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Narrative Review of Essential Oils in Infection Control

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ABSTRACT

Essential oils (EOs) are complex mixtures of volatile compounds extracted from plants that have been historically employed for therapeutic and preventive purposes. Their antimicrobial, antiviral, antifungal, antioxidant, and immunomodulatory properties have generated increasing interest in infection control, particularly in the context of rising antimicrobial resistance. This review explores the composition, mechanisms of action, and clinical relevance of EOs, highlighting their role as complementary and adjunctive agents in bacterial, viral, and fungal infections. Tea tree, lavender, peppermint, eucalyptus, and oregano oils are among the most studied, demonstrating broad-spectrum antimicrobial activity and synergistic effects with conventional drugs. Application methods include topical use, aromatherapy, and inhalation, with ongoing studies evaluating delivery systems for improved efficacy. Despite promising laboratory and preclinical evidence, challenges persist in standardization, safety, toxicity, and regulatory approval. Addressing these gaps through rigorous clinical studies and quality control measures could enhance the integration of essential oils into modern infection control strategies.

Keywords: Essential oils; Infection control; Antimicrobial resistance; Antifungal activity; and Antiviral effects.

INTRODUCTION

Essential oils are liquids derived from the aroma of plants, obtained by distillation or mechanical methods. They are secreted into plant flowers, leaves, seeds, bark, wood, and roots, and contain combinations of chemical properties that may be used for therapeutic purposes, according to a long historical record spanning many cultures and centuries [1]. Traditionally used for general maintenance of well-being and relief from daily stress, aromatic oils have been applied as bactericides or virucides, many with high efficacy. They are employed in topical, inhalative, or aromatic application methods, and are often cited by the medical community as complementary medicine. Because it is not yet practical to use these oils as the sole source of medication during infection, they are more commonly seen as enhancers of standard medical therapy. They have also been used to augment the potency of conventional pharmaceuticals; in particular, some combinations of the two have demonstrated a synergistic effect. Related research with the use of essential oils against other infection types yielded positive results; many studies show promising efficacy and low toxicity, although limitations on their standardization, toxicity, and suitability of the various delivery modalities complicate adoption outside of complementary medicine [2]. The rise of infection motivates a parallel rise in the use of complementary or adjunctive treatments. The appearance and spread of antimicrobial-resistant bacteria and early outbreaks of viral diseases such as SARS and MERS once again directed interest toward alternative medicine. With an expanding chemical library and known health-enhancing properties, the oils may represent a valuable resource with untapped potential. Nonetheless, the lack of standardization for production procedures and quality control hampers adoption; composition can vary widely even among samples collected from similar regions.

Overview of Essential Oils

Essential oils are concentrated hydrophobic liquids containing volatile chemical compounds derived from plants. Historically, essential oils have been used as part of the medicinal armamentarium of ancient cultures, including the Egyptians and physicians of Greco-Roman antiquity [1, 3]. The most abundant antimicrobial agents are monoterpenes, the principal components of essential oils, and aromatic compounds generally responsible for fragrance; in addition, the chemical family, the relative amount of the components, and their possible synergy also play an important role [3].

Definition and Composition

Essential oils are complex mixtures of volatile constituents, characterized by a strong odor, obtained from plant materials mainly through steam distillation [4]. Plants produce essential oils as secondary metabolites, primarily composed of terpenes, terpenoids, and other aromatic and aliphatic compounds. Components such as alcohols, phenolic terpenes, and hydrocarbons present in essential oils can exert antimicrobial properties. Essential oils have been used for centuries in traditional medicine and exhibit antimicrobial, antioxidant, anti-inflammatory, and anticancer effects [4]. Establishing a scientific rationale for the broad applications of essential oils remains a challenge. However, due to their antimicrobial properties and ability to modulate cell-mediated and humoral immune responses, essential oils are of interest for infection control [4].

Historical Use in Medicine

The history of essential oils dates to around 3000 BC. Extractions were found in materials dating back to the ancient Egyptians and Persian civilizations. The first physical extraction method, invented by Avicenna in Persia around 1000 AD, was steam distillation [1]. During the Great Plague, which was spread by airborne 'noxious vapors', essential oils were considered an effective barrier to transmission. Dr. John Parkinson documented that physicians who carried the 'pocket bottle' of essential oil did not catch the plague. The anticipated 'infection control' properties were recognized even before the establishment of germ theory [1, 2, 3]. Modern interest in the therapeutic properties of essential oils arose in 1928 when René Gattefosse discovered their tissue repair capabilities. He coined the term aromatherapy in 1937. Since then, the therapeutic use of essential oils has expanded to include treatment for cancer, pain, stress, insomnia, depression, and various infections. These applications are administered topically, in aromatherapy, or orally [1].

