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Review Paper

Pharmacognosy Of Essntial Oils: Recent Advances in Extraction and Therapeutic Applications

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ABSTRACT

Essential oils, volatile secondary metabolites derived from various plant sources, have garnered significant attention because of their diverse therapeutic properties and industrial applications. Recent advances in pharmacognosy have revolutionized the extraction, characterization, and utilization of these bioactive compounds. Innovative extraction techniques, such as supercritical fluid extraction, microwave-assisted hydrodistillation, and ultrasound-assisted extraction, have improved the yield, quality, and environmental sustainability of essential oil production. These methods enable the selective isolation of key phytochemicals, ensuring high purity and bioavailability. The therapeutic potential of essential oils spans antimicrobial, anti-inflammatory, antioxidant, and neuroprotective activities, underpinned by active constituents such as terpenoids, phenolic compounds, and alkaloids. Recent research also highlights their synergistic effects and mechanisms of action, paving the way for their integration into modern pharmacotherapy. Moreover, advancements in nanotechnology have facilitated the development of essential oil-based drug delivery systems, enhancing their stability, controlled release, and efficacy. Despite these breakthroughs, challenges such as variability in composition due to environmental factors, standardization, and regulatory constraints persist. Addressing these issues is essential to unlock the full potential of essential oils in therapeutic applications. This review explores the latest advancements in essential oil extraction technologies, their chemical and pharmacological profiles, and their emerging applications in medicine, offering insights into future directions for research and clinical practice.

INTRODUCTION

Pharmacognosy, the study of natural products and their medicinal properties, has increasingly focused on essential oils due to their diverse therapeutic benefits and complex chemical compositions. Essential oils, which are volatile

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compounds extracted from different parts of plants,Essential oils have been treasured for ages for their delightful aromas and healing properties.Recent scientific developments have enhanced our comprehension of their pharmacological characteristics and expanded their utilization in contemporary healthcare practices.Traditionally, Essential oils are obtained through techniques such as steam distillation and solvent extraction [1]. However, Recent technological advancements have ushered in a new era of more efficient and eco-friendly extraction methods. Techniques such as supercritical fluid extraction and microwave-assisted extraction are now at the forefront of this evolution.and ultrasound-assisted extraction. These modern methods offer significant advantages, including higher yields, improved purity, and the preservation of thermolabile components, making them preferable in contemporary applications. For instance, supercritical CO_2 extraction is particularly valued for producing high-quality essential oils without thermal degradation, thus preserving their bioactive compounds [2]. The therapeutic potential of essential oils extends to various domains, including antimicrobial, anti-inflammatory, antioxidant, and anticancer activities. These biological activities are. attributed to the diverse phytochemicals present in essential oils, such as terpenes, phenolics, and aldehydes [3]. Recent studies have explored their use in complementary and alternative medicine, as well as in integrative health approaches. For example, essential oils like eucalyptus and peppermint have shown promising results in respiratory conditions, while lavender continues to be studied for its anxiolytic effects . Additionally, the incorporation of essential oils into nanocarriers and delivery systems is enhancing their efficacy and stability, clearing a path for new treatment possibilities [4].

Bio-active Compounds in Essential Oils

The therapeutic effects of essential oils are credited to their complex mixtures of bioactive compounds, primarily composed of terpenes, phenolics, aldehydes, alcohols, and other secondary metabolites. Each essential oil contains a specific profile of bioactive constituents that determine its efficacy in various biological activities [5].

Terpenes and Terpenoids

Terpenes and terpenoids form the largest group of bioactive compounds in essential oils. Monoterpenes (e.g., limonene, α-pinene, and geraniol) and sesquiterpenes (e.g., β-caryophyllene, humulene) are extensively researched for their properties that combat microbes, reduce inflammation, and inhibit cancer growth. Recent research has shed light on their significance in modulating cellular pathways that can affect immune responses, oxidative stress, and even cancer cell proliferation. For example, β-caryophyllene, found in clove and black pepper oils, has demonstrated both anti-inflammatory and neuroprotective properties through its interaction with cannabinoid receptors [6].

Phenolic Compounds

Phenolic compounds such as eugenol (found in clove oil) and thymol (present in thyme oil) are recognized for their potent antimicrobial, antioxidant, and anti-inflammatory activities. Studies conducted between 2019 and 2023 have explored their use in combating microbial resistance and reducing oxidative stress, with promising applications in wound healing and skin care [7]. Eugenol, in particular, has been shown to inhibit bacterial biofilm formation, a critical aspect in preventing chronic infections [8].

