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A COMPREHENSIVE REVIEW OF MINT ESSENTIAL OILS – COMPOSITION, QUALITY AND APPLICATIONS

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Abstract

Mint essential oils, extracted from various species of Mentha, are highly valued for their aromatic, therapeutic, and industrial uses. This comprehensive review examines the chemical composition, quality assessment techniques, and broad applications of mint essential oils. Key bioactive compounds such as menthol, menthone, and isomenthone play a pivotal role in the characteristic aroma and functional properties of these oils. Emerging tools, including chemometric models combined with spectroscopy, promise rapid, non-destructive quality control. Advanced techniques like liquid chromatography-electrospray ionization time-of-flight mass spectrometry (HPLC-ESI-TOF/MS), headspace solid-phase microextraction coupled with gas chromatography-mass spectrometry (HS-SPME/GC-MS), and ATR-FTIR spectroscopy offer improved detection of adulteration and detailed profiling of both volatile and non-volatile components. Nonetheless, factors such as processing, storage, and environmental conditions can significantly alter oil composition, emphasizing the need for standardized protocols to ensure consistent quality. These advancements are set to solidify the role of mint essential oils in aromatherapy, pharmaceuticals, and diverse industrial applications.

Key words: *esential oil, Mentha sp., analytical techniques, volatile and non-volatile compounds, quality.*

INTRODUCTION

Peppermint (*Mentha × piperita*), a valued member of the mint family (Lamiaceae), is widely recognized for its medicinal, culinary, and industrial significance. Renowned for its distinct aroma and therapeutic properties, it has been used for centuries in traditional medicine and modern applications (Liang et al., 2024). This versatile plant is a cornerstone of the global essential oils (EOs) industry, valued at over $400 million annually. Its adaptability to diverse agro-climatic conditions and extensive use across multiple sectors underscore its economic and pharmacological importance (Sercan et al., 2025).

Taxonomically, peppermint (*Mentha × piperita*) belongs to the Mentha genus, which includes approximately 42 species (Mokhtarikhah et al., 2020), with the most common species illustrated in Figure 1. It is a natural hybrid of *Mentha spicata* (spearmint) and *Mentha aquatica* (watermint) and is cultivated worldwide for its essential oil.

Peppermint essential oil (EO) is a complex mixture of volatile compounds, primarily terpenes and phenols, extracted from various plant parts through methods like steam distillation. Its key bioactive components, including menthol, menthone, and carvone, contribute to its distinct properties, with composition and quality influenced by geographical and climatic factors (Mahendran et al., 2021). The oil is valued not only for its characteristic fragrance but also for its potent bioactive effects.

Recognized for its antimicrobial, antioxidant, and therapeutic properties, peppermint EO is widely used in food preservation, pharmaceuticals, and cosmetics. Unlike synthetic alternatives, it is biodegradable, environmentally friendly, and classified as generally recognized as safe (GRAS), further increasing its industrial appeal (Burt, 2004).

Beyond its medicinal and aromatic properties, peppermint has been traditionally used to treat gastrointestinal and respiratory ailments and as a carminative and sedative agent. Today, it is extensively incorporated as a flavoring agent in food and beverages, as well as in cosmetics and oral hygiene products (Saleem et al., 2018). The rising demand for natural, eco-friendly solutions has amplified interest in its pharmacological potential and industrial applications. These factors make peppermint EO a subject of extensive scientific research, particularly in the fields of pharmacology and quality control.

Figure 2 illustrates the prominence of the Lamiaceae family in essential oil production, alongside contributions from families such as Apiaceae and Lauraceae. Additionally, smaller families like Zingiberaceae and Rutaceae contribute to the diverse sources of essential oils used in pharmacology and traditional medicine.

