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Prevention of Bacterial Infections Using Encapsulated Phytophenolic Actives

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The recent overuse of antibiotics has led to the emergence of multidrug-resistant bacteria (MRB) responsible for severe infections, which are often difficult or impossible to treat. In the world of infectious diseases, the lack of development of new antibacterial molecules by the pharmaceutical industry is a major problem. Today, the number of new drugs able to treat Gram-negative MRB infections is significantly limited. It is therefore important to find new therapeutic approaches that are effective but limit the emergence of bacterial resistance. Medicinal plants containing essential oils constitute a potentially large source of antibacterial molecules that can be used to treat MRB infections. Essential oils, which primarily consist of phenolic compounds, have been demonstrated to have antibacterial effects against a wide variety of microorganisms. However, these molecules exhibit poor solubility in water and are biologically unstable. In addition, these molecules tend to bind to food constituents, resulting in decreased bioavailability and antimicrobial activity. To overcome these challenges, essential oils can be encapsulated within nanoparticles to enhance their solubility in aqueous media and to increase their antibacterial activity by facilitating contact with bacterial cells. The high antibacterial effectiveness of several delivery systems, including emulsions, liposomes and nanoparticles, indicates the potential of encapsulated phenols. The anti-infective potential of essential oils, combined with various technologies from nanomedicine, provides a new hope in the fight against infectious diseases.

KEYWORDS: *Multiresistant Bacterial Infections, Essential Oils, Phenols, Delivery System, Nanoparticles.*

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INTRODUCTION

Since 1945, many antibiotics have been developed, and many of these antibiotics possess a broad activity spectrum. Since the 1960s, the abuse of antibiotics in many areas (e.g., human health, agriculture, and veterinary practice) has led to the emergence of resistant bacteria that have developed or acquired several mechanisms of drug resistance. As a result, some bacteria are now resistant to most of the antibiotics commonly used in clinical settings and are responsible for hospital infections that are difficult to treat. Among MRB strains, multiresistant *Acinetobacter baumannii* (MRAB), methicillin-resistant *Staphylococcus aureus* (MRSA) and extended spectrum B-lactamase- or carbapenemase-producing Enterobacteriaceae (ESBLE, CPE) are the most prevalent MRB strains in Europe.¹ Thirty to 35% of nosocomial infections are caused by MRB.² The struggle against nosocomial infections is a public health priority because such infections are characterized by high morbidity and mortality rates.³

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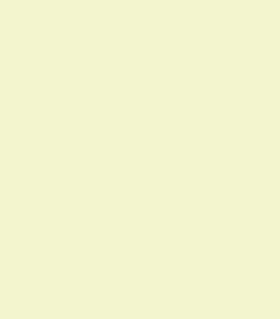
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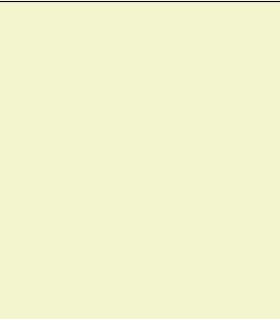
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According to the World Health Organization (WHO), 1.4 million people suffered from nosocomial infections in 2007. In developed countries, up to 10% of hospital patients acquire nosocomial infections. In some developing countries, this infection rate can be as high as 25%. According to a 2012 survey conducted in France, 5% of hospital patients acquired an infection. The bacteria responsible for such infections can quickly adapt

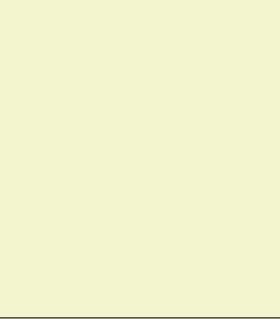
and develop several resistance mechanisms, including decreased membrane permeability, bacterial efflux pumps, enzymatic degradation of antibiotics and modification or alteration of the target antibiotic. These mechanisms, which are often acquired through the uptake and integration of foreign genetic material, can transform bacteria into powerful MRBs.⁴ Spurred by the current global prevalence of Gram-positive MRBs, the pharmaceutical industry has