Aldehydes and Alcohols

Aldehydes and alcohols, including citral (from lemongrass oil) and linalool (from lavender oil), are bioactive compounds known for their calming and sedative effects. Their role in the modulation of the nervous system has been extensively studied, particularly in relation to stress, anxiety, and sleep disorders. Recent findings suggest that linalool's interaction with GABAergic neurotransmission pathways contributes to its anxiolytic and sedative properties, supporting its use in aromatherapy for mental health [9].

Therapeutic Efficacy of Essential Oils

Antimicrobial Activity

One of the most well-established uses of essential oils is their antimicrobial efficacy. The volatile bioactive compounds in EOs target the lipid membranes of bacteria, fungi, and viruses, causing damage to the membrane and resulting in cell death. Recent studies have emphasized the importance of the ability of essential oils to act as antimicrobials in the preservation of food and the management of infections. A 2022 study demonstrated that Tea tree oil and eucalyptus oil exhibit strong antimicrobial properties against multidrug-resistant pathogens, including Staphylococcus aureus and Escherichia coli [10]. This highlights The capabilities of essential oils as alternatives to synthetic microbial inhibitors in preventing infections and contamination.

Anti-inflammatory and Antioxidant Properties

Bioactive compounds in essential oils, particularly terpenes and phenolics, have been shown to regulate inflammatory processes and oxidative stress. Essential oils like frankincense (Boswellia spp.) and chamomile are rich in anti-inflammatory compounds, which have demonstrated efficacy in reducing inflammation in Disorders including arthritis and inflammatory bowel disease [11]. Additionally, The antioxidant characteristics of phenolic compounds such as eugenol and thymol are beneficial in neutralizing free radicals. This protective effect helps to shield cells from oxidative damage and can reduce the risk of serious conditions like cardiovascular diseases and cancer.

Neuroprotective and Mood-Enhancing Effects

The neuroprotective potential of essential oils has been an area of increasing interest, especially in addressing neurodegenerative diseases and mental health disorders. Compounds such as linalool, citral, and β-caryophyllene have demonstrated the ability to protect neural cells from Oxidative stress and inflammatory responses. In studies from 2021 to 2023, lavender oil and bergamot oil were found to improve mood, reduce anxiety, and Elevate cognitive capabilities through their influence on the limbic system and the regulation of neurotransmitter activity. [12]. These findings underscore the growing role of essential oils in supporting mental well-being and brain health.

Cancer Prevention and Treatment

Recent studies have indicated that shown that Certain bioactive constituents present in essential oils have been shown to possess anticancer capabilities by triggering apoptosis in cancer cells and hindering the growth of tumors. Compounds like limonene (from citrus oils) and α-pinene (from pine oil) have been studied for their role in modulating signaling pathways involved in cancer cell proliferation. A 2021 study revealed that limonene could induce cell cycle arrest within breast cancer cells., highlighting. its effectiveness as a complementary therapy in cancer treatment [13].

Safety and Toxicity Considerations

While essential oils offer numerous therapeutic benefits, it is necessary to consider their safety and potential toxicity. Overexposure to certain bioactive compounds, such as phenols, can cause skin irritation, allergic reactions, and hepatotoxicity. Recent studies emphasize the importance of proper dilution, dosage, and administration methods to ensure the safe and effective use of essential oils [14].

Recent Advances in Extraction Techniques

Over the past years, there have been significant advancements in the extraction methods for essential oils. These innovations aim to enhance the yield, purity, and efficiency of extraction while maintaining the integrity of essential oil constituents.

Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction is recognized for its ability to selectively extract essential oils at lower temperatures, preserving sensitive bioactive compounds. Supercritical carbon dioxide (SC-CO_2) is often used as a solvent due to its non-toxicity, low cost, and ability to operate under relatively mild conditions. Recent studies have focused on optimizing parameters such as pressure, temperature, and co-solvent use to improve efficiency and yield.

Advancement: New research highlights the use of co-solvents like ethanol, which enhances the extraction of polar compounds, broadening the spectrum of extracted phytochemicals. Additionally, advancements in the recycling of CO_2 have reduced the overall environmental footprint of SFE operations [15].

