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REVIEW

Essential oils and microencapsulation: mechanisms and efficacy in the inhibition of biofilms and pathogens

Aceites esenciales y microencapsulación: mecanismos y eficacia en la inhibición de biofilms y patógenos

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ABSTRACT

Introduction: essential oils (EOs) have been the subject of extensive investigation due to their diverse biological properties, including antimicrobial, antioxidant, fungicidal, and anti-inflammatory activities. Synthesized by over 17 500 plant species, EOs are intricate mixtures of terpenes, terpenoids, and phenylpropanoids, among other bioactive compounds. These attributes render EOs as promising candidates for addressing microbial infections, particularly those associated with biofilms, which account for a substantial proportion of nosocomial infections and microbial infections at large.
Method: a systematic literature search was performed using the PubMed and SciELO databases. Articles were selected based on predefined inclusion criteria, emphasizing studies that explored the chemical composition and antimicrobial mechanisms of EOs, the processes of biofilm formation, their structural characteristics, resistance mechanisms, and the application of microencapsulation techniques to enhance EO stability and antimicrobial efficacy.
Results: a total of 30 articles met the inclusion criteria and were subjected to detailed review. These studies provide a comprehensive analysis of the antimicrobial potential of EOs and demonstrate the significant enhancement of their efficacy through microencapsulation. The compiled data enable the assessment of both the inherent antimicrobial activity of EOs and the mechanisms by which microencapsulation amplifies this activity.
Conclusions: this review underscores the chemical composition and antimicrobial mechanisms of EOs, as well as the dynamics of biofilm formation and resistance. Furthermore, it highlights the role of microencapsulation as a strategy to preserve and enhance the antimicrobial properties of EOs.

Keywords: Essential Oils; Antimicrobial Activity; Biofilms; Microencapsulation; Chemical Composition; Antimicrobial Mechanisms.

RESUMEN

Introducción: los aceites esenciales (AEs) han sido objeto de una amplia investigación debido a sus diversas propiedades biológicas, incluidas actividades antimicrobianas, antioxidantes, fungicidas y antiinflamatorias. Producidos por más de 17 500 especies vegetales, los AEs son mezclas complejas de terpenos, terpenoides y fenilpropanoides, entre otros compuestos bioactivos. Estas características posicionan a los AEs como candidatos prometedores para abordar infecciones microbianas, especialmente aquellas asociadas con

biopelículas, que constituyen una proporción significativa de las infecciones nosocomiales y microbianas en general.
Método: se realizó una búsqueda sistemática de literatura en las bases de datos PubMed y SciELO. Los artículos fueron seleccionados en función de criterios de inclusión predefinidos, con un enfoque en la composición química y los mecanismos antimicrobianos de los AEs, la formación, estructura y resistencia de las biopelículas, así como las técnicas de microencapsulación y sus beneficios en términos de estabilidad y eficacia antimicrobiana.
Resultados: un total de 30 artículos que cumplían con los criterios de inclusión fueron revisados en detalle. Estos estudios ofrecen un análisis exhaustivo del potencial antimicrobiano de los AEs y demuestran la mejora significativa de su eficacia a través de la microencapsulación. Los datos recopilados permiten evaluar tanto la actividad antimicrobiana intrínseca de los AEs como los mecanismos mediante los cuales la microencapsulación amplifica esta actividad.
Conclusiones: esta revisión resalta la composición química y los mecanismos antimicrobianos de los AEs, así como las dinámicas de formación y resistencia de las biopelículas. Además, destaca el papel de la microencapsulación como una estrategia para preservar y potenciar las propiedades antimicrobianas de los AEs.

Palabras clave: Aceites Esenciales; Actividad Antimicrobiana; Biopelículas; Microencapsulación; Composición Química; Mecanismos Antimicrobianos.