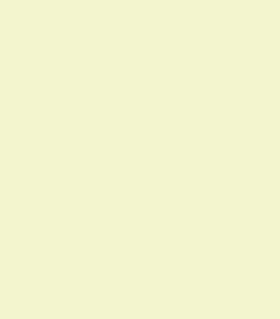
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Patrick Saulnier



Elisabeth Rossines



Marie-Laure Joly Guillou

focused recently on developing new antibiotics that target Gram-positive MRBs such as methicillin-resistant *S. aureus* and glycopeptide-resistant enterococci. In contrast, very little effort is expended on developing new molecules against Gram-negative MRBs. Given the limited number of antibiotics in development as well as the spread of ESBL and CPE, the discovery of novel antibacterial strategies is a critical endeavor.

Various actives have been explored for antibacterial activity, including silver nanoparticles,^{5,6} gold nanoparticles,^{7,8} zinc nanoparticles^{9,10} and nitric oxide nanoparticles.^{11,12} Until now, natural resources have been poorly explored.

Essential oils (EOs), composed mainly of phenolic compounds, have been shown to have antibacterial properties against a wide variety of microorganisms. However, these molecules possess various lipophilic characteristics that reduce bioavailability. To overcome these challenges, these phenols can be encapsulated within nanoparticles to enhance their solubility in aqueous media.

The objective of this review is to describe various delivery systems such as emulsions, liposomes and nanoparticles and to discuss the possibility of encapsulating phenolic actives using these nanodelivery systems. The anti-infective potential of essential oils, combined with various technologies from nanomedicine, provides a new hope in the fight against infectious diseases.

ANTIBACTERIAL PHENOLIC COMPOUNDS

Definition of Essential Oils (EOs)

Essential oils (EOs) are complex, volatile mixtures of low molecular weight molecules. EO are synthesized within various plant organs and can contain between 20 to 60 components at various concentrations.¹³ Essential oils are characterized by two or three major components in relatively high concentrations (20–70%), while the other components are present in trace amounts. For example, carvacrol (30%) and thymol (27%) are the major components of the EO from *Origanum compactum*.¹³ The composition of the EO depends on various factors, including the stage of plant development, the organs present and the period and geographical area of harvest.¹⁴

EOs are secondary plant metabolites synthesized in glandular structures within plant cells¹⁵ and are known to have strong antibacterial potential.¹⁴ The biological activity of EO is mainly due to their chemical composition. EO can contain both phenols and terpenoids. EO components induce endogenous protective enzymes and have beneficial regulatory effects on signaling pathways, acting as antioxidants.¹⁶

The major components of EO can be divided into 2 groups based on the distinct pathways for their biosynthesis: phenylpropanoids and terpenoids.¹³

Terpenoid components derive from a 5-carbon isoprene precursor, isopentenylpyrophosphate (Fig. 1). Terpenoids exist in various forms, including mono-, di-, tri-, hemi-,

sesqui-, and tetra-terpenes. Monoterpenes are characterized by two isoprene units ($(C_5H_8)_2$) and are the building block for 90% of all EO molecules, including hydrocarbons, aldehydes, alcohols, esters, ethers, ketones, peroxides and phenols.¹³

Phenolic compounds (phenylpropanoids) derive from aromatic amino acids such as phenylalanine and tyrosine (Fig. 2). Phenolic compounds are composed of aldehydes, methoxy derivatives, methylene dioxy components, phenols and alcohols.

Phenols are characterized by the presence of a hydroxyl group attached to a phenyl ring. Phenolic compounds possess the greatest antibacterial potential, followed by aldehydes, ketones, alcohols and hydrocarbons.¹⁵

Antimicrobial Activity of EO

Various studies have shown that phenols, aldehydes and terpenes mainly target the cytoplasmic cell membrane. Hydrophobic in nature, these compounds affect the unsaturated fatty acid content in the membrane and thus alter the membrane's structure.^{17,18}