Microwave-Assisted Extraction (MAE)

Microwave-assisted extraction has gained popularity due to its rapid heating mechanism, which results in faster extraction times and higher yields. MAE uses electromagnetic radiation to heat the plant matrix, breaking down cellular structures and allowing for the efficient release of essential oils.

Advancement: Recent innovations include the development of hybrid systems that combine MAE with other extraction techniques, such as hydrodistillation. This synergistic effect allows for more complete extraction while reducing energy consumption. Furthermore, MAE has been optimized for use with various solvents, including eco-friendly solvents like water and ethanol [16].

Ultrasonic-Assisted Extraction (UAE)

Ultrasonic-assisted extraction uses high-frequency sound waves to help break down plant cell walls. facilitating the release of essential oils. The UAE presents several advantages, such as quicker extraction processes and lower solvent requirements, and enhanced yields compared to conventional methods.

Advancement: In recent years, low-frequency ultrasound (20–25 kHz) has been optimized for the extraction of essential oils, achieving better yields with minimal thermal degradation. Recent studies have also explored the integration of UAE with green solvents, reducing environmental impacts while maintaining efficiency. Additionally, continuous-flow UAE systems have been developed to allow for large-scale extractions [17].

Enzyme-Assisted Extraction (EAE)

Enzyme-assisted extraction leverages enzymes to disassemble the protective walls of plant cells and facilitate the release of essential oils. This technique is particularly useful for extracting oils from plant matrices that are difficult to process through conventional methods.

Advancement: Recent studies have concentrated on employing cellulases, pectinases, and hemicellulases to decompose the wall of plant cell,it improving the extraction of essential oils. Additionally, the integration of enzyme-assisted extraction (EAE) with other extraction methods has been explored, such as UAE or MAE, has been explored to improve extraction efficiency and yield. Furthermore, enzyme immobilization has been developed to allow for the reuse of enzymes, reducing costs and improving sustainability [18].

Traditional Extraction Methods of Essential Oils: Steam Distillation and Cold Pressing

Essential oil extraction predominantly relies on traditional techniques like steam distillation and cold pressing. These methods are still widely used today, especially for large-scale production. Every technique offers its own set of benefits, limitations, and applications, the variation is contingent upon the specific type of plant material and desired oil quality. This report focuses on steam distillation and cold pressing, explaining their mechanisms, benefits, and challenges. [19]

Steam Distillation

A widely used technique for extracting essential oils is steam distillation. particularly from herbs, flowers, and woody plants. In this process, Steam is introduced to plant material, which cause the breakdown of plant cells and the release of fragrant essential oils.Then the steam and oil vapor are subsequently condensed and separated, allowing the essential oil to be collected from the upper layer of the distillate.[20]

Mechanism: The plant material is positioned inside a distillation chamber, and steam generated from boiling water passes through the material. The heat and moisture from the steam cause the oil-containing glands in the plant to burst, releasing the essential oils. These volatile compounds, along with the steam, are carried into a condenser where they cool and liquefy. As oil and water are unable to blend, the essential oil is found floating above the water,making it easy to separate.

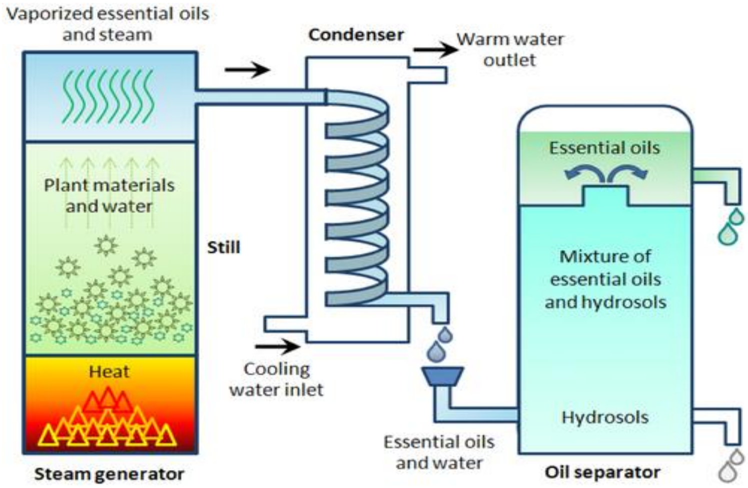

Fig.1.1. [65]

Advantages: Steam distillation allows for the extraction of high-quality oils without the use of chemicals, making it suitable for organic production. It is also effective for a wide range of plants, including those with woody stems or tough leaves.