INTRODUCTION

Essential oils (EOs) are widely studied for their outstanding biological properties, including antimicrobial, antioxidant, fungicidal, and anti-inflammatory activities.[1] Produced by more than 17 500 plant species, EOs are characterized as complex mixtures of terpenes, terpenoids, and phenylpropanoids, among other bioactive compounds.[2] Due to their broad spectrum of action, they have been proposed as promising candidates for the treatment of various microbial infections, in particular those associated with biofilm formation, which constitutes a significant proportion of nosocomial and microbial infections in general.[3]

Biofilm formation is a survival mechanism of bacteria and yeasts that favors their adhesion to surfaces while promoting the production of an extracellular matrix composed of proteins, polysaccharides, and DNA.[3] This matrix confers to microbial communities a marked resistance to conventional antimicrobials, making their eradication difficult and complicating the treatment of the resulting infections.[4] The intrinsic robustness of biofilms highlights the need to explore new strategies that allow their effective prevention and control.

In this context, microencapsulation of essential oils has emerged as a strategy of great interest. This process protects EOs from volatilization and degradation, prolonging their shelf life and enhancing their antimicrobial efficacy.[4] Techniques used include spray drying, complex coacervation, and lyophilization, all of which are effective for the stabilization and controlled release of EOs.[5] Recent studies indicate that microencapsulation not only maintains but also enhances the antimicrobial activity of EOs. For example, encapsulation of lemongrass and peppermint essential oils has shown significantly greater inhibition of pathogens and biofilms.[6] Additionally, the selection of the encapsulation material, such as maltodextrin or gum arabic, is critical to maximizing the antimicrobial effectiveness of encapsulated EOs.[7]

This review aims to analyze the chemical composition and antimicrobial mechanisms of essential oils, as well as microencapsulation techniques and their impact on inhibiting biofilms and pathogens. For this purpose, 30 articles selected from PubMed and SciELO databases are reviewed to provide a comprehensive view of the capabilities and applications of microencapsulated EOs in microbial infection control.

METHOD

For the preparation of this review article, an exhaustive literature search was carried out in the PubMed and SciELO databases. The selection of articles was made following specific inclusion and exclusion criteria. The inclusion criteria covered original articles on the chemical composition and antimicrobial mechanisms of essential oils, studies on microencapsulation techniques of essential oils, and their benefits in terms of stability and antimicrobial efficacy. Additionally, only open-access publications available in the consulted databases were included.

The search and selection process was conducted using the following keywords: “essential oils,” “antimicrobial activity,” “biofilms,” “microencapsulation,” “chemical composition,” and “antimicrobial mechanisms.” The search was restricted to articles published in the last ten years to ensure the timeliness of the information.

DEVELOPMENT AND RESULTS

A total of 30 articles that met the established inclusion criteria were reviewed. The selected studies cover

research on the chemical composition and antimicrobial mechanisms of essential oils, biofilm formation and resistance, and microencapsulation techniques applied to improve the stability and efficacy of essential oils.

A detailed analysis of the most relevant findings of the reviewed articles is presented below, organized in sections that address the main topics of interest: the chemical composition of essential oils, their antimicrobial mechanisms, biofilm formation and resistance, and microencapsulation techniques and benefits.

Chemical composition and antimicrobial mechanisms of essential oils

Essential oils (EOs) originate from more than 17 500 plant species belonging to various angiosperm families, including Lamiaceae, Rutaceae, Myrtaceae, Zingiberaceae, and Asteraceae; however, only about 300 are available on an industrial scale.[8,9] These compounds exhibit a broad spectrum of biological properties, which include larvicidal, antioxidant, fungicidal, analgesic, anti-inflammatory, and antitumor activity.[9]