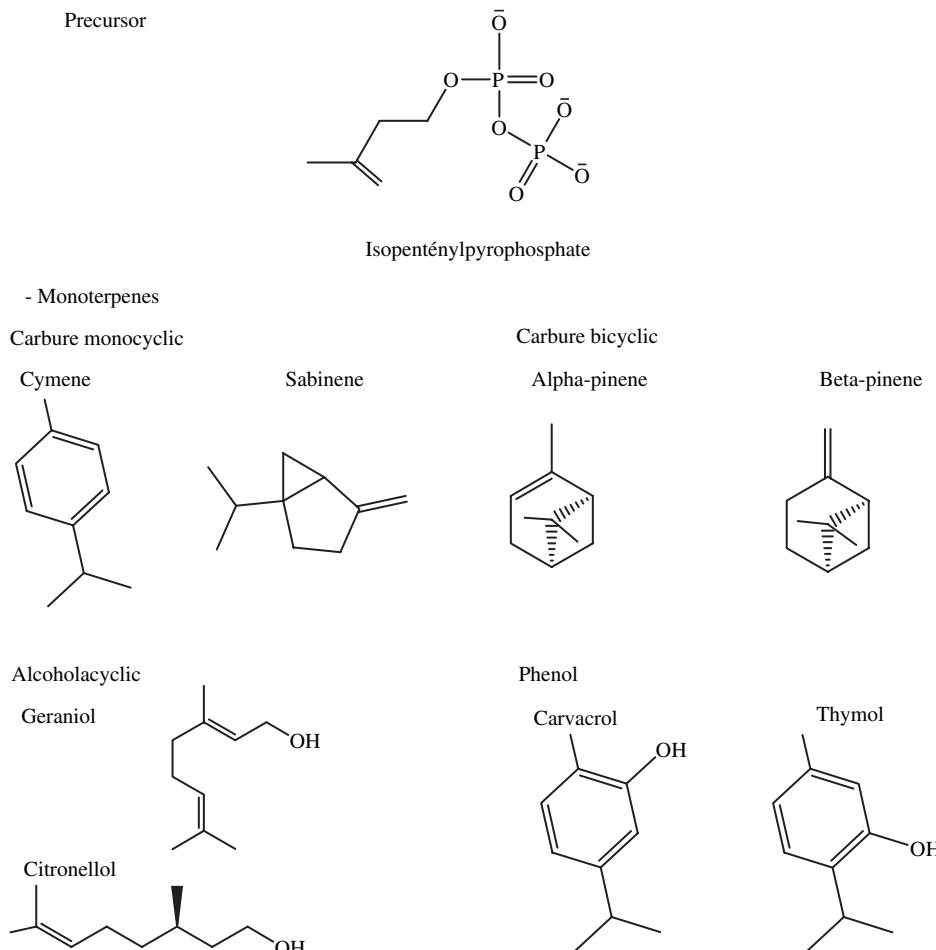
The presence of phenols (e.g., eugenol, carvacrol, and thymol) and aldehydes (e.g., cinnamaldehyde, perillaldehyde, and citral) in EO may be responsible for the broad spectrum activity of EO on microorganisms such as bacteria, fungi, viruses, parasites and insects.¹³

Bacteria can be classified into two groups according to the composition and structure of their cell wall, which is revealed by a Gram stain. Gram-positive bacteria possess a thick peptidoglycan layer. Gram-negative bacteria, on the other hand, possess a thin peptidoglycan layer between the outer and cytoplasmic membranes (Fig. 3). EO have been shown to have antibacterial activity against both Gram-negative (e.g., *Escherichia coli* and *Pseudomonas aeruginosa*) and Gram-positive bacteria (e.g., *S. aureus*). However, Gram-negative bacteria appear to be less susceptible to EO, likely due to the presence of an outer membrane which may limit the diffusion of hydrophobic compounds into the cell.¹⁹ Of the bacterial strains tested, the strain least sensitive to EO is *P. aeruginosa*.¹⁴

The activity of EO is independent from the antibiotic resistance phenotype. Consequently, EO are also active on MRBs. The growth of certain MRBs such as methicillin-resistant *S. aureus* (MRSA)²⁰ and vancomycin-resistant enterococci²¹ can be inhibited by certain EO, including citrus, lavender, mint, juniper, tea tree, thyme and eucalyptus oils. Another study showed that EO extracted from two species of Korea thyme were able to inhibit the growth of pathogenic bacteria such as *Streptococcus pneumoniae*, *Salmonella typhimurium*, *Salmonella entereditidis* and *S. aureus*.²²

Antibacterial Actions of Phenolic Compounds

Phenols are aromatic chemical compounds with an attached hydroxyl group. Phenols include thymol

1.Terpenes**Figure 1.** Terpene chemical structures.