Mechanisms of Action

Essential oils act on infections through their antimicrobial nature and their ability to modulate the host's immune response. Antimicrobial activity depends on the volatile constituents, the proportions of active components, genetic and chemical compositions, and synergistic interactions among components [1, 6, 5]. Their hydrophobicity enhances permeation into non-ionic membranes and partitions lipophilic compounds within the lipid bilayer, disrupting cell structures and altering immunomodulatory pathways [1]. Essential oils exert antifungal effects by damaging cell membranes, disrupting mitochondrial function, and causing membrane coagulation. They penetrate fungal cell walls and cytoplasmic membranes, leading to mitochondrial damage, perturbed electron flow, and subsequent cell death [1]. Interference with ion channels, proton pumps, and ATP pools may alter membrane permeability and induce apoptosis or necrosis. Antiviral activity involves inhibition of virion entry and replication, disturbance of viral protein synthesis, and blockage of early gene expression processes [5]. Concentrated solutions of essential oils can suppress microbial growth rate parameters and viability at low concentrations, working through mechanisms that remain incompletely understood [6].

Antimicrobial Properties

Essential oils have demonstrated antimicrobial activity against both Gram-positive and Gram-negative bacteria, including carbapenem-resistant Enterobacteriaceae [2]. Oregano, thyme, and tea tree oil exhibited the strongest efficacy among 27 oils tested, followed by cinnamon bark, lemongrass, manuka, and Thieves oil blend. Cinnamon bark displayed the broadest spectrum of activity, including effectiveness against normally resistant Pseudomonas aeruginosa isolates. The major antimicrobial constituents are primarily terpenoids such as thymol and carvacrol, and phenylpropenes like eugenol; many of these compounds occur together in the effective EOs [1]. The complex mixtures of compounds provide enhanced antimicrobial activity through additive/synergistic effects and may also synergize with antibiotics [2]. The main mechanisms involve increased cell membrane permeability and disruption of membrane structure. The generally higher efficacy against Gram-positive bacteria is associated with their simpler cell wall structure. Essential oils have also eradicated biofilms of Pseudomonas spp. and Staphylococcus aureus, demonstrating an additional mode of antibacterial action [1]. The predominant method used for activity assessment has been agar disk diffusion; however, the hydrophobic nature of essential oils limits the amount of oil diffusing into agar, potentially constraining the extent of antimicrobial activity observed. Applications comprise topical use, ingestion (often highly diluted), and inhalation, with the latter appearing presently as the safest route. Further clinical studies are essential to evaluate safety, efficacy, and practical application [1, 2].

Immune Modulation

Essential oils modulate immune responses by two major mechanisms: (i) activation of immune cells, (ii) modulation of inflammatory mediators [6]. They influence functions of immunocompetent cells, such as macrophages, dendritic cells, natural killer cells, and lymphocytes, impacting the production of cytokines, chemokines, and reactive species, thereby fine-tuning immune surveillance and defense [6]. Many essential oils reduce proinflammatory molecules and stimulate anti-inflammatory ones, a pattern documented for Origanum vulgare and Lavandula angustifolia. Echinacea purpurea EO decreases proinflammatory cytokines in animal models [4].

Other plant-derived oils, such as those from Astragalus, clove, basil, sage, and rosemary, reduce nitric oxide and reactive oxygen species, conferring antioxidant effects. Some essential oils, such as Allium sativum, eucalyptus, Pinus sylvestris, and Melissa officinalis, increase macrophage activity and lymphocyte proliferation; by contrast, Nigella sativa EO does not affect neutrophil activity, and its principal component thymoquinone inhibits lymphocyte proliferation and promotes apoptosis. Certain oils influence neutrophil $Ca2+$ mobilization and functional activation, as observed for Juniperus and Rhododendron species [7]. Research remains incomplete, but ongoing investigations on thyme, tea tree, and peppermint oils reveal positive effects on human phagocyte functions. Immunomodulatory activity has been proposed for Artemisia, Pistacia, Citrus, and Zingiberaceae species, but underlying molecular pathways remain largely unexplored [7]. Despite limited clinical data and occasional contradictory findings, essential oils show promise as immunomodulators whose efficacy can surpass that of conventional pharmaceuticals. Although generally safe at low doses, their pharmacological application requires concentration within accepted boundaries and scientific evidence of efficacy. Standardized testing methods are urgently needed to evaluate efficacy and safety and to promote broader clinical use [1, 7].