This review provides a comprehensive analysis of mint essential oils, emphasizing advanced analytical techniques, quality control measures, and methods for detecting adulteration. It also compares traditional and modern extraction techniques, evaluating their impact on oil composition and bioactivity. Beyond pharmaceuticals and cosmetics, peppermint essential oil is explored for its industrial and environmental applications, with a key focus on linking specific bioactive compounds to pharmacological properties. Encapsulation techniques are also discussed for improving the stability and efficacy of these bioactive components.

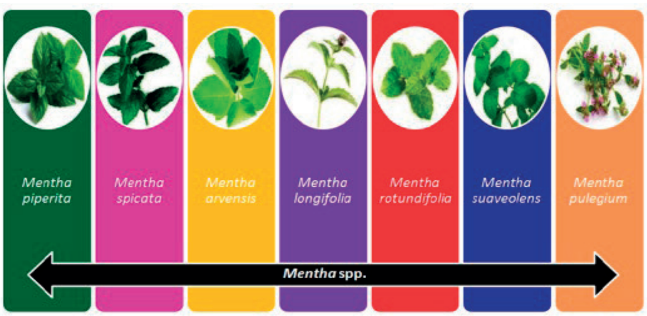

Figure 1. Common species of *Mentha* (Source: Eftekhari et al., 2021)

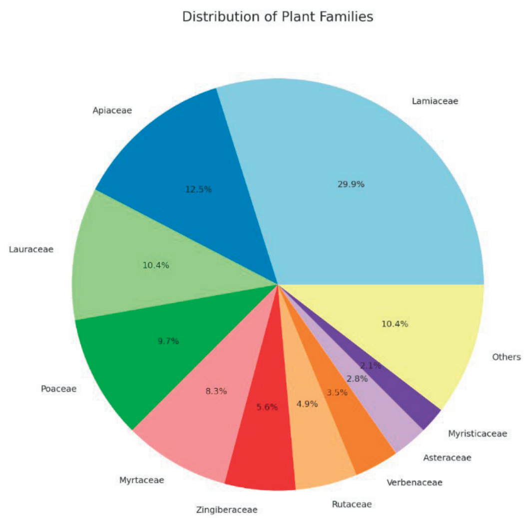

Figure 2. Distribution of various plant families used for essential oils (Source: Liang et al., 2024)

EOs EXTRACTION METHODS

Essential oils from herbs and spices possess strong antioxidant and antimicrobial properties, but their quality depends largely on the extraction method. Traditional techniques like steam distillation and hydrodistillation are widely used due to their simplicity and cost-effectiveness; however, they often require high temperatures and large amounts of solvents, which can degrade heat-sensitive compounds (Thuyen et al., 2023; Abbas et al., 2024).

In contrast, modern methods such as supercritical fluid extraction (SFE) and microwave-assisted extraction (MAE) offer higher efficiency and better preservation of bioactive compounds but require expensive equipment and precise optimization to prevent degradation (Rasekh et al., 2023; Pogorzelska-Nowicka et al., 2024). Emerging techniques like ultrasound-assisted extraction (UAE) strike a balance between efficiency and sustainability by improving yield while reducing energy consumption. However, improper optimization can still lead to the breakdown of sensitive compounds (Pogorzelska-Nowicka et al., 2024). The selection of an extraction method depends on factors such as the oil's chemical composition, intended application, and economic feasibility. Table 1 compares various extraction techniques, outlining their principles, advantages, disadvantages, and examples of commonly extracted oils.