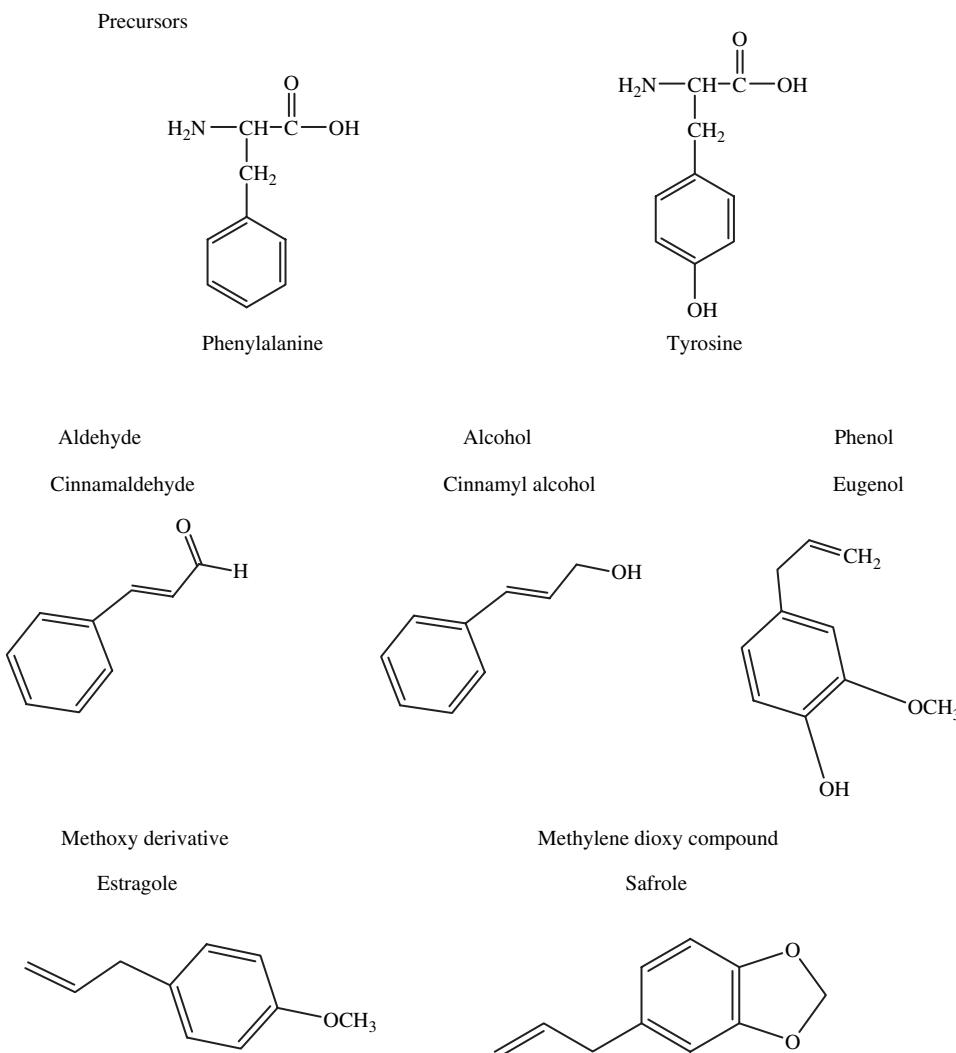
(5-methyl-2-propan-2-ylphenol), carvacrol (2-methyl-5-propan-2-ylphenol) and eugenol (4-allyl-2-methoxyphenol). The strong antimicrobial activity of phenols is due to the presence of a hydroxyl group, which can donate electrons to functional groups on cell membranes (Fig. 4). Thus, EOs saturated with phenols (e.g., thyme, clove and oregano oils) possess the highest antibacterial activity. The mechanism of action of these antimicrobial components is microorganism-dependent^{13, 14, 23} (Fig. 5).