From the biosynthetic point of view, EOs are formed in the cytoplasm and plastids of plant cells through the malonic acid, mevalonic acid, and methyl-d-erythritol-4-phosphate pathways.[10,11] Once synthesized, they accumulate in specialized structures, such as glands, secretory cavities, and resin ducts, and are present as droplets in leaves, stems, flowers, fruits, bark, and roots.[1,2,10] Their chemical composition is remarkably complex, composed mainly of terpenes, terpenoids, and phenylpropanoids, although they may also contain fatty acids, oxides, and sulfur-derived compounds.[10,11] Advanced extraction methods, including supercritical fluid extraction, subcritical liquid phase extraction, solventless microwave extraction, and conventional methods, have been employed to obtain them. Among these, hydrodistillation, steam distillation, hydrodiffusion, and solvent extraction stand out.[11]

In addition to the compounds mentioned above, molecules such as acids, alcohols, aldehydes, aliphatic hydrocarbons, acyclic esters or lactones, nitrogen and sulfur-containing compounds, coumarins and phenylpropanoid homologs have been identified in EOs.[12] Physically, EOs are volatile liquids, limpid, of various colors, soluble in lipids and organic solvents, and generally show a density lower than that of water.[1,3] Among their multiple biological actions, their antimicrobial properties stand out: in particular, some phenolic compounds can penetrate and depolarize the cytoplasmic membrane of microorganisms. A relevant example is eugenol, a hydroxyphenylpropene naturally present in the EOs of families such as Lamiaceae, Lauraceae, Myrtaceae, and Myristicaceae.[1,4]

The essential oils, as well as their main components and activity are synthesized in table 1.

Table 1. Essential oils with antimicrobial activity

Essential oils	Components	Activity
Oregano Origanum vulgare	Carvacrol, thymol, α-terpinene, γ -terpinene, terpinen-4-ol, p-cymene, α-terpineol and sabinene.	Antioxidant, antifungal and antibacterial.
Peppermint *Mentha spp.*	Menthol, menthone, limonene, isomentone, menthyl acetate, carvone, ß-pinene, 1,8-cineole, pulegone, piperitone oxide and mycene.	Antioxidant, antifungal and antibacterial.
Basil *Ocimum Basilicum*	Phenolic acid and terpenoid derivatives include methyl eugenol (42,58 %) followed by caryophyllene (26,88 %) and eugenol.	Antioxidant, antifungal and antibacterial.
Rosemary *Rosmarinus officinalis*	Volatile phenolic compounds (1,8-cineole volatiles (1,8-cineole, camphor and α-pinene.	Antibacterial and Antifungal.
Lemon verbena *Cymbopogon citratus*	E-citral, Z-citral, beta-myrcene, selin-6-en-4-ol and cis-ocimene.	Antibacterial and Antifungal.
Thymus *Thymus musili*	Carvacrol, cinnamaldehyde, thymol, geraniol, and eugenol salicylaldehyde, geraniol, citral, perillaldehyde and methyl chavicol	Antibacterial and Antifungal.
Dill *Anethum graveolens*	Limonene (48,05 %), carvone (37,94 %), cis-dihydrocarvone (3,5 %) and trans-carvone.	Antibacterial and Antifungal.
Lavender *Lavender angustifolia*	1,8-cineole (eucalyptol), ocimene, ocimene(1,5-6,0),linalool(25,0-38,0),camphor, terpine -1-en-4-ol ,α-terpineol, linalyl acetate and lavandulyl acetate.	Antibacterial and Antifungal

Biofilms: formation, structure and antimicrobial **resistance**

Biofilms constitute a form of multicellular microbial growth with wide clinical relevance since it is estimated that more than 65 % of nosocomial infections and up to 80 % of microbial infections, in general, are related to their formation.[12] These structures can develop on biotic (tissues) or abiotic (medical devices, water pipes, among others) surfaces and are mainly composed of bacteria or yeasts that adhere to and produce an

extracellular matrix of proteins, polysaccharides, and DNA, also known as extracellular polymeric substance.[15]