Table 1. Comparison of Different Extraction Methods for Essential Oils

Extraction Method	Principle	Advantages	Disadvantages	References
Steam Distillation	Steam passes through plant material, vaporizing the volatile oils, which are then condensed.	Simple, widely used, and cost-effective.	Can cause thermal degradation of sensitive compounds.	Thuyen et al., 2023
Solvent Extraction	Solvents like ethanol or hexane are used to dissolve oils, followed by solvent removal.	Can extract oils from delicate flowers and non-aromatic plants.	Residual solvent can be harmful; more complex process.	Thuyen et al., 2023
Supercritical Fluid Extraction (SFE)	Uses supercritical CO_2 to extract oils.	High efficiency, preserves sensitive compounds, no solvent residue.	Expensive equipment, high energy requirements.	Rasekh et al., 2023
Hydrodistillation	Similar to steam distillation but with the plant material submerged in water.	Effective for large quantities, relatively simple.	Loss of some volatile compounds in water, less suitable for delicate oils.	Abbas et al., 2024
Microwave-Assisted Extraction (MAE)	Uses microwave radiation to assist in extracting oils.	Fast extraction, less solvent required.	May cause uneven heating, leading to degradation of some compounds.	Pogorzelska-Nowicka et al., 2024
Ultrasound-Assisted Extraction (UAE)	Uses ultrasonic waves to break cell walls and release oils.	Fast, energy-efficient, can improve yield.	May cause degradation of sensitive compounds if not optimized.	Pogorzelska-Nowicka et al., 2024

EOs QUALITY EVALUATION

The quality assessment of EOs is critical due to their high volatility and susceptibility to oxidation. Various techniques have been developed to evaluate EO quality and detect adulteration. ***Sensory evaluation*** involves both human sensory analysis and electronic devices, such as electronic noses and tongues, to assess aroma and appearance. ***Physico-chemical analysis*** measures intrinsic properties like density, optical rotation, and refractive index to ensure quality standards (Ayu et al., 2024 a,b). Chemical composition analysis employs chromatography, mass spectrometry, and spectroscopy to identify and quantify volatile and non-volatile components. Advanced methods, including Raman spectroscopy, Selected-Ion Flow-Tube Mass Spectrometry (SIFT-MS), and Nuclear Magnetic Resonance (NMR), provide precise and rapid analysis (Sousa et al., 2022). Combination approaches integrate multiple techniques for comprehensive and accurate quality control, ensuring consumer safety and market stability (Gabetti et al., 2021).

Sensory evaluation of essential oils

Sensory evaluation of EOs involves human sensory analysis and electronic sensor technologies to assess aroma and appearance. It includes biological sensory evaluation, conducted by trained evaluators, and electronic chemical sensing, using devices like electronic noses and tongues (Albuquerque et al., 2016). Both methods play a crucial role in determining EOs quality and authenticity. While human sensory analysis is reliable, it requires careful selection and training of evaluators. Combining human expertise with electronic devices provides a more comprehensive and objective assessment (Gabetti et al., 2021).

Electronic noses and tongues have gained traction in the food industry due to their speed and efficiency compared to human evaluation (Albuquerque et al., 2016). These devices utilize chemical sensors and pattern recognition systems to analyze samples, generating fingerprint data for both qualitative and quantitative assessments. They are effective in establishing databases, detecting adulteration, and classifying EO quality (Rasekh et al., 2023). Electronic noses can differentiate essential oils, detect adulteration, and assess the quality of mint oil. These technologies offer a rapid, reliable, and objective approach to EO quality evaluation (Gabetti et al., 2021).

Physicochemical properties evaluation

To ensure accurate and comprehensive EO quality assessment, physicochemical properties are evaluated using standardized methods. These properties provide vital insights into the composition, purity, and potential adulteration of essential oils (Cárdenas et al., 2020).

Key physicochemical properties include:

- *Density*, which measures the mass per unit volume of an EO, helps assess its purity and composition.
- *Optical rotation*, which refers to the deviation of light as it passes through the EO, is essential for distinguishing synthetic oils from pure ones. Synthetic oils often exhibit different optical rotation values compared to authentic EOs.
- *Refractive index*, which indicates how light bends as it passes through the oil, offers a quick and reliable method for evaluating EO purity and detecting adulteration (Guil-Guerrero et al., 2017).

These physicochemical properties are essential for quality control and detecting adulteration. For example, the peppermint oil adulterated with turpentine will show a lower freezing point than the standard 10.5°C, indicating possible tampering (Cárdenas et al., 2020).