Essential Oils in Infection Control

An ever-increasing number of acute and chronic infections have become resistant to conventional chemical and biochemical treatments. Historically, essential oils (EOs) have played a pivotal role in humankind's quest to remedy infections and promote health [4]. There is now a growing body of experimental evidence confirming that EOs possess potent antimicrobial activity against bacterial, viral, and fungal infections, as well as significant immunomodulatory effects [4]. Among the most popularly studied EOs, tea tree, lavender, peppermint, eucalyptus, and oregano oils have grown in importance as topical and emerging inhalation therapies for infection control. The antimicrobial properties of EOs make them appealing alternatives to conventional chemical antibiotics, antiseptics, and disinfectants, especially for prophylaxis and early-stage treatment of infections caused by multidrug-resistant strains [1]. The resistance of pathogenic bacteria towards commonly used chemical drugs has led to a global public health crisis. It is therefore essential to explore alternative strategies, such as infection control based on the antibacterial effects of Eos [1]. EOs are complex mixtures of volatile organic compounds produced by aromatic plants as secondary metabolites essential for mediating interactions with the environment and for protection under biotic and abiotic stresses [3]. The antimicrobial properties of EOs have been the most exploited attribute throughout history, yet many gaps still exist in our knowledge of these substances [3].

Bacterial Infections

Essential oils exhibit a broad spectrum of action, encompassing antibacterial properties that target various bacterial strains through mechanisms such as membrane disruption, permeability alteration, proton motive force depletion, and disruption of genetic material [1]. Specific oils, including oregano, thyme, cinnamon bark, lemongrass, and manuka, demonstrate pronounced antimicrobial activity, with cinnamon bark displaying notable efficacy against both Gram-positive and Gram-negative bacteria; Pseudomonas aeruginosa is the least susceptible among the tested strains [2]. The antibacterial activity primarily derives from components such as thymol, carvacrol, eugenol, and cinnamaldehyde, which exhibit synergistic interactions when combined [2]. The mode of action entails augmentation of bacterial cell permeability followed by membrane disorganization, resulting in cytoplasmic component leakage [1,2]. Gram-positive bacteria are generally more sensitive due to the absence of an outer membrane. Essential oils can also eradicate biofilms formed on various surfaces. Common in vitro assessment employs agar disk diffusion; however, the hydrophobic nature of essential oils complicates broth microdilution, the preferred method for determining minimal inhibitory concentration [1, 2]. At present, data regarding the safety and toxicity of essential oils remains limited. Application possibilities include direct topical administration, inhalation, or intranasal delivery for prophylaxis against bacterial infections [1, 5].

Viral Infections

Numerous essential oils are efficacious against viruses such as influenza, Coxsackie virus B4, hepatitis A virus, herpes simplex virus, human immunodeficiency virus, rhinovirus, yellow fever virus, and Zika virus, as well as insect-borne viruses [8]. The oils of thyme, tea tree (Melaleuca alternifolia), eucalyptus, peppermint, clove, and rosemary are attractive, traditional remedies for respiratory infections because their constituent compounds have anti-inflammatory, mucolytic, and bronchodilator effects [8]. Inhalational, oral, and transdermal dosage forms can be used. A broad-spectrum antibacterial and anti-SARS-CoV-2 screening program was conducted on several volatile oils, guided by the transport of SARS-CoV-2 into alveolar type 2 cells [7, 8]. The transport of SARS-CoV-2 into alveolar type 2 cells begins with viral spike-protein attachment to the cell-membrane receptor, angiotensin-converting enzyme 2 (ACE-2). Transmembrane protease serine 2 (TMPRSS2) cleaves the spike protein, facilitating viral-endosomal membrane fusion and the release of viral RNA into the host cell. Modulation of viral-transport proteins has therefore been extensively investigated for drug discovery [8]. Focus was given to two proteins; the first, the complex of the SARS-CoV-2 spike-protein receptor-binding domain bound to ACE-2 (6LZG); the second, the closed-form spike-protein trimer (6VXX). The first highly populated cluster of each essential-oil compound was docked into the active sites of both 6LZG and 6VXX. A library of small molecules was compiled, and SARS-CoV-2 anti-transport-screening and antibacterial-screening programs were developed to identify constituents with potent efficacy [8]. The chemical composition of some volatile oils was analysed, and their ability to inhibit Gram-positive and Gram-negative bacterial strains, Staphylococcus aureus, Pseudomonas aeruginosa, and Escherichia coli, and the yeast Candida albicans, was also examined. Only the oil(s) that exhibited the greatest broad-spectrum potency was/were selected for inhibition of viral-transport proteins 6VXX and 6LZG [9]. According to assessment by docking scores and ADME properties, the most potent anti-transport and broad-spectrum inhibitory candidates were formulated in nano-emulsion dosage form and studied for stability, particle size, and zeta-potential to identify the best candidate(s) for anti-SARS-CoV-2 drug development [9].