The biogenesis of biofilms involves several stages. Initially, microorganisms attach reversibly to a surface, mediated in part by physicochemical interactions, and subsequently become irreversibly attached through the production and secretion of matrix components.[22,23] As the biofilm matures, microorganisms form microcolonies and establish networks of aqueous channels for the distribution of nutrients and the removal of waste products.[22,24] This process is primarily regulated by intercellular communication (quorum sensing), which coordinates gene expression and determines specific phenotypic characteristics, including those associated with antimicrobial resistance.[22,25]

One of the most outstanding properties of biofilms is their high tolerance to antimicrobial treatments. This multifactorial resistance is explained by:

- Physical protection of the matrix: the dense polymeric structure hinders the penetration of antibiotics and disinfecting agents to the deepest cells.
- Phenotypic changes in cells, such as bacteria and yeasts in a biofilm, can express specific resistance genes and exhibit slower growth rates, which reduces the effectiveness of certain drugs targeting cell division processes.[21,23]
- Persistent cells: Within the community, subpopulations of "persistent cells" may emerge that can tolerate high concentrations of antibiotics without exhibiting classical genetic resistance, making complete eradication even more challenging.[22,24]
- Horizontal gene transfer: the confined environment of biofilms facilitates the exchange of plasmids and mobile genetic elements, increasing the dissemination of resistance genes.[23]

In the hospital setting, this tolerance to antimicrobial agents translates into a significant increase in therapeutic failure, particularly in infections associated with medical devices such as catheters, joint prostheses, and heart valves.[21,24] In many cases, the only effective strategy for infection control is the removal of the infected device or, in more extreme situations, the resection of the affected tissue.[21]

Given the prevalence and clinical relevance of biofilms, the search for new strategies to prevent and treat them represents an urgent public health challenge. Recent research encompasses approaches ranging from surface modification of medical devices to the application of matrix-disrupting molecules and the combination of conventional antimicrobial therapies with emerging technologies such as nanotechnology or controlled drug release.[25,26,27] These innovative approaches aim to counteract the complexity of biofilm resistance mechanisms, thereby enhancing the efficacy of antimicrobial treatments.

Microencapsulation techniques and their benefits

Microencapsulation has become one of the most versatile and innovative strategies to protect and release bioactive substances in a controlled manner in various industrial fields, including the food, pharmaceutical, cosmetic and agrochemical industries.[28] Its relevance lies in its ability to preserve the stability of sensitive compounds, mask undesirable tastes and odors, and ensure the release of these compounds at the optimum time and place for maximum efficacy.

In general terms, microencapsulation involves enveloping solid, liquid, or gaseous particles (typically between 1 and 1 000 microns in size) with a protective coating or membrane. This coating can be of a polymeric or lipidic nature, and, depending on the technique employed, it is obtained through physical, chemical, or physicochemical processes.[29] The most common methods include spray drying, coacervation (simple and complex), interfacial polymerization, liposome encapsulation, and fluidized bed coatings.

Spray drying has been widely adopted in the food and pharmaceutical industry due to its scalability and relatively low cost. It starts with an emulsion or suspension containing the active material and an encapsulating agent, which is sprayed and exposed to a stream of hot air to remove the solvent. This results in the formation of solid microparticles that protect and retain the active principle.[30] However, there is a risk that certain heat-sensitive compounds may be affected, so it is essential to control the operating parameters strictly.

Another relevant technique is coacervation, which can be simple or complex. Simple coacervation is based on the desolvation of a polymer (e.g., gelatin) through changes in pH, ionic strength, or temperature. This phenomenon leads to the formation of polymer droplets (coacervate) that envelop the active material. In complex coacervation, on the other hand, two polymers with opposite charges (e.g., gelatin and gum Arabic) form a complex that precipitates and surrounds the substance to be encapsulated.[31] Although this methodology offers good reproducibility and allows control of the capsule morphology, it requires careful adjustment of the medium conditions, which sometimes hinders scalability.