Chemical properties evaluation

For precise and objective evaluations of essential oils (EOs), advanced techniques like chromatography, mass spectrometry, and spectroscopy are crucial. These methods detect and identify volatile, chiral, and non-volatile compounds, key to understanding the true composition of EOs. Volatile compounds, responsible for the distinct aroma of EOs, are especially important for quality control (Łyczko et al., 2023). Techniques like liquid chromatography-electrospray ionization time-of-flight/mass spectrometry (HPLC-ESI-TOF/MS) (El Omari et al., 2024) and headspace solid-phase microextraction coupled with gas chromatography and mass spectrometry (HS-SPME/GC-MS) (Kataoka et al., 2000) provide detailed analysis of these compounds, linking chemical composition with aroma profiles (de Sousa et al., 2023).

Chiral compounds, such as terpenes, significantly influence the aroma and flavor of EOs. Analyzing enantiomeric ratios using chiral gas chromatography can confirm authenticity, with deviations, such as in α-pinene, signaling potential adulteration (Gabetti et al., 2021).

Non-volatile compounds, though less relevant to aroma, offer vital insights into authenticity and overall quality. Sterols, fatty acids, and waxes, detectable via high-performance liquid chromatography (HPLC), serve as valuable markers for adulteration. This method is particularly effective in distinguishing authentic citrus oils, such as orange, mandarin, and lemon, from adulterated samples (Tranchida et al., 2013). The article written by Boren et al. (2015), highlights various methods used to detect adulteration and the challenges associated with ensuring the purity of essential oils. This essay examines the key aspects of adulteration in mint essential oils and the analytical techniques used to maintain their authenticity.

When comparing analytical methods for essential oils, Gas Chromatography (GC) and Gas Chromatography-Mass Spectrometry (GC-MS) both focus on volatile compounds but differ in depth. GC-MS adds mass-to-charge ratio analysis, enhancing its ability to identify a broader range of compounds, such as menthol, menthone, and pulegone (Łyczko et al., 2023).

In the study by El Omari et al. (2024), these techniques were employed to characterize the chemical composition of *Mentha piperita* (peppermint) essential oils. The analysis identified menthol and menthone as predominant constituents, underscoring the efficacy of GC and GC-MS in profiling volatile substances in essential oils. Fourier Transform Infrared Spectroscopy (FTIR) offers a unique approach, identifying functional groups in molecules, making it useful for characterizing terpenes and alcohols (Kucharska-Ambrożej et al., 2021).

Headspace Solid-Phase Microextraction (HS-SPME) coupled with GC excels in extracting volatile compounds from a sample's headspace, ideal for analyzing compounds like menthol and carvone (Łyczko et al., 2023; Nasreddine et al., 2024). Meanwhile, Thin-Layer Chromatography (TLC), though less precise, offers a simpler, cost-effective method for separating compounds like menthol and terpenes (Radu et al., 2023).

For detecting metal content, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) effectively identifies heavy metals such as lead and mercury in EOs, ensuring safety and quality (Mei et al., 2024). In contrast, Refractive Index (RI) Measurement offers a quick and cost-effective assessment of EO purity and concentration, especially for oils like mint (Mahboub et al., 2020).

ATR-FTIR spectroscopy, combined with advanced chemometric models such as PCA-LDA, PLS-DA, and SIMCA, has proven effective for detecting adulterations in EOs, particularly Mentha arvensis oil. This method provides a rapid, non-destructive approach for detecting adulterants with high accuracy (Kucharska-Ambrożej et al., 2021). The combination of UV-VIS spectrophotometry and ATR-FTIR spectroscopy has further demonstrated its strength in mint quality control, achieving accuracy rates of 60-80% depending on data and harvest season (Kucharska-Ambrożej et al., 2019). The development of portable ATR-FTIR spectrophotometers may further enhance on-site EO analysis, making these methods more accessible for routine quality assurance (Kucharska-Ambrożej et al., 2021).