Fungal Infections

Fungal infections have historically been less common than bacterial and viral infections; however, growing numbers of immunosuppressed individuals and the extended survival of at-risk populations may support epidemics of mycoses [10]. Numerous endemic fungal infections exhibit specific geographic distributions influenced by climate change, human habitat encroachment, travel, and migration [9, 10]. Pathogenic fungi must colonize or penetrate surface barriers, obtain nutrients from host tissues, counteract immune defenses, and grow at human body temperature. The inability of the human host to meet these requirements determines the outcome of fungal encounters [10]. Additionally, the currently available therapeutic arsenal is restricted to a limited number of traditional antifungal agents [12]. Several pathogenic fungi have acquired resistance to standard therapies and continue to display resistance to multiple available drugs, highlighting the urgent need for new antifungal approaches. Essential oils (EOs) are highly concentrated oily mixtures of volatile compounds produced by aromatic plants. They have been widely employed as antifungal agents. Their mode of action mainly involves alteration of the cell membrane permeability and membrane functionality [11]. EOs represent a relevant potential antifungal therapy to combat yeast and mould fungal infections. In vitro studies demonstrate antifungal properties against a broad spectrum of pathogenic fungi such as Candida [12]. Numerous essential oils are capable of controlling fungal infections, particularly in healthy individuals [11]. Popp et al. (2020) identified 23 essential oils with antifungal activity against Candida spp., including cinnamon, clove, lemongrass, bay, eucalyptus, ylang ylang, thyme, ginger, and citronella [12]. Lavender essential oil also exhibits a high degree of antifungal activity [21]. Various studies describe the antifungal activity of geranium oil against different fungi. Moreover, essential oils have been evaluated against non-albicans species and uncommon yeasts; most oils exhibit good activity against both clinical isolates and reference strains of emerging opportunistic pathogens [23].

Popular Essential Oils and Their Efficacy

The previous section, "Essential Oils in Infection Control," catalogued their application against bacterial, viral, and fungal pathogens. Complementarily, the present section reviews five widely studied oils that exhibit confirmed antimicrobial efficacy: Melaleuca alternifolia (tea tree), Lavandula angustifolia (lavender), Mentha piperita (peppermint), Eucalyptus globulus (eucalyptus), and Origanum vulgare (oregano)—highlighting their distinctive components and documented activity [1, 5]. Tea tree has garnered the most empirical attention among more than 20 oils assessed for dermatological efficacy [3]. It remains the standard for comparative purposes owing to its potent activity against Gram-negative and Gram-positive bacteria [1]. Commercially sourced samples consistently demonstrate high terpinen-4-ol content, a primary antimicrobial constituent. Genuine tea tree oils rank among the most effective agents against methicillin-resistant Staphylococcus aureus (MRSA) and other Gram-negative and Gram-positive bacteria. Lavender frequently tops lists of antimicrobial potency across various oil collections [6]. Peppermint's menthol-rich oils exhibit elevated antimicrobial effects relative to the majority of tested commercial counterparts, which dominate the mid-purpose activity spectrum. Eucalyptus and oregano rank as the third- and fourth-most potent antimicrobials, respectively, among samples intended for skin disease treatment. Oregano, characterized by substantial carvacrol content, and geraniol account for significant activity against Staphylococcus strains, including resistant forms [2].

Tea Tree Oil

Tea tree oil (TTO) is the essential oil derived from the leaves and terminal branches of the Melaleuca alternifolia plant native to Australia [12, 13]. The spectrum of antimicrobial effects of TTO is extensive: it is effective against a variety of bacteria, including Mycobacterium tuberculosis, Staphylococcus aureus, and Escherichia coli, numerous yeasts and fungi (such as Cryptococcus neoformans and Aspergillus niger), and the viruses herpes simplex and influenza [13]. The reported effective concentrations fall within a few per cent, which implies that the essential oil is present in treatment concentrations commercially available from reputable suppliers, and it is also considered safe for humans and animals at amounts of up to 10%. TTO has proved useful in wound infection, acne, and oral hygiene products, but a clearer definition of the mechanisms responsible for its antimicrobial effects, optimal formulations, and efficacy in in vivo situations is required to enable the essential oils' adoption as a clinical treatment [13].

Lavender Oil

The plant Lavandula angustifolia, also known as lavender, is cultivated on a large scale for its aromatic flowers, which are used in the production of lavender essential oil. It has over 30 various species spread throughout the planets [1]. It is traditionally used to treat various illnesses such as anxiety, headache, insomnia, depression, fatigue, and wound care. One of the most widely used essential oils in cosmetics, food, and complementary medicine to treat infections is lavender [2]. Due to its antibacterial, antifungal, insecticidal, antioxidant, and anti-inflammatory properties, lavender essential oil shows considerable promise as a natural antimicrobial agent in both the food and medical industries [1]. Lavender essential oil has antimicrobial properties against various fungal and bacterial pathogens, the majority of which are involved in skin and respiratory disorders. Additionally, it has antioxidant, anti-inflammatory, and immunomodulatory properties, which imply that it is capable of stimulating the host immune response [14]. Lavender oil has demonstrated anti-inflammatory and antimicrobial activity against respiratory tract pathogens in vitro and ex vivo through nebulization and lavage [15].