As for interfacial polymerization, this technique is characterized by the reaction between oil-soluble and water-soluble monomers, generating a polymer at the interface of two immiscible phases. Due to its high efficiency in encapsulating hydrophobic substances and the mechanical strength of the resulting capsules, it is frequently used for compounds such as pesticides or dyes. However, it involves the use of potentially toxic

reagents and requires the disposal of reaction by-products, which can increase costs and hinder regulatory acceptance.[32]

Fluidized bed coating, on the other hand, involves circulating solid particles in an upward flow of gas while they are sprayed with a solution or emulsion. As the solvent evaporates, protective layers form around the particles. This technique, widely used in the pharmaceutical sector to produce solid dosage forms with controlled release, offers the advantage of precise control of the layer thickness. However, it requires specific equipment and the optimization of numerous parameters (temperature, air velocity, solution viscosity) to obtain uniform capsules.[33]

Liposome encapsulation is also one of the most widespread methods in the formulation of drugs and cosmetic products. Liposomes are vesicles formed by one or several phospholipid bilayers, which mimic the structure of cell membranes. Thanks to this similarity, they offer excellent biocompatibility and the possibility of encapsulating both hydrophilic and lipophilic active ingredients.[34] However, their large-scale production and long-term stability remain limiting factors.

The benefits derived from microencapsulation are vast and range from improved stability of compounds sensitive to environmental factors (such as light, oxygen, humidity, and pH) to controlled or targeted release, thereby optimizing product efficacy and reducing dosage and side effects, particularly in the pharmaceutical field.[35] In the food sector, masking unpleasant odors or flavors and preserving nutrients during storage and digestion are obvious advantages. For its part, the agrochemical industry utilizes microencapsulation to release pesticides and fertilizers in a controlled manner, thereby minimizing environmental impact and the risk of acute toxicity.

Despite its benefits, some challenges drive research in the area. Among the most outstanding needs is the development of release systems that are even more specific and sensitive to stimuli (such as changes in pH, temperature, or the presence of enzymes) so that the release of the active compound responds promptly to biological or environmental requirements.[36] Additionally, production costs and the availability of safe and environmentally friendly encapsulant materials are growing concerns, particularly in light of an increasingly stringent regulatory environment.

In conclusion, microencapsulation is emerging as a crucial tool for developing products with enhanced technological and functional properties. Each technique, from spray drying to liposome encapsulation, offers a specific solution to different problems related to the stability and release of active substances. Looking ahead, the integration of biotechnological approaches, nanoencapsulation, and additive manufacturing (e.g., 3D printing) will strengthen its application in emerging areas, positioning microencapsulation as a fundamental pillar in the innovation of high-value-added products.

DISCUSSION

The results of this review suggest that the use of essential oils (EOs) with antimicrobial activity, combined with microencapsulation techniques, represents a promising approach to address challenges associated with the instability of natural compounds and microbial resistance, particularly in the context of biofilms. The analysis of 30 articles, selected under strict inclusion and exclusion criteria, highlights both the diversity in the chemical composition of EOs and the complexity of their mechanisms of action.[8,9] In this regard, the presence of terpenes, phenols, and other bioactive compounds confers on EOs a broad antimicrobial spectrum, with demonstrated effects against bacteria and fungi, as well as a potential to modulate processes such as biofilm formation and resistance.[10,11]

Despite the chemical diversity of EOs, the review highlights that their antimicrobial efficacy may be limited by degradation factors, volatility, and sensitivity to environmental conditions (pH, temperature, light, and presence of oxygen).[12,13] This instability poses one of the primary challenges for large-scale applications, particularly in industries such as pharmaceuticals and food, where the formulation of final products must ensure the preservation of antimicrobial activity throughout storage and distribution processes.[3,14] It is at this point that microencapsulation emerges as an innovative strategy, allowing the protection of EOs against adverse conditions, prolonging their shelf life, and facilitating their controlled release.[28,29]