Essential oils (EOs) are analyzed using various techniques, each suited for specific compounds as described in Table 2. Gas Chromatography (GC) - FID separates volatile compounds like menthol and menthone based on their interaction with a column. GC-MS combines GC with mass spectrometry to identify compounds such as carvone and pulegone by their mass-to-charge ratio. FTIR detects functional groups in terpenes and alcohols by measuring infrared light absorption. Other methods like HS-SPME-GC, TLC, and Mass Spectrometry (MS) also contribute to comprehensive EO analysis, ensuring accurate composition and purity. These techniques support quality control and safety in EO applications.

Table 2. Analytical methods used for essential oils (EOs) mint analysis

Analytical Method	Principle	Typical Compounds Analyzed	References
Gas Chromatography (GC-FID)	Separation of volatile compounds based on their interaction with a column.	Monoterpenes (e.g., menthol, menthone)	Loi et al., 2024
Gas Chromatography-Mass Spectrometry (GC-MS)	GC coupled with mass spectrometry to identify compounds based on mass-to-charge ratio.	Menthol, menthone, carvone, pulegone	Mogoșan et al., 2017
Headspace Solid-Phase Microextraction (HS-SPME) Gas Chromatography (GC)	Extraction of volatile compounds from a sample's headspace followed by GC analysis.	Volatiles such as menthol, carvone	Łyczko et al., 2023; Nasreddine et al., 2024
Fourier Transform Infrared Spectroscopy (FTIR)	Measures absorption of infrared light to identify functional groups in molecules.	Functional groups in terpenes, alcohols	Kucharska-Ambrożej et al., 2021
Thin-Layer Chromatography (TLC)	Separation of compounds on a stationary phase based on their different affinities.	Menthol, menthone, carvone, terpenes	Radu et al., 2023
Mass Spectrometry (MS)	Ionizes compounds to measure their mass-to-charge ratio and deduce structure.	Terpenes, phenolic compounds	Rasekh et al., 2023
Inductively Coupled Plasma Mass Spectrometry (ICP-MS)	Measures metal content in a sample by ionizing the sample and analyzing mass-to-charge ratios.	Heavy metals (lead, mercury)	Mei et al., 2024
Refractive Index (RI) Measurement	Measures the refractive index of the sample to assess purity or concentration.	Concentration of essential oils (e.g., mint)	Mahboub et al., 2020

COMPOUNDS OF ESSENTIAL MINT OIL

EOs from spearmint (*Mentha spicata*) have been extensively studied for their chemical composition, ecological adaptations, and potential applications. High EO content is observed in landraces grown at lower altitudes and in arid climates, where rainfall is minimal, reflecting specific ecological adaptations (Sangwan et al., 2001). Gas chromatography-mass spectrometry (GC-MS) has identified 40 components in spearmint EO, with oxygenated monoterpenes comprising 12.6% to 86.61% of the total composition. The major constituents are carvone (0.1% to 73.4%) and menthone (0.02% to 62%), consistent with findings by Kizil et al. (2010) and other studies (Zheljazkov et al., 2010).

Cluster analysis of 25 landraces revealed three distinct clusters based on EO composition and ecological traits, illustrating the diversity within the species. The biosynthesis of these EOs involves terpene synthase and cyclase enzymes, which produce terpenes and phenylpropanoids through the pyruvate-mevalonate and shikimate pathways (Kizil et al., 2010). Variations in carvone and limonene content across global regions further emphasize the role of environmental factors in EO composition (Snoussi et al., 2015).