Peppermint Oil

Mentha piperita (peppermint) is a cultivated hybrid originating from the Mediterranean region but grown worldwide. The essential oil extracted from this plant shows wide applications in treating several diseases. The oil's therapeutic properties include treatment of respiratory tract diseases, nausea, vomiting, and it also acts as a stimulant and antispasmodic. Studies confirm that peppermint EO contains extensive antimicrobial properties [1]. Several chemical components from Moroccan M. piperita EO were tested against bacteria and fungi involved in spoilage and pathogenicity [16]. Peppermint EO is generally classified as GRAS by the U.S. Food and Drug Administration and is used in food preparations as flavoring agents and food additives [1]. Despite its extensive antimicrobial properties, only preliminary research has tested its application in healthcare environments. Demonstrated the antimicrobial activity of commercially available peppermint EO volatile substances against bacteria and fungi commonly found on human skin and in hospitals. Blends of essential oils can provide a broader spectrum of antimicrobial activity than individual oils. Reducing the proportion of orange oil and increasing peppermint EO in mixtures may enhance antimicrobial effects [17].

Eucalyptus Oil

The elevated virulence of respiratory infections prompts an evaluation of the effectiveness of natural antimicrobial agents, particularly EO [18]. EO is a movable, odorous, and volatile complex that contains many bioactive compounds that promote biological activity. EO exerts its therapeutic benefits by exerting antimicrobial action and thus indirectly promotes immune modulation [18]. The EO derivatives such as cineole (eucalyptol), terpinen-4-ol, thymol, α-terpineol, and α-pinene have wide-ranging activities and potential in the infection control sector. These derivatives also provide low to moderate toxicity, molecular allergenic, and mucosal irritation effects. E. globulus is the most widely used EO in the pharmaceutical and personal-care industry. It has a strong antimicrobial effect against the common bacteria S. aureus and E. coli. EO also applies as a mineral supplement to prevent animal diseases. The antimicrobial and anti-inflammatory effects of Eucalyptus EO also made it effective against respiratory viruses and were added as active ingredients in OTC cold and flu medications [12].

Oregano Oil

Oregano (Origanum vulgare L., syn. Origanum heracleoticum L.) is native to the Mediterranean region, Madeira, the Azores, and the Canary Islands [19]. The herb thrives in the hilly regions of the southern Balkans, Turkey, Syria, Iran, the Caucasus, and the Crimea. It is cultivated extensively in numerous countries. Oregano leaves from different regions display variation in physical attributes such as length, width, and surface color [19]. The essential oil, extracted through hydro-distillation from the aerial parts, appears as a clear, light to yellow or red liquid. It possesses a warm, pungent, and aromatic spicy odor and registers a rather strong taste; therefore, the leaves are often employed as a pungent seasoning agent for certain Italian dishes. Bacterial clearance in infected tissues is a major issue because delayed treatment or the use of ineffective formulations and antibiotics gives microorganisms the opportunity to colonize tissue and invade deeper layers [18]. There is increasing evidence that respiratory tract infections caused by Candida strains may be a major cause of morbidity and mortality in critically ill patients [1, 14]. Medical gas plasma generated in a specific kINPen med device might be able to eradicate Candida albicans, the most frequent fungal pathogen worldwide. The high ORAC value and strong chemical power point to the ability of the Oregano extracts to effectively scavenge the highest amounts of ROS, while the endurance of the antioxidant system in the animals. Hence, incubation with the Oregano water extract killed microbial cells without affecting macrophage viability, independent of plasma treatment time [1, 2, 20].

Application Methods

Essential oils can be applied topically to the skin, aromatized into the air, or inhaled. Their use is multifactorial, with applications including therapeutic massages, relaxation, and treatment of various ailments [1]. When applied to the skin, essential oils are diluted with a carrier oil to mitigate irritation since they can be highly concentrated. This method allows direct contact between the oil and skin ailments [4]. Diffusing essential oils into the air as a vapor quickly disperses the fragrance and volatile components, providing relaxation and stress relief [5]. Although few studies exist, preliminary research indicates that aerosolized essential oils may impart direct health benefits when inhaled [3]. For example, aromatic application of tea tree oil has demonstrated a reduction in the rate of airborne Staphylococcus aureus. While topical administration predominates, inhalative use either via inhaler devices or vaporization is gaining clinical attention [6]. However, the volatile nature of essential oil constituents can diminish sustained medicinal effects, suggesting that controlled release mechanisms might enhance efficacy for a range of conditions [1, 3].