Limitations: The process can be energy-intensive and requires careful control of temperature and pressure to avoid degrading heat-sensitive compounds. Additionally, some oils with lower volatility may not be fully extracted by steam alone.

Applications: Steam distillation is widely used for essential oils such as lavender, eucalyptus, peppermint, and rose [21].

Cold Pressing

Cold pressing, also known as expression, This method is viewed as the optimal choice for extracting essential oils from citrus fruits like oranges, lemons, and grapefruits. Unlike steam distillation, Cold pressing operates without the application of heat, making it ideal for extracting oils that are sensitive to temperature.[22]

Mechanism: The process involves mechanically pressing the peel of citrus fruits to release the essential oils. The outer layer of the fruit, which contains the oil glands, is first punctured or shredded. Pressure is then applied to squeeze out the oil, which is subsequently filtered and separated from any juice or water.

Advantages: Cold pressing preserves the natural scent and integrity of the oil since no heat is applied. This method is simple, cost-effective, and Appropriate for the extraction of substantial amounts of essential oil from citrus fruits.

Limitations: Cold pressing is limited to fruits with oil-rich rinds and is not suitable for most non-citrus plants. Furthermore, the oils obtained can be more prone to oxidation and may require stabilization to extend shelf life.

Applications: Cold pressing is primarily used for citrus oils, including lemon, lime, orange, and bergamot [23].

Steam distillation and cold pressing remain the cornerstones of essential oil extraction. Steam distillation offers versatility across a range of plant materials, though it requires precise control to prevent thermal degradation. Cold pressing, on the other hand, is a straightforward, heat-free method that is ideal for citrus fruits. Both methods have stood the test of time due to their effectiveness in producing high-quality essential oils without chemical solvents.

Green Chemistry Approaches in Essential Oil Extraction: Supercritical Fluid Extraction and Microwave-Assisted Extraction

The goal of green chemistry is to diminish the environmental impact associated with chemical processes by lowering both waste production and energy consumption, and the use of hazardous substances. [24] During the extraction process of essential oils, traditional methods like steam distillation and solvent extraction often involve high energy use or potentially harmful solvents. Innovative extraction approaches, such as Supercritical Fluid Extraction (SFE) and Microwave-Assisted Extraction (MAE), that prioritize environmental sustainability, offer more environmentally friendly alternatives. [25] These methods are gaining popularity because they significantly improve efficiency while reducing the environmental impact of the extraction process. This review discusses the principles and advantages of these green chemistry approaches in essential oil extraction. [26]

Supercritical Fluid Extraction (SFE)

This innovative extraction method, known as supercritical fluid extraction, make use of a supercritical fluid—usually carbon dioxide (CO_2)—to efficiently extract essential oils in an environmentally conscious manner. Supercritical CO_2 exhibits properties of both a gas and a liquid, enabling it to effectively infiltrate plant matter and extract essential oils without relying on organic solvents. [27]

Mechanism: When subjected to pressures exceeding 73.8 bar and temperatures above 31.1°C, carbon dioxide enters a supercritical state, displaying characteristics of both a liquid, characterized by high density, and a gas, noted for its low viscosity. This unique state allows CO_2 to act as a solvent, the process involves extracting essential oils from plant materials. After the extraction is finalized, the pressure is reduced, allowing the CO_2 to revert to its gaseous form, which results in the essential oil being left behind free of any solvent residues. [27]

Advantages:

Non-toxic and eco-friendly: CO_2 is non-toxic, non-flammable, and leaves no harmful residues, making it ideal for extracting essential oils used in food, cosmetics, and pharmaceuticals.

Low-temperature process: SFE operates at lower temperatures compared to steam distillation, preventing the deterioration of heat-sensitive substances and preserving the integrity of the essential oil.

Selective extraction: The solubility of essential oils in supercritical CO_2 can be adjusted by changing the pressure and temperature. enabling the targeted extraction of particular compounds.

Limitations: The significant expense associated with equipment and the necessity for specialized knowledge to operate SFE systems can be a barrier to its widespread use, particularly for small-scale producers.

Applications: SFE has proven effective in extracting essential oils from a variety of plant materials, like mint, lavender, rosemary, and citrus peels [27].