The chemical composition of mint EO is complex, with oxygenated monoterpenes being the most abundant class. Carvone, a major compound, contributes significantly to both the aroma and flavor of mint EO, ranging from 0.1% to 73.4% (Hussain et al., 2010). Menthone, another prominent compound, is found in concentrations of 0.02% to 62%, varying across landraces (Eftekhari et al., 2021). Other oxygenated monoterpenes, such as neo-dihydrocarveol (0.08-54.7%) and pulegone (0.2-32.2%), show considerable variation based on ecological factors (Shrigod et al., 2016).

In addition to carvone and menthone, compounds like 1,8-Cineole (eucalyptol) (0.1-46.28%) and iso-menthone (0.03-39.1%) are present in varying concentrations, depending on regional varieties (Padalia et al., 2013; Arzani et al., 2005). Menthol (up to 3.02%) is found in specific samples, contributing to the cooling sensation associated with mint (Dambrauskienė et al., 2008). Research on *Mentha rotundifolia* essential oils revealed the presence of two chemotypes: one characterized by high piperitone oxide content and the other by elevated piperitenone levels (Brada et al., 2007). Monoterpene hydrocarbons, including limonene (1.9-31%), show a negative correlation with carvone, resulting in distinct EO profiles (Hussain et al., 2010). Myrcene (0.4-6.1%) and β-pinene (1.3-3.2%) are minor constituents but contribute to the overall aroma (Oliveira et al., 2022; Padalia et al., 2013).

Sesquiterpene hydrocarbons like trans-caryophyllene (0.1-20.3%) and germacrene D (0.2-23.4%) are prevalent in mint EO and contribute to its complex aroma (Spadaccino et al., 2021). β-Caryophyllene, found in concentrations ranging from 1.8% to 5.5%, adds to the EO's bioactivity (Shrigod et al., 2016).

In addition to these primary components, phenylpropanoids are present in small quantities, derived from the shikimate pathway (Ghasemzadeh et al., 2011). Thymol, though found in trace amounts, contributes to the medicinal properties of mint EO, particularly its antimicrobial activity (Mohammed et al., 2024). Mint essential oils (EOs) contain a wide range of compounds, with oxygenated monoterpenes like carvone and menthone being key contributors to aroma and flavor. Table 3. groups the main classes of chemical compounds.Monoterpene hydrocarbons, such as limonene, provide additional fragrance, though they are negatively correlated with oxygenated compounds. Sesquiterpene hydrocarbons, like trans-caryophyllene and germacrene D, further enhance the EO profile. Phenylpropanoids, though in small quantities, offer medicinal properties derived from the shikimate pathway. Minor compounds, like thymol, contribute to the therapeutic effects of mint EOs.

Tabel 3.Chemical composition of mint essential oil

Class	Component Name	Concentration Range (%)	Notable Observations	References
Oxygenated Monoterpenes	Carvone	0.1-73.4%	Major compound contributing to aroma and flavor.	Hussain et al., 2010
	Menthone	0.02-62%	Found in significant quantities in various landraces.	Eftekhari et al., 2021
	Neo-dihydrocarveol	0.08-54.7%	Varies significantly among landraces.	Shrigod et al., 2016
	1,8-Cineole (Eucalyptol)	0.1-46.28%	Negatively correlated with limonene and menthone.	Padalia et al., 2013
	Iso-Menthone	0.03-39.1%	Found in varying amounts in different landraces.	Arzani et al., 2005
	Pulegone	0.2-32.2%	Present in notable amounts in specific landraces.	Shrigod et al., 2016
	Menthol	Up to 3.02%	Found in specific samples.	Dambrauskienė et al., 2008
	Piperitenone Oxide	Up to 17.6%	High concentration in certain regional varieties.	Brada et al., 2007
	Piperitone	Up to 54.9%	Dominant in certain regional varieties.	Brada et al., 2007
	Linalool	Up to 86.7%	Significant aromatic contribution to EO profiles.	Mollaei et al., 2022
Monoterpene Hydrocarbons	Limonene	1.9-31%	Negatively correlated with carvone.	Hussain et al., 2010
	Myrcene	0.4-6.1%	Minor monoterpene hydrocarbon.	Oliveira et al., 2022
	β-Pinene	1.3-3.2%	Found in specific cultivars.	Padalia et al., 2013
Sesquiterpene Hydrocarbons	Trans-Caryophyllene	0.1-20.3%	Commonly found sesquiterpene hydrocarbon.	Spadaccino et al., 2021
	Germacrene D	0.2-23.4%	Major sesquiterpene hydrocarbon.	Spadaccino et al., 2021
	β-Caryophyllene	1.8-5.5%	Found in various samples.	Shrigod et al., 2016
Phenylpropanoids	-	Present in small quantities	Includes shikimate pathway-derived compounds.	Ghasemzadeh et al., 2011
Other Minor Compounds	Thymol	Variable	Found in traces, contributes to medicinal properties.	Mohammed et al., 2024