The specific mechanism of action of these EO components remains poorly characterized, however. The antibacterial properties of EO components are attributed to several properties, including the components' lipophilicity, which enables EO accumulation in the cytoplasmic membrane. This accumulation leads to alteration of the fatty acid profile and modification of the cell envelope's structure.²⁴ This alteration of fatty acid profiles, in addition to the alteration of phospholipids in the bacterial membranes, increases membrane permeability. Phenolic components are able to penetrate mitochondrial membranes, leading to potassium ion leakage. The leakage of ions and cellular components

caused by pores in the bacterial membrane leads to a cessation of energy metabolism and bacterial death.^{24–26} Some studies carried out by scanning electron microscopy (SEM) showed membrane pore formation and loss of intracellular material in *E. coli* O157:H7 cells following treatment with oregano EO.²⁷

The chemical structure of EO components directly affects their activity. A study by Ultee¹⁷ revealed the importance of the benzene ring: menthol, which lacks a benzene ring, was significantly less active than carvacrol, which possesses a benzene ring. While a hydroxyl group in the benzene ring is essential for activity, the hydroxyl group's position has little influence on the degree of activity.^{17, 28} Thus, thymol and carvacrol, which differ in the position of the hydroxyl group (ortho and meta, respectively) exhibit comparable activities on *Bacillus cereus*, *S. aureus* and *P. aeruginosa* strains.^{17, 28}

The aromatic ring of phenols, which is highly electronegative, attracts oxygen electrons away from the hydroxyl group. This attraction facilitates interactions between the hydroxyl group and monovalent cations

2. Aromatic compounds**Figure 2. Chemical structures of aromatic compounds.**

(H⁺/K⁺) through the cell membrane, altering both pH and potassium gradients across the membrane.²⁹ Furthermore, the aromatic ring's electronegativity depolarizes the membrane, altering electron flow and increasing membrane permeability, leading to the membrane destabilization.¹⁴

To insulate itself from environmental effects, a cell regulates its fluidity by changing the average fatty acid chain length, ratio of protein and fatty acid composition in its membrane.²⁴ For example, a decrease in growth temperature induces an increase in unsaturated fatty acids and a concurrent increase in membrane fluidity in several microbes.³⁰ In the same study, it was shown that the unsaturated fatty acid contents of *E. coli* and *Salmonella* were altered by the presence of carvacrol and eugenol. *Pseudomonas fluorescens* and *S. aureus* were unaffected, however, likely due to their naturally high resistance to antimicrobial compounds.

In one study, it was shown that *E. coli* K12 increases the degree of saturation of its fatty acids in the presence of sub-lethal concentrations of phenol and phenol derivatives.³¹ Moreover, the addition of saturated fatty acids or lecithin to the culture media reduces the inhibitory effects of phenols. These data suggest that absorption of free fatty acids into the *E. coli* membrane provides some protection against phenols.

Various methods are used to characterize membrane lipid molecules. One such method is differential scanning calorimetry (DSC), which was used by Cristani³² to evaluate the ability of monoterpenes to interact with pure dimyristoylphosphatidylcholine (DMPC) liposomes. The results showed that carvacrol induces a decrease in the liposome's transition melting temperature. An enthalpy variation was also observed upon comparison with reference samples, suggesting that monoterpenes act as substitutional