Microwave-Assisted Extraction (MAE)

Microwave-assisted extraction is an creative and environmentally friendly technique that utilizes microwave radiation to heat botanical materials, thereby improving the extraction of essential oils. The technique is favored for its ability to minimize the time required for extraction and lower energy consumption, and solvent usage.

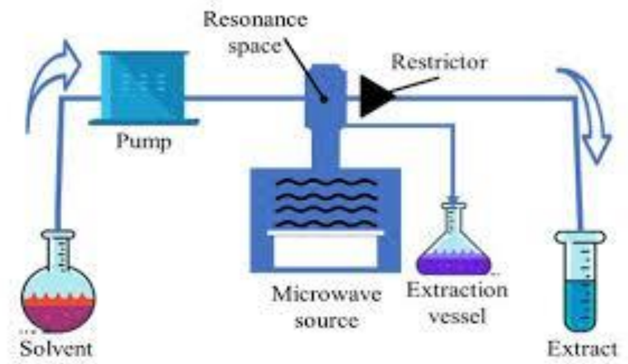

Fig.1.1

Mechanism: Microwaves generate heat by causing the water molecules in plant cells to oscillate. This rapid internal heating causes plant cell walls to rupture, releasing the essential oils into the surrounding solvent (or water, in the case of solvent-free MAE). The released oil is then collected by standard separation techniques. [28]

Advantages:

Fast and energy-efficient: MAE significantly reduces extraction times, often requiring just a few minutes to achieve results comparable to conventional methods that can take hours. This leads to lower energy consumption and operational costs.

Improved yield: MAE can increase the yield of essential oils compared to traditional methods, particularly for plant materials with low oil content or tough cellular structures.

Solvent flexibility: MAE may be executed with the use of solvents or without any solvents at all. When solvents are used, eco-friendly options like ethanol or water are often chosen, aligning with green chemistry principles.

Thermal control: Since microwave heating occurs internally and selectively within the plant matrix, there is less risk of thermal degradation of heat-sensitive compounds compared to conventional heating methods. [28]

Limitations: While MAE offers many advantages, its application is limited by the type of plant material, as not all materials respond well to microwave heating. Additionally, specialized equipment is required, which can be expensive to install and maintain.

Applications: MAE has been engaged in the extraction of essential oils from various plants, including basil, eucalyptus and oregano. The technique is particularly effective for herbs and flowers that contain sensitive compounds susceptible to heat damage during traditional extraction [25].

Green chemistry approaches like supercritical fluid extraction and microwave-assisted extraction represents a shift toward more sustainable and environmentally conscious methods in essential oil production. SFE uses carbon dioxide as a non-toxic solvent, operating under conditions that preserve the integrity of essential oils. Similarly, MAE reduces extraction time and energy consumption while allowing for the use of green solvents. Both methods align with the principles of green chemistry, offering efficient, eco-friendly alternatives to conventional extraction techniques. [25]

Comparison of extraction techniques: yield, purity, and sustainability

1. Solvent Extraction

Yield: Solvent extraction is known for its high yields due to how target compounds dissolve in different solvents. Recent studies suggest that optimizing solvent type and extraction conditions can further enhance yields [29].

Purity: The purity of the extracts can be impacted by the presence of impurities in the solvent, necessitating additional purification steps [30].

Sustainability: Traditional solvent extraction often raises environmental concerns due to the utilization of toxic solvents. The adoption of greener solvents is increasingly being promoted [31].

2. Steam Distillation

Yield: This method typically provides moderate yields, especially for volatile compounds. Factors such as temperature and pressure significantly affect extraction efficiency [32].

Purity: Steam distillation generally yields high-purity extracts due to its separation mechanism based on boiling points [33].

Sustainability: Considered a relatively sustainable method, steam distillation primarily uses water, although its energy consumption can be a drawback [34].

3. Cold Press Extraction

Yield: Commonly used for oil extraction, cold-pressing yields can vary but are substantial for oil-rich materials [35].

Purity: This technique usually maintains high purity levels, as it avoids heat, preserving sensitive compounds [36].

Sustainability: Cold pressing is highly sustainable due to its low energy requirements and absence of harmful solvents [37].

4. Supercritical Fluid Extraction (SFE)

Yield: SFE can achieve high yields and is particularly effecient in extracting both polar and non-polar compounds using supercritical CO2 [38].

Purity: This method often produces high-purity extracts due to its selective extraction capabilities [39].