PROPERTIES OF MINT ESSENTIAL OIL

Mint EOs are renowned for their diverse range of bioactive properties, including antibacterial, antifungal, antioxidant, anti-inflammatory, and insecticidal effects, making them valuable in both therapeutic and agricultural applications.

Antioxidant activity

The antioxidant potential of *Mentha spicata* EO has been extensively studied, demonstrating significant free radical scavenging activity. In DPPH assays, the EO exhibited 25.14-63.39% inhibition at concentrations of 10-40 µg/mL, compared to ascorbic acid's 40.11-93.89% inhibition under similar conditions (Sangwan et al., 2001; Shah et al., 2024). The EO's antioxidant activity is attributed to its high levels of monoterpenes and oxygenated sesquiterpenes. *Mentha spicata* EO from South Tunisia, with menthone and pulegone as major components, exhibited an IC50 of 10 µg/mL, demonstrating even greater antioxidant potency (de Sousa et al., 2023). The antioxidant activity supports its potential use in food preservation, pharmaceuticals, and health supplements (López-Pedrouso et al., 2022).

Cancer and phytotherapy

EOs, with their diverse chemical compositions, including terpenes, phenols, and ketones, are emerging as promising complementary cancer therapies. For example, thymol and β-caryophyllene disrupt mitochondrial integrity and increase reactive oxygen species (ROS), leading to cell death. EOs from *Mentha arvensis* have shown cytotoxic effects against leukemia (Lampronti et al., 2006), and various Mentha species exhibit activity against breast cancer cells (Hussain et al., 2010). However, challenges such as bioavailability and selective toxicity limit their standalone use. Despite these challenges, EOs continue to show potential as adjuvants in cancer treatment, particularly when combined with chemotherapy drugs (Alabrahim et al. 2024)

Anti-inflammatory and cognitive benefits

Mentha spicata EO has demonstrated potent anti-inflammatory and antipyretic effects in Swiss NMRI mice (Desam et al., 2019). Additionally, spearmint extract has been shown to improve learning and memory in aging models, enhancing cognitive function (Zhang et al., 2021). Daily consumption of spearmint extract has been linked to improved attention and cognitive performance (Fernández-Lorente et al., 2019), with recent studies further confirming its positive effects on mood, sleep, and overall quality of life (Riaz et al., 2017).

Phytoremediation Potential

Mentha piperita has shown a strong capacity for phytoremediation, particularly in accumulating and translocating chromium species in contaminated soils. Studies indicate it can grow in fly ash-treated soil, accumulating various heavy metals in different plant parts without contaminating essential oils. Additionally, the ash from *Mentha piperita* can effectively remove Cr (VI) from water, offering a sustainable method for managing aquatic environments (Kedia et al., 2014).

Antifungal properties

Mint EOs, including those from *Mentha spicata*, *Mentha viridis*, and *Mentha piperita*, have proven effective as natural antifungal agents. Rich in bioactive compounds like carvone, menthol, menthone, and limonene, they disrupt fungal physiology and exhibit significant antifungal activity against various pathogens (Kedia et al., 2014).

