: 3,7-Dimethylocta-1,6-dien-3-ol
Molecular Formula & Weight: $C_{10}H_{18}O$ and (154.25 g/mol)
Boiling Point & Density: 176 °C (349 °F) and 0.841 g/cm³

Figure 3. Molecular Structure of β-Linalool

Anxiolytic: β-Linalool is known for its calming effects and can help reduce anxiety and stress when inhaled or applied topically.
Sedative: β-Linalool has mild sedative properties, which can aid in improving sleep quality.
Anti-inflammatory: β-Linalool helps reduce inflammation and can be beneficial in treating conditions associated with chronic inflammation.
Anti-microbial: β-Linalool exhibits anti-microbial activity against a variety of pathogens, including bacteria and fungi (Saini et al., 2022).

3. Trans-Citral (Geranial): is a mixture of two geometric isomers, geranial and neral, and is found in high concentrations in lemon and lime oils. It has a strong lemon aroma.

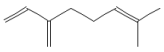


IUPAC: 3,7-Dimethyl-2,6-octadienal
Molecular Formula & Weight: $C_{10}H_{16}O$ and 152.23 g/mol
Boiling Point & Density: 229 °C (444 °F) and 0.888 g/cm³

Figure 3. Molecular Structure of Trans-Citral (Geranial)

Anti-microbial: Trans-Citral has potent anti-microbial properties, making it effective against bacteria, fungi, and viruses.
Anti-inflammatory: Trans-Citral helps in reducing inflammation by modulating inflammatory responses.
Anti-cancer: Trans-Citral has shown potential in inhibiting the growth of cancer cells and inducing apoptosis, particularly in skin and colon cancers.
Digestive Aid: Trans-Citral can help improve digestion and alleviate digestive disorders, including indigestion and bloating (Sharma et al., 2020).

4. β-Myrcene: is a monoterpene found in various citrus oils, particularly in grapefruit. It has an earthy, musky aroma with hints of citrus.



IUPAC: 7-Methyl-3-methylene-1,6-octadiene
Molecular Formula & Weight: $C_{10}H_{16}$ and 136.24 g/mol
Boiling Point & Density: 167 °C (333 °F) and 0.794 g/cm³

Figure 4. Molecular Structure of β-Myrcene

Analgesic: β-Myrcene has pain-relieving properties and can help reduce pain and discomfort.
Anti-inflammatory: β-Myrcene helps to decrease inflammation, making it beneficial for conditions such as arthritis.
Sedative: β-Myrcene can have a sedative effect, promoting relaxation and improving sleep quality.
Anti-oxidant: β-Myrcene exhibits anti-oxidant properties, protecting cells from oxidative damage (Surendran et al., 2021).

5. α-Pinene: is a bicyclic monoterpene found in small amounts in citrus oils. It has a fresh, pine-like aroma with hints of citrus.

IUPAC: 2,6,6-Trimethylbicyclo[3.1.1]hept-2-ene
Molecular Formula & Weight: $C_{10}H_{16}$ and 136.24 g/mol
Boiling Point & Density: 156 °C (313 °F) and 0.858 g/cm³

Figure 5. Molecular Structure of α-Pinene

Anti-inflammatory: α-Pinene has strong anti-inflammatory properties, which can help in managing inflammatory conditions.

Bronchodilator: α-Pinene can help improve airflow to the lungs, making it beneficial for respiratory conditions such as asthma.
Anti-microbial: α-Pinene exhibits anti-microbial activity, particularly against bacteria and fungi (Vespermann et al., 2017).

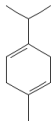
6. β-Pinene: is another monoterpene present in citrus oils, known for its woody, pine-like aroma with slight citrus notes.

IUPAC: 6,6-Dimethyl-2-methylene-bicyclo[3.1.1]heptane
Molecular Formula & Weight: $C_{10}H_{16}$ and 136.24 g/mol
Boiling Point & Density: 165 °C (329 °F) and 0.872 g/cm³

Figure 6. Molecular Structure of β-Pinene

Anti-inflammatory: β-Pinene helps reduce inflammation and is beneficial in treating inflammatory conditions.
Anti-microbial: β-Pinene possesses anti-microbial properties, effective against a range of bacterial and fungal pathogens.
Bronchodilator: β-pinene can improve respiratory function by acting as a bronchodilator.
Anti-oxidant: β-Pinene helps protect cells from oxidative damage through its anti-oxidant properties (Ndao & Adjallé, 2023).