Sustainability: SFE is regarded as sustainable because it utilizes CO2, which is recyclable and non-toxic [40].

5. Ultrasound-Assisted Extraction (UAE)

Yield: UAE has been shown to significantly enhance yields compared to conventional methods by improving mass transfer [41].

Purity: While the UAE can yield high-purity extracts, careful control of the cavitation process is necessary to minimize impurities [42].

Sustainability: This technique is considered sustainable due to its lower energy consumption and reduced extraction times [43].

Recent Innovations in Extraction Technology

1. Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction has gained prominence for its efficiency and environmental benefits. Using supercritical CO2, SFE allows for selective extraction of compounds without residual solvents, thus improving product purity and yield. Recent studies have optimized parameters such as pressure and temperature to maximize extraction efficiency, demonstrating a significant reduction in energy use compared to conventional methods [44].

2. Ultrasonic Extraction

The process of ultrasonic extraction leverages high-frequency sound waves to deconstruct the walls of plant cells, which enhances the liberation of bioactive compounds. Research from 2021 to 2023 indicates that optimizing ultrasonic parameters can lead to extraction efficiencies exceeding those of traditional methods, particularly in the recovery of antioxidants and essential oils [45]. The method is also noted for its rapid processing times and reduced solvent consumption.

3. Microwave-Assisted Extraction (MAE)

Microwave-assisted extraction has emerged as a highly effective technique, leveraging microwave energy to heat solvents and enhance the extraction of compounds. Recent advancements have focused on developing hybrid systems that combine MAE with other extraction techniques to further improve efficiency and yield [46]. Studies show that MAE can reduce extraction times significantly while increasing the concentration of desired compounds [47].

4. Membrane Technology

Membrane technology is increasingly used in extraction processes, particularly for liquid-liquid extractions. Innovations in membrane materials have led to higher permeation rates and selectivity, improving efficiency. Research indicates that integrating membrane processes can reduce the volume of solvents required and lower energy consumption in large-scale operations [48].

5. Green Extraction Techniques

The emphasis on sustainability has spurred the development of green extraction methods that minimize environmental impact. Innovations such as enzymatic extraction and the use of ionic liquids are gaining momentum. These methods not only enhance extraction efficiencies but also reduce hazardous waste [49].

Pharmacological Activities of Essential Oils

Essential oils, composed primarily of terpenes, aldehydes, phenols, and alcohols, are known for their distinctive fragrances. Aromatherapy and traditional medicine have made use of these for a considerable time. Beyond their aromatic Characteristics, EOs have garnered significant interest in pharmacology for their potential therapeutic effects. This review discusses the latest findings on the pharmacological activities of essential oils [50].

1. Antimicrobial Activity

Essential oils are primarily recognized for their significant antimicrobial properties, which have been the focus of numerous studies., which includes antibacterial, antifungal, and antiviral effects. EOs have been found effective against drug-resistant pathogens, making them candidates for new antimicrobial therapies. Numerous research efforts have shown that essential oils such as oregano, thyme, and tea tree oil possess strong antimicrobial properties because of their elevated levels of phenolic compoundslike carvacrol and thymol. A 2021 study highlighted the effectiveness of oregano oil against multidrug-resistant 'Escherichia coli'and 'Staphylococcus aureus strains, showing significant antibacterial activity with low cytotoxicity in human cells. Furthermore, tea tree oil has been reported to disrupt biofilm formation, a key factor in chronic infections, especially in medical device-related infections [51].

2. Anti-inflammatory Activity

Chronic inflammation is a key factor in various diseases, like cardiovascular conditions, cancer, and autoimmune disorders. Essential oils have shown promise in modulating inflammatory responses by suppressing the synthesis of pro-inflammatory cytokines. For example, lavender and Eucalyptus oils have undergone investigation regarding their potential anti-inflammatory benefits., particularly in conditions such as arthritis and colitis. In a 2020 study, eucalyptus oil was found to suppress lipopolysaccharide (LPS)-induced inflammation by downregulating pro-inflammatory mediators like nitric oxide and prostaglandins in macrophages [52]. Similarly, Lavender oil demonstrated promise in alleviating symptoms of rheumatoid arthritis in preclinical studies by influencing the nuclear factor-kappa B (NF-κB) signaling pathway [53].