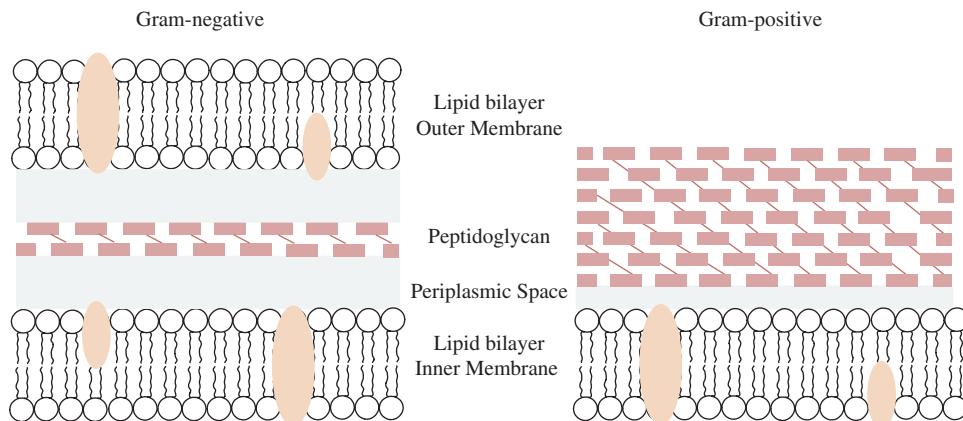


Figure 3. Composition of gram-positive and gram-negative bacteria.

impurities.³² Ultee¹⁸ calculated the phase transition temperature from FTIR (Fourier-transformed infrared) spectra, noting a decrease in the melting temperature of *B. cereus* membranes after carvacrol addition. Another study by Di Pasqua²⁴ using total lipid extraction and analytical gas chromatography demonstrated alterations in cellular fatty acid composition in the presence of thymol, carvacrol and eugenol on *E. coli* and *Salmonella* strains.

Oxygenated compounds that can cross the membrane can also influence the expression of certain genes and can bind to cytoplasmic proteins. A study conducted by Dubois-Brissonnet³³ showed decreased expression of cyclopropane synthetase, which is involved in fatty acid synthesis, in the presence of phenolic compounds.

The action of phytophenolic compounds also depends on the stage of cell growth: one study demonstrated that

dividing cells of *Saccharomyces cerevisiae* are more sensitive than quiescent cells to these compounds. One can hypothesize that phytophenolic compounds are able to penetrate the cell membrane more effectively during the first budding stages.¹³

Carvacrol and Thymol

Carvacrol and thymol are phenolic terpenes. These two compounds are the major components of oregano (80%) and thyme (10% to 64%) oils.

As mentioned previously, carvacrol and thymol have very similar chemical structures, differing only in the position of the hydroxyl group on the phenolic ring. Therefore, one could expect the compounds to have similar activities on bacteria. Nevertheless, it is important to note that antibacterial activity depends on factors

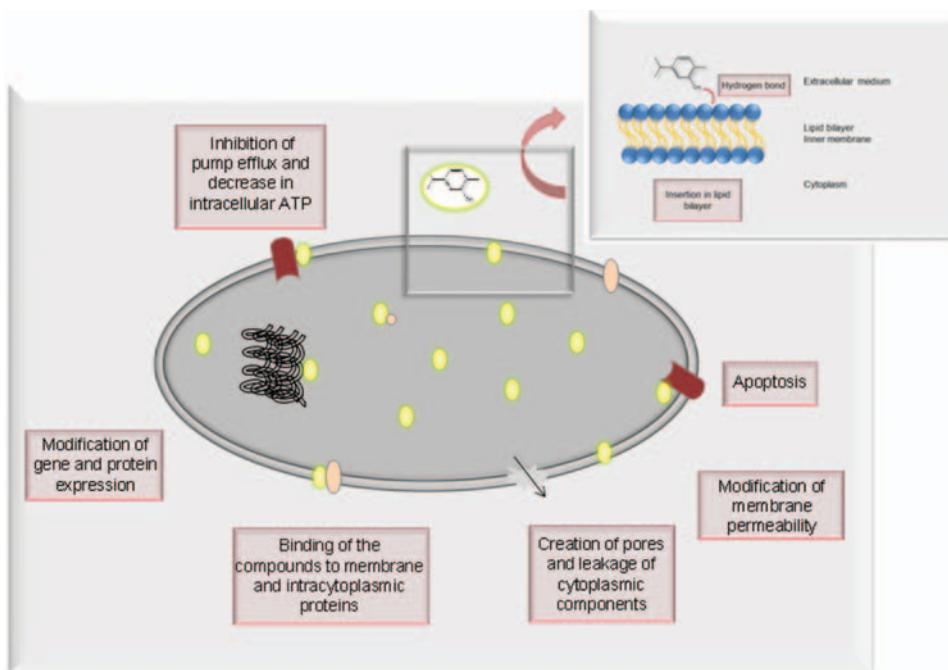


Figure 4. Mode of antibacterial action of phenolic compounds.