The literature review confirms the effectiveness of multiple microencapsulation methods, among which spray drying, coacervation (both simple and complex), interfacial polymerization, fluidized bed coating, and liposome encapsulation are notable.[30,34] These techniques offer the possibility of adjusting process variables— such as temperature, pH, and concentration of encapsulating agents —to obtain particles with specific morphological and physicochemical characteristics. However, each method has its advantages and limitations, which must be weighed according to the desired application. For example, spray drying is a highly scalable and relatively inexpensive process. Still, it can lead to losses in the biological activity of heat-sensitive EOs.[30] Interfacial polymerization, on the other hand, achieves capsules with high mechanical strength but requires the use of potentially toxic reagents and extensive purification.[32]

The application of microencapsulated EOs as an antimicrobial strategy is particularly relevant in the control

and prevention of biofilms, structures that have shown high resistance to conventional treatments.[21,22] The ability of EOs, and in particular of certain phenolic compounds such as eugenol, to destabilize microbial membranes or interfere with essential metabolic pathways could improve the control of biofilms, especially if the compounds are released in a localized and sustained manner.[13,25] Thus, microencapsulation could enhance the penetration of EOs into the extracellular matrix of biofilms by maintaining an adequate concentration of active ingredients over a prolonged period. However, there are still few studies that systematically explore the efficacy of microencapsulated EOs in complex biofilm systems, which represents an area of opportunity for future research.

On the other hand, the selection of environmentally friendly and biocompatible encapsulant materials is becoming increasingly important in light of a more stringent regulatory landscape.[36] Natural and biodegradable polymers, such as alginates, chitosan, and proteins, have demonstrated compatibility with EC encapsulation, thereby decreasing toxicity and enhancing their potential application in the food and cosmetic industries.[31] In addition, advances in nanoencapsulation, optimization of controlled release processes, and the use of emerging technologies such as 3D printing could offer high-precision solutions for the delivery of ECs in clinical, industrial, and agri-food contexts.[35]

Finally, it is essential to note that the available evidence, although promising, primarily comes from in vitro or small-scale studies. To validate the industrial and clinical application of microencapsulated EOs, clinical trials, and pilot tests are required that take into account the complexity of production processes, product stability during storage, and the specific regulations of each sector.[36] Multidisciplinary collaboration - between chemists, pharmacists, microbiologists, process engineers, and health professionals - will be essential to design and evaluate formulations with high potential for transfer to the market.

In summary, microencapsulation of essential oils emerges as a comprehensive approach that simultaneously addresses the protection of bioactive compounds, targeted release, and enhancement of antimicrobial efficacy. The results reviewed support the hypothesis that this combination may represent a significant advance in the face of the growing problem of microbial resistance and instability of EOs. Nevertheless, numerous lines of research remain open, focusing on the optimization of encapsulation methods, the detailed understanding of the mechanisms of action against biofilms, and the establishment of scalable industrial parameters that promote the safe and efficient use of this type of product.

CONCLUSIONS

The evidence gathered in this review highlights the remarkable potential of essential oils as antimicrobial agents, as well as the importance of microencapsulation in maximizing their efficacy and stability. On the one hand, the diversity of bioactive compounds present in essential oils provides a broad and versatile spectrum of action against multiple microorganisms, including those that form highly resistant biofilms. On the other hand, various microencapsulation techniques enable the protection of these compounds from degradation and their controlled release, thereby favoring the sustainability of their biological activity.

Despite the progress achieved, challenges remain regarding the optimization of encapsulation methodologies, the search for environmentally friendly materials, and the evaluation of the efficacy of these systems in authentic contexts. Further studies are also required to address the interaction with complex biofilms and to explore multidisciplinary approaches that integrate process engineering, molecular biology, and nanotechnology to enhance the results.

Overall, the findings highlight the importance of continuing to investigate the synergy between essential oils and microencapsulation strategies, both to enhance their applicability in the food and pharmaceutical industries and to address emerging public health challenges related to antimicrobial resistance. If research and development efforts in this area continue, essential oil microencapsulation will become a key tool in formulating more effective and safer products shortly.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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