Studies have shown *Mentha spicata* EO to be highly effective against *Aspergillus flavus*, a mold that produces aflatoxin B1 (Makkar et al., 2018). Mentha viridis EO demonstrated fungitoxicity against molds in stored corn, with its activity classified as fungicidal against several molds, including *Alternaria alternata*, *Cladosporium cladosporioides*, *Curvularia lunata*, and *Mycelia sterilia*. Furthermore, mint EOs have shown effectiveness against yeast species like *Candida albicans* by disrupting biofilm formation and reducing fungal loads (Sameena et al., 2024). *Mentha piperita* EO has also proven effective against *Botrytis cinerea*, a pathogen responsible for significant agricultural losses, with enhanced stability and antifungal efficacy when incorporated into solid lipid nanoparticles.

Repellent and insecticidal properties

Mint essential oils (EOs), particularly from *Mentha piperita*, are also gaining attention for their insecticidal and repellent properties. Bioactive compounds such as terpenes, phenols, and aldehydes disrupt insect sensory systems, including olfactory receptors, preventing them from detecting attractants like human body odor and carbon dioxide (Kedia et al., 2014). *Mentha piperita* EO has been shown to disrupt the nervous system of insects, preventing them from approaching treated areas (Silva et al., 2021).

Fresh *Mentha piperita* EO emulsion exhibits 70-88% repellency against houseflies, though effectiveness diminishes over time. EO nanoparticles show high mortality rates in housefly larvae and are also effective against vector mosquitoes like *Anopheles stephensi* and *Aedes aegypti*. Additionally, the oil protects wheat grains from pests, demonstrating strong antifeedant activity. However, its efficacy is reduced when used with biological control agents like *Trichogramma pretiosum*, due to decreased female longevity.

Moreover, *Mentha spicata* EO has been found to inhibit oviposition in groundnut bruchid pests at a 2% concentration, indicating its potential as an eco-friendly repellent (Oliveira et al., 2022). Studies suggest that components of mint oils may mimic bruchid pheromones, further enhancing their application in sustainable agriculture (Fallah et al., 2024).

CONCLUSIONS

Mint essential oils are highly valued for their aromatic, therapeutic, and industrial applications, owing to their diverse chemical composition and bioactive properties. This review emphasizes the intricate relationship between sensory evaluation, physico-chemical analysis, and advanced instrumental techniques in assessing the quality and authenticity of mint essential oils. While traditional methods such as refractive index measurement, density determination, and acid value analysis remain crucial for quality control, their inability to detect subtle adulterations calls for the integration of more sophisticated analytical techniques.

Instrumental methods like GC, FTIR, and TLC have proven indispensable for identifying both volatile and non-volatile components, verifying oil authenticity, and detecting adulterants with high precision. The use of advanced chemometric models alongside ATR-FTIR spectroscopy provides rapid, non-destructive solutions for quality assessment, offering an effective bridge between laboratory research and practical applications. These cutting-edge technologies not only improve accuracy but also facilitate the development of portable devices, enabling on-site, field-level quality control.

However, challenges remain. Environmental factors, processing methods, and storage conditions continue to significantly affect the chemical composition and therapeutic properties of mint essential oils. To ensure consistency across different production scales and regions, there is a critical need for standardized analytical protocols and a wider adoption of modern techniques. Further research into non-volatile compounds and chiral analysis could provide deeper insights into the authenticity and functionality of these oils.

Sustainable cultivation and eco-friendly extraction practices, combined with advancements in green chemistry, will be key to meeting the growing demand for high-quality mint essential oils while preserving ecological balance.

In conclusion, the ongoing development of analytical techniques and interdisciplinary approaches will enhance the quality, authenticity, and potential applications of mint essential oils, solidifying their role in aromatherapy, pharmaceuticals, food, and cosmetics industries.

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