3. Antioxidant Activity

Oxidative stress is a crucial factor in the development of numerous diseases, such as neurodegenerative conditions and cardiovascular disorders. Essential oils are composed of numerous bioactive compounds that function as antioxidants, helping to neutralize free radicals and mitigate oxidative damage within cells. A study conducted in 2019 investigated the antioxidant capacity of clove oil, showcasing its capacity to neutralize free radicals and prevent lipid peroxidation in vitro [54]. mAdditionally, essential oils like rosemary and cinnamon have been shown to protect neurons from oxidative stress, this may carry significance for neurodegenerative diseases, including Alzheimer's and Parkinson's disease [55].

4. Anticancer Activity The potential anticancer properties of essential oils have attracted significant interest in recent years, Numerous studies have concentrated on their capacity to suppress the proliferation of cancer cells, promote apoptosis, and diminish metastasis. Essential oils like frankincense, rosemary, and thyme have shown promise in cancer treatment, particularly against breast, colon, and prostate cancers [56].

A 2022 study reported that frankincense oil exhibited significant antiproliferative effects against breast cancer cells by inducing apoptosis and Blocking the PI3K/AKT/mTOR signaling cascade. Moreover, thyme oil was found to inhibit tumor growth in colorectal cancer models by suppressing angiogenesis and promoting tumor cell apoptosis [57].

5. Neuroprotective Effects

The neuroprotective effects of essential oils have been a topic of increasing interest in recent studies Neurodegenerative disorders like Alzheimer's disease and Parkinson's disease are typically marked by oxidative stress, inflammation, and neuronal damage. Essential oils such as lavender, rosemary, and peppermint have been studied for their neuroprotective effects [58]. In a 2023 study, rosemary essential oil was shown to enhance cognitive function in a mouse model of Alzheimer's disease by reducing oxidative stress and beta-amyloid accumulation. Additionally, peppermint oil demonstrated neuroprotective effects in models of ischemic stroke, reducing infarct size and improving functional recovery by modulating inflammatory pathways [59].

6. Anti-diabetic Activity

Diabetes, particularly type 2 diabetes, is a growing global health concern. Research has explored the potential of essential oils to modulate blood sugar levels and enhance insulin sensitivity. Oils such as cinnamon, fenugreek, and coriander have shown antidiabetic properties in both animal models and clinical studies [60]. A 2020 study on cinnamon essential oil demonstrated its ability to reduce blood glucose levels in diabetic rats, potentially by enhancing insulin sensitivity and reducing oxidative stress. Similarly, coriander oil was found to improve lipid metabolism and reduce hyperglycemia in a 2021 clinical trial involving type 2 diabetic patients [61].

7. Essential oils as immunomodulators

Essential oils have emerged as promising immunomodulators, offering potential therapeutic benefits by influencing the immune system. Recent studies from 2019 to 2024 have demonstrated that certain essential oils can enhance or suppress immune responses, depending on their bioactive constituents [62]. For instance, essential oils such as eucalyptus, thyme, and frankincense have been reported to modulate cytokine production, regulate inflammatory pathways, and improve immune cell function. A 2021 study found that eucalyptus oil significantly reduced inflammation in LPS-induced macrophages by downregulating pro-inflammatory cytokines like TNF-α and IL-6, suggesting its potential role in treating inflammatory diseases [63]. Similarly, thyme essential oil has been demonstrate Augment the immune response by stimulating the activity of NK cells and T lymphocytes, enhancing immune surveillance against pathogens and tumors. Frankincense oil was highlighted in a 2022 study for its ability to suppress autoimmunity by modulating the Th1/Th2 balance, offering potential in autoimmune disease management. These findings underscore the growing interest in essential oils as natural immunomodulatory agents, with applications in treating infections, inflammation, and autoimmune disorders [64].

Safety, Toxicology, and Regulatory Aspects

The period from 2019 to 2024 witnessed substantial progress in the fields of safety, toxicology, and regulatory science. Evolving scientific understanding, coupled with heightened public awareness, has driven regulatory agencies to update guidelines and implement new safety standards across various industries [67]. the third edition of "Regulatory Toxicology" was published, offering comprehensive insights into safety assessments required for a wide range of marketed products.Regulatory Requirements for Genetically Modified Organisms (GMOs), and Regulatory Requirements for Tobacco and Marijuana, reflecting the evolving landscape of product safety and regulation [68].

Toxicity Profiles of Common Essential Oils

The toxicity of EOs varies based on their chemical composition, concentration, and mode of application. Some EOs contain constituents that can cause skin irritation, sensitization, or systemic toxicity.