7. γ-Terpinene: is a monoterpene found in the essential oils of many citrus fruits, particularly in lemons and limes. It has a citrusy, slightly spicy aroma.

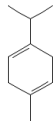


IUPAC: 1-Isopropyl-4-methyl-1,4-cyclohexadiene
Molecular Formula & Weight: $C_{10}H_{16}$ and 136.24 g/mol
Boiling Point & Density: 183 °C (361 °F) and 0.846 g/cm³

Figure 7. Molecular Structure of γ-Terpinene

Anti-oxidant: γ-Terpinene exhibits significant anti-oxidant activity, helping to protect cells from damage caused by free radicals.
Anti-microbial: γ-Terpinene has anti-microbial properties, effective against a variety of microorganisms, including bacteria and fungi.
Anti-inflammatory: γ-Terpinene helps reduce inflammation and can be used in managing inflammatory diseases.
Anti-cancer: γ-terpinene may have anti-cancer properties, particularly in preventing the growth of certain cancer cells (Bagińska et al., 2024).

8. α-Terpineol: is a monoterpene alcohol found in citrus oils, particularly in lime and orange oils. It has a pleasant floral aroma with citrus undertones.



IUPAC Name: (2-(4-Methylcyclohex-3-en-1-yl)propan-2-ol)
Molecular Formula & Weight: $C_{10}H_{18}O$ and 154.25 g/mol
Boiling Point & Density: 218 °C (424 °F) and 0.935 g/cm³

Figure 8. Molecular Structure of α-Terpineol

Sedative: α-Terpineol has sedative properties that can help induce relaxation and improve sleep.
Anti-microbial: α-Terpineol exhibits anti-microbial activity against a wide range of pathogens, including bacteria and fungi.
Anti-inflammatory: α-Terpineol can help reduce inflammation, making it useful in treating inflammatory conditions.
Anti-oxidant: α-Terpineol has anti-oxidant properties that help protect cells from oxidative stress (Khaleel et al., 2018).

Mechanism of Volatile Organic Compounds in Pharmacology Effect

Citrus volatile organic compounds have garnered significant attention for their various health benefits. These naturally occurring compounds exhibit a wide range of pharmacological activities, making them valuable in preventive and therapeutic healthcare. Below, the benefits of Citrus volatile organic compounds and their underlying mechanisms.

1. Anti-oxidant: Protects cells from damage caused by free radicals, reducing the risk of chronic diseases such as cardiovascular diseases, cancer, and neurodegenerative disorders.
    a. Scavenging Free Radicals: Citrus volatile organic compounds, such as limonene and γ-terpinene, neutralize reactive oxygen species by donating electrons, thereby preventing oxidative damage to cells.
    b. Enhancing Anti-oxidant Enzyme Activity: Citrus volatile organic compounds upregulate endogenous anti-oxidant enzymes like superoxide dismutase, catalase, and glutathione peroxidase, which help detoxify reactive oxygen species.
    c. Inhibiting Lipid Peroxidation: Citrus volatile organic compounds prevent the oxidative degradation of lipids in cell membranes, protecting cellular integrity and function (Kaur & Kaur, 2015).
2. Anti-inflammatory: Helps manage conditions such as arthritis, inflammatory bowel disease, and cardiovascular diseases by reducing inflammation.
    a. Inhibition of Pro-inflammatory Cytokines: Citrus volatile organic compounds like linalool and limonene reduce the production of pro-inflammatory cytokines such as TNF-α, IL-1β, and IL-6.
    b. Downregulation of NF-κB Pathway: Citrus volatile organic compounds inhibit the NF-κB signaling pathway, which plays a crucial role in the inflammatory response.
    c. Cyclooxygenase Inhibition: Citrus volatile organic compounds inhibit Cyclooxygenase enzymes, particularly Cyclooxygenase -2, reducing the synthesis of pro-inflammatory prostaglandins (Yang et al., 2023).
3. Anti-cancer: Inhibits the growth and spread of cancer cells and promotes apoptosis, particularly in cancers such as breast, colon, and lung cancer.
    a. Induction of Apoptosis: Citrus volatile organic compounds like limonene and citral activate apoptotic pathways by upregulating pro-apoptotic proteins (Bax) and downregulating anti-apoptotic proteins (Bcl-2).
    b. Cell Cycle Arrest: Citrus volatile organic compounds interfere with cell cycle progression, often by inhibiting cyclin-dependent kinases (CDKs), leading to cell cycle arrest at G1 or G2/M phases.
    c. Anti-metastatic Activity: Citrus volatile organic compounds inhibit metastasis by reducing the expression of matrix metalloproteinases (MMPs) and altering cell adhesion molecules (Antonelli et al., 2020).