Topical Application

Skin infections are common and often require topical treatment, although microbial resistance has emerged, notably methicillin-resistant Staphylococcus aureus (MRSA). In some regions, infections are unresponsive to all known antibiotics, and simple infections can become life-threatening [2]. The World Health Organization warns that common infections may become untreatable as antibiotic resistance increases. One potential solution involves natural products such as essential oils, which have gained popularity in dermatology and alternative medicine. They are especially favored for treating fungal skin infections and are increasingly used in hospitals and by healthcare professionals worldwide [4]. More than 90 commercial essential oils are reported for dermatological uses, primarily targeting infections caused by bacteria, fungi, or viruses. They are also applied to inflammatory skin conditions such as dermatitis and eczema, and for general skin maintenance, including reducing wrinkles and scars [3].

Aromatherapy

Aromatherapy involves the process of breathing in essential oils, in the form of vapor or mist, with the intent to promote well-being [8]. Often referred to as Essential Oil Diffusion, it can be accomplished through steam or heat applied to an infused oil [1]. Currently, there are three primary methods of diffusion: ultrasonic, evaporative, and heat. Ultrasonic diffusers use high-frequency vibrations to disperse the oil into the air [3]. The evaporative method releases scents into the air by the natural evaporation of the oil, often using a ventilating fan [4]. Finally, heat diffusers utilize low-grade heat to encourage dispersion into the air [2]. The ultrasonic method is the most commonly used method due to its ability to preserve the integrity of the oil. Care must be taken with heat diffusion as elevated temperatures can alter the chemical composition. In medical settings, aromatherapy introduced through diffusers as vapor has been shown to decrease stress and anxiety [1]. Concerning infections, when the vapor diffusion constituents of five essential oils were examined for antiviral and antimicrobial activity, tea tree and eucalyptus oils exhibited the broadest activity against the influenza virus, Streptococcus pyogenes, methicillin-resistant Staphylococcus aureus (MRSA), Candida auris, and Aspergillus fumigatus. Aromatherapy remains a low-cost, easily accessible calming technique with antimicrobial potential [1].

Inhalation Techniques

Inhalation of essential oils is the most direct means of delivering the oils to the respiratory tract 20. Essential oils are inhaled by diffusion into the air or by direct inhalation from a cosmetic drop [1]. The main way to benefit from the components of essential oils that are recognized as safe is to prepare inhalation or apply them on the skin before inhaling vapors one to two times a day, over a maximum of 7 days [3]. Eucalyptus species produce an essential oil rich in 1,8-cineol, which is used as an active ingredient in medications and a symptomatic remedy in the treatment of upper respiratory tract diseases [4]. Eucalyptus essential oil is absorbed through inhalation by diffusion into the air, vaporizers, or direct inhalation, and it exhibits confirmed mucolytic, decongestant, and anti-inflammatory activities. The activity of the vapor phase of three essential oils obtained from Origanum majorana, Origanum vulgare, and Thymus vulgaris against the food-borne pathogens, Target: Salmonella enterica Typhimurium, was previously reported. Additionally, the biological effect of 1,8-cineole on bacterial biofilm formation and virulence answered the need for novel antimicrobial agents to control biofilms or other pathogenic mechanisms [1].

Safety and Toxicity

Several trials have reported adverse effects from the use of some essential oils [2]. For instance, oregano oil may act as an irritant to the sensitive external skin, and some individuals may be allergic to tea tree oil and other essential oils [3]. Moreover, certain oils should be avoided altogether in specific situations, as their use has been linked to adverse clinical outcomes [2]. Overall, most reported effects appear to be minor. Consequently, widespread use of essential oils is generally considered safe, provided they are used in recommended doses [1]. As with any active substance, it is important to recognize that essential oils carry some degree of risk for toxicity. Therefore, users should exercise caution and adhere to appropriate dosing guidelines to minimize potential hazards [1, 4].

Potential Side Effects

Considerable human experience has demonstrated that essential oils have a low order of toxicity; nevertheless, under certain circumstances, adverse effects may arise. In this context, the adverse effects may be either irritant or allergic [7]. It should be noted that the inability to distinguish between these two types of effects has led to the common misconception that these oils are strongly allergenic. Essential oils have a complex composition, including a vast majority of different chemical components, and it is this distribution of constituents that determines the final toxic or nontoxic properties of the materials [9]. It must be pointed out, however, that the drastic toxic effects obtained with some particular oils cannot be assigned to a single component but, in most cases, arise from the simultaneous action of several chemical compounds [8]. Hyperpigmentation, skin damage, and dermatitis are the frequently reported adverse effects associated with the topical application of several essential oils, while exposure to bergamot, lemon, and other citrus oils has often led to photosensitivity [4]. Furthermore, information from the Lhasa Limited database reports several adverse effects, including allergic reactions and irritation, caused by essential oils of orange, peppermint, tea tree, peppermint, eucalyptus, lavender, and Calamus, with the last one being the most dangerous [3]. Essential oils should be diluted properly before applying them to the skin surface. People with sensitive skin or with a history of allergies and children should avoid their topical use. Additional toxicological data focusing on the genotoxic and reproductive effects of essential oils are needed for a more comprehensive health risk assessment of these materials [11].