- **Tea Tree Oil**: extensively used for its antimicrobial properties, tea tree oil has been associated with cases of poisoning, especially in children. Between 2014 and 2018, Australia reported 1,387 cases of essential oil poisoning, with tea tree oil being a significant contributor. Symptoms included nausea, vomiting, and, in severe cases, convulsions. [69]
- **Eucalyptus Oil**: Known for its respiratory benefits, eucalyptus oil can be toxic if ingested in large amounts. In young children, consuming as little as 0.6 to 5 mL of pure eucalyptus oil can lead to serious health issues. Tragically, there was a reported fatality involving an 8-month-old infant who ingested 30 mL.
- **Clove Oil**: Containing high levels of eugenol, clove oil has been linked to adverse reactions such as allergic contact dermatitis and respiratory issues upon inhalation. [70]

Safe Dosage and Application Guidelines

To minimize the risk of adverse effects, it is essential to adhere to recommended guidelines for EO usage:

- **Dilution**: Always dilute EOs with a suitable carrier oil before applying them to your skin. This helps minimize the chances of irritation. A common recommendation is a 2% dilution, equating to about 12 drops of EO per ounce (30 mL) of carrier oil.
- **Patch Testing**: Before full application, to ensure safety, apply a small amount of the diluted EO to a small area of your skin and observe for any negative reactions. [71]
- **Inhalation**: When using EOs for inhalation, ensure the area is well-ventilated. Be cautious when using diffusers around individuals with respiratory conditions or allergies.
- **Ingestion**: Ingesting EOs is generally discouraged unless under the supervision of a qualified healthcare provider, as some EOs can be toxic when consumed. [72]

Quality Control and Standardization Guidelines.

Updates in Medical Laboratory Standards

The International Organization for Standardization (ISO) released an updated version of ISO 15189, titled "Clinical Laboratories: Requirements for Quality and Competence." This revision introduced structural changes and incorporated for point-of-care testing (POCT), aiming to enhance patient safety and promote continuous improvement. The updated standard emphasizes a risk-based approach and integrates aspects of ISO 22870:2016, which previously focused on POCT [73]. Despite these advancements, critiques have emerged regarding the clarity and applicability of ISO 15189:2022. Some experts argue that the standard's language can lead to misinterpretation among medical professionals, suggesting a need for more precise, evidence-based recommendations to ensure effective implementation [74].

Developments in Statistical Quality Control

The Clinical and Laboratory Standards Institute (CLSI) published the fourth edition of guideline C24, "Statistical Quality Control for Quantitative Measurement Procedures: Principles and Definitions." This edition offers refreshed definitions, principles, and strategies for the design, implementation, and evaluation of laboratory quality control, aiming to enhance the reliability of quantitative measurement procedures [75].

Standardization in Steel Production

In September 2024, India's Ministry of Steel issued the "Steel and Steel Products (Quality Control) Order, 2024," superseding previous quality control directives. This order mandates that specified steel products adhere to corresponding Indian Standards and uphold the Standard Mark pursuant to a license from the Bureau of Indian Standards. The order also outlines penalties for non-compliance, underscoring the government's commitment to maintaining high-quality standards in steel production [76].

CONCLUSION: Essential oils, with their multifaceted therapeutic potential and wide-ranging applications, continue to serve as a cornerstone in pharmacognosy and natural product research. Advances in innovative extraction technologies, like supercritical fluid extraction, microwave-assisted techniques, and ultrasound-assisted methods, possess significantly enhanced the efficiency, quality, and environmental sustainability of essential oil production. These developments have not only improved the yield of bioactive compounds but also enabled a deeper understanding of their complex chemical profiles and synergistic interactions. The incorporation of essential oils into modern therapeutic practices, particularly through nanotechnology-driven drug delivery systems, underscores their growing relevance in contemporary medicine. Despite these achievements, several challenges remain, including the standardization of essential oil compositions, addressing variations due to environmental and geographical factors, and navigating regulatory frameworks to ensure their safe and effective use. Future research should focus on addressing these limitations through multidisciplinary approaches, integrating advanced analytical techniques, and fostering collaborations between academia, industry, and regulatory bodies. By building on the recent progress and overcoming existing barriers, essential oils have the potential to emerge as integral components in the development of novel, sustainable, and efficacious therapeutic solutions for global health challenges.

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