4. Anti-microbial: Effective against a wide range of pathogens, including bacteria, fungi, and viruses, helping prevent and treat infections.
    a. Disruption of Cell Membranes: Citrus volatile organic compounds such as citral and terpineol integrate into microbial cell membranes, causing increased permeability and leakage of cell contents.
    b. Inhibition of Microbial Growth: Citrus volatile organic compounds interfere with essential microbial processes, including enzyme activity and protein synthesis.
    c. Induction of Oxidative Stress: Citrus volatile organic compounds can induce oxidative stress in microbial cells, leading to cell damage and death (Josselin et al., 2022).
5. Gastro-protective: Protects the gastric lining and helps manage conditions like acid reflux and gastric ulcers.
    a. Neutralizing Stomach Acid: Citrus volatile organic compounds like limonene reduce gastric acidity, providing relief from acid reflux and protecting the gastric mucosa.
    b. Enhancing Mucosal Defense: Citrus volatile organic compounds promote the production of mucus and bicarbonate, which protect the stomach lining from acidic damage.
    c. Anti-inflammatory Action: Citrus volatile organic compounds reduce inflammation in the gastric mucosa, aiding in the healing of ulcers and other gastric lesions (Herdiana, 2023).
6. Bronchodilator: Helps manage respiratory conditions such as asthma and chronic obstructive pulmonary disease (COPD) by improving airflow.
    a. Relaxation of Bronchial Smooth Muscles: Citrus volatile organic compounds such as α-pinene and β-pinene relax bronchial smooth muscles through the modulation of calcium ion channels, leading to improved airflow.
    b. Anti-inflammatory Effects: Citrus volatile organic compounds reduce inflammation in the respiratory tract, further aiding in bronchial dilation and reducing symptoms of conditions like asthma (Heghes et al., 2019).
7. Analgesic: Helps manage pain from various conditions, including chronic pain, headaches, and arthritis.
    a. Modulation of Pain Pathways: Citrus volatile organic compounds like myrcene interact with opioid receptors and modulate the endocannabinoid system, providing pain relief.
    b. Reduction of Inflammatory Mediators: Citrus volatile organic compounds reduce pain associated with inflammation, by inhibiting COX enzymes and reducing pro-inflammatory cytokines (Gonçalves et al., 2020).
8. Anxiolytic: Helps manage anxiety and stress, promoting mental well-being.
    a. Enhancement of GABAergic Activity: Citrus volatile organic compounds act by inhibiting COX enzymes and reducing pro-inflammatory cytokines such as linalool enhance the effects of GABA, the primary inhibitory neurotransmitter in the central nervous system, promoting relaxation and reducing anxiety.
    b. Modulation of Serotonin Receptors: Citrus volatile organic compounds interact with serotonin receptors, which play a role in mood regulation, further reducing anxiety (Ríos et al., 2022).
9. Sedative: Promotes relaxation and improves sleep quality, helping manage insomnia and other sleep disorders.
    a. Interaction with GABA Receptors: Citrus volatile organic compounds like linalool and terpineol enhance GABAergic neurotransmission, promoting sedation and improving sleep quality.
    b. Modulation of the Sleep-Wake Cycle: Citrus volatile organic compounds interact with neurotransmitter systems involved in sleep regulation, such as adenosine receptors, leading to improved sleep onset and maintenance (Lizarraga-Valderrama, 2021).

CONCLUSION

The volatile organic compounds in Citrus species offer numerous health benefits, including anti-oxidant, anti-inflammatory, anti-cancer, anti-microbial, gastro-protective, bronchodilator, analgesic,

anxiolytic, and sedative effects. These compounds achieve their therapeutic effects through diverse mechanisms, such as scavenging free radicals, modulating inflammatory pathways, inducing apoptosis in cancer cells, disrupting microbial membranes, and enhancing neurotransmitter activity. The diverse pharmacological actions of Citrus volatile organic compounds highlight their potential as natural agents for promoting health and preventing disease.

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