Contraindications

Contraindications are specific situations in which essential oil use is considered inappropriate and potentially harmful. Allergic reactions, including severe anaphylaxis, represent one such contraindication [1]. Additionally, patients with hypertension and cardiac disease should avoid tea tree, peppermint, and eucalyptus oils due to their potential to exacerbate these conditions [3]. Eucalyptus and camphor oils are contraindicated in pregnancy; however, Wedgewood and Brickell may be used safely during this time. Caution is advised when recommending essential oils for children under two years of age, and oils should never be ingested to avert toxicity risks [2,3].

Regulatory Considerations

The United States Food and Drug Administration (US FDA) oversees the regulation of essential oils used for aroma or topical application, classifying them under cosmetics and general wellness products [13]. Essential oils, considered mixtures of chemical compounds, must satisfy regulatory quality and safety specifications, including controls of toxic contaminants [15]. Internationally, transferable jurisdictions such as pharmacopeias as well as World Health Organization (WHO) quality standards provide further regulatory frameworks, particularly when essential oils serve as ingredients in medicinal products [16]. The breadth of applications and the variety of existing commercial sources stipulate the supplemental engagement of reference methods and monographs that define standardized compositions and required inventories of chemical constituents for specific essential oils [17]. Nonetheless, the numerous reference materials and monographs in use, combined with the lack of official standards (particularly in the case of volatile substances), complicate international trade and enforcement. Compounding these regulatory challenges, the considerable variability in chemical composition among commercially available essential oils presents an additional obstacle to the adoption of such products in clinical environments and hinders the standardization of safety and antimicrobial tests [1, 3].

FDA Regulations

In the United States, the Food and Drug Administration rigorously enforces standards that determine whether substances may be considered safe and effective for medicinal purposes [1, 6]. Currently, medicinal claims for essential oils cannot legally be made, except when specific chemical components present in the oil are individually recognized as active pharmaceutical ingredients [1, 7]. Rather, the FDA asserts that improper use of many essential oils can lead to serious adverse events, such as hepatotoxicity and photosensitivity, and oils of inferior quality may be adulterated with harmful chemicals or contain insufficient levels of the active ingredient. That said, several companies do manufacture locally sourced, organic essential oils that have been properly GC-MS–tested and documented to Purity Standards, and they are increasingly available without a prescription [2,3, 4, 5]. The ecological aspects of essential oils are also of high importance, meaning that oils should be commercially sourced in a way that protects the plant resource from depletion and ensures agricultural sustainability. Properly regulated and documented essential oils, therefore, represent one important option for research and clinical testing of infection control and prevention strategies [3].

Quality Control Standards

The quality of essential oils has emerged as a primary concern amid their increased use. Despite growing requirements for quality control (QC) and standardization, such procedures remain unavailable for many traditionally applied oils that are commercialized and used [1]. Obtaining essential oils of consistent quality and properties is difficult. Analytical techniques such as gas chromatography (GC) and mass spectrometry (MS) are widely used to identify and quantify the chemical composition of essential oils [1, 2]. Since various factors like seasonal variations, storage, and oxidative degradation affect the chemical composition of essential oils, chromatographic fingerprint profiles are often employed in QC and standardization [21]. External quality attributes of essential oils, including colour, odour, and density, contribute to determining their quality and are also affected by storage. Standards play a crucial role in ensuring high-quality oils and assisting in product assessment[3]. Essential Oils Monographs provide specifications regarding traceability, identification, appearance, purity, physico-chemical properties, soluble matter, and moisture content, serving as valuable references [18]. Within European Union regulations and other international directives, guidelines for establishing specifications and control procedures for essential oils as pharmaceutical raw materials have been set forth, encompassing aspects such as nomenclature, botanical and geographical origin, production methods, and analytical tests [19].

Challenges in Research

A majority of essential oils on the commercial market mix the pure oil with other substances to increase volume or decrease cost. Only 16% among 223 products tested in Germany contained 100% pure essential oil, while the remainder comprised oils with fewer constituent compounds or essential oils with additives such as vegetable oils [21]. The absence of a standard method for extraction and purification further results in variations in composition from one batch to another, posing challenges for assessing the oils' antimicrobial activity [2]. Due to the complex mixtures consisting of hundreds of constituents, uncertainty in composition, and variability in antimicrobial activity, essential oils have yet to be adopted for clinical use [2, 20, 21].

Lack of Standardization

Essential oils represent an attractive research target due to the potential application of existing natural products and can serve as an alternative to seriously overused antibiotics [2, 22]. On the other hand, many important problems still prevent their wide adoption in clinical practice; the lack of complete standardization remains a major issue.

Variability in Composition

The term "essential" refers to the "essence" of a plant's fragrance. Essential oils have been used for antimicrobial activities for thousands of years [20]. Different plants produce their own distinctive quantitative and qualitative combinations of terpenes, which are responsible for the specific odor of the plant. Despite their complex mixtures, essential oils can be characterized by their chemical composition, the volatile, aromatic-terpenic odoriferous components [23]. This composition varies among different plant parts and depends on environmental factors, such as geographic location, soil type and quality, air composition, rainfall, minerals, biotic and abiotic stresses, and time of harvest (December to March is usually the best). Additional factors include the plant parts extracted and the distillation technique used. Plants from the same species can present different chemical patterns, differing both qualitatively and quantitatively because of the genotype and environmental effects [22]. Thus, several species may present different chemical patterns and accordingly may differ in their biological activities and therapeutic properties [1].

Future Directions

Future research is focusing on developing solutions to antibiotic resistance, elucidating molecular mechanisms, and undertaking clinical trials for new therapeutic approaches [22]. Essential oils have shown promise in acting synergistically with antibiotics, particularly against resistant bacteria, by disrupting bacterial membranes and enhancing antibiotic uptake [22]. Molecular profiling of bacterial responses to essential oils can inform such combinational strategies. Clinical trials are needed to verify the safety and efficacy of phytopharmaceuticals before widespread adoption. Broader governmental support could facilitate the standardization, quality control, and regulatory frameworks essential for integrating essential oils into contemporary medicine. Once these challenges are addressed, essential oils may constitute a valuable component of the medical arsenal against infections [1].

Emerging Research Areas

Emerging research largely focuses on the translation of essential oils from historically based remedies to evidence-based clinical applications in infection control and antimicrobial practices [1, 2]. Many essential oils in this area offer active antibiotic alternatives for routine use at home and, along with conventional antibiotics, in clinical settings. To address translational challenges, nomenclature standardization aligns scientific communications on oil quality control, composition, and chemotypes [1]. Additional research defines effective combination formulations in infection control, examines synergies of multiple essential oils, and explores the potential for dose reduction of active components to mitigate unwanted side effects. Macroscopic and microscopic studies, including advanced primary human cell models of the intestinal and respiratory systems, provide insights into immunomodulation during infection control [2]. Techniques such as differential scanning calorimetry and the Langmuir–Blodgett approach, supplemented with computational investigations, evaluate the bioactivity of lipophilic essential oils [4]. In addition to immunomodulatory functions, these oils have significant anti-inflammatory and antinociceptive properties [23]. The therapeutic effects of essential oils are established in many complementary medicines, where they serve as antimicrobial agents, analgesics, sedatives, anti-inflammatories, and immune boosters across diverse infection and inflammation contexts, ranging from oral care to agriculture and human infectious diseases [21]. The roles of individual oils and blends are reviewed according to medicinal properties and application [22].

Potential Clinical Applications

Based on their historical uses and confirmed antimicrobial efficacy, essential oils warrant further investigation across a spectrum of microbial infections [1]. For instance, Melaleuca alternifolia (tea tree), Lavandula angustifolia (lavender), Mentha piperita (peppermint), and Eucalyptus globulus (eucalyptus) exhibit antimicrobial properties proven effective against specific bacterial, fungal, and viral pathogens [1, 2]. For Candida albicans in particular, several essential oils deemed promising for clinical development include M. alternifolia, L. angustifolia, Cinnamomum verum (cinnamon), Foeniculum vulgare (fennel), Salvia rosmarinus (rosemary), Cupressus funebris, C. Stapf, and Eucalyptus robusta [23]. Notably, despite effectiveness demonstrated in more limited contexts, Origanum vulgare (oregano) has been reported to be the most potent antimicrobial essential oil [24-26].

CONCLUSION

Essential oils hold significant potential as natural agents in infection control, offering antimicrobial, antifungal, antiviral, and immunomodulatory effects that may complement conventional therapies. Their efficacy against multidrug-resistant pathogens positions them as valuable alternatives or adjuncts in managing infectious diseases. However, clinical application remains limited by challenges in standardization, variable composition, safety concerns, and lack of regulatory harmonization. Future efforts should focus on establishing quality control standards, optimizing formulations, and conducting robust clinical trials to validate their therapeutic effectiveness. If these barriers are overcome, essential oils could play a crucial role in advancing safer, more sustainable, and effective infection control strategies.

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