| | Chemical structure | Bacteria | Antibacterial actions | References |
|-----------|----------------------------|----------------------------------|--|------------|
| Thymol | Phenol (terpene) | <i>Pseudomonas aeruginosa</i> | Damage to membrane integrity | [40] |
| | | <i>Staphylococcus aureus</i> | | |
| | | <i>Staphylococcus aureus</i> | Permeability modification, Loss of intracellular components | [42] |
| | | <i>Escherichia coli</i> | | |
| | | <i>Listeria monocytogenes</i> | Decrease in bacteria size Bacterial wall modification Cytoplasm aggregation | [43] |
| | | <i>Pseudomonas fluorescens</i> | Modification of fatty acids in membranes | [24] |
| | | <i>Escherichia coli</i> | Modification of cytoplasmic membrane | [26] |
| | | <i>Escherichia coli</i> | Disintegrate outer membrane | [41] |
| | | <i>Salmonella typhimurium</i> | Decrease intracellular ATP | |
| Carvacrol | Phenol (terpene) | <i>Pseudomonas aeruginosa</i> | Damage to membrane integrity | [40] |
| | | <i>Staphylococcus aureus</i> | | |
| | | <i>Bacillus cereus</i> | Insertion in lipid bilayer Increase in membrane permeability Decrease in intracellular ATP Decrease in membrane potential Ion leakage | [17] |
| | | <i>Brochothrix thermosphacta</i> | Modification of fatty acids in membranes | [24] |
| | | <i>Salmonella typhimurium</i> | | |
| | | <i>Escherichia coli</i> | Modification of cytoplasmic membrane | [26] |
| | | <i>Escherichia coli</i> | Disintegration of outer membrane | [41] |
| | | <i>Salmonella typhimurium</i> | | |
| | | <i>Escherichia coli</i> | Alteration of proteins (heat shock protein 60); inhibition of flagellin synthesis | [39] |
| Eugenol | Phenol (aromatic compound) | <i>Listeria monocytogenes</i> | Cell wall alteration | [45] |
| | | <i>Lactobacillus sakei</i> | Inhibition of ATP synthases in membranes | |
| | | <i>Bacillus cereus</i> | Inhibition of amylase and protease production | [44] |
| | | <i>Brochothrix thermosphacta</i> | Modification of fatty acids in membranes | [24] |
| | | <i>Salmonella typhimurium</i> | | |
| | | <i>Enterobacter aerogenes</i> | Binding to protein (histidine decarboxylase) | [47] |

Figure 5. Antibacterial action of phenols.

such as type of microorganism, pH and incubation temperature.³⁴

The mechanism of carvacrol activity has been studied in *B. cereus*.^{17, 18} According to Ultee,¹⁸ carvacrol acts as a protonophore, a carrier proton that binds to the lipid bilayer. Carvacrol inserts into the membrane and interacts with cations via its hydroxyl group, disrupting the membrane's structure.¹⁷ This interaction decreases the intracellular ATP concentration and the membrane potential in addition to causing leakage of ions, ATP, amino acids and nucleic acids, leading to cell death.

Studies by Cristani³² with *E. coli* ATCC showed that carvacrol inserts into cell membranes, affecting membrane lipid composition by destabilizing the cell membrane and increasing membrane fluidity. The presence of carvacrol ultimately leads to increased membrane proton permeability and a type of cytoplasmic clotting.¹⁷ In addition, carvacrol can pass through the lipid bilayer and interact with cytoplasmic targets.³² By inserting into the membrane and binding to cytoplasmic protein complexes,

eugenol and carvacrol affect both membrane integrity and functionality.³⁵

Unfortunately, bacterial growth has been observed in the presence of moderate concentrations of phytophenolic actives. This growth has been explained by an adaptive mechanism: cells can adapt to the presence of antimicrobial agents by altering their membrane's fatty acid profile. Cells with a persistent phenotype are more likely to survive and proliferate.³⁶ Even though no specific resistances or adaptations to EOs have been identified, a resistance to carvacrol by *B. cereus* was observed after growing in the presence of sub-lethal carvacrol concentrations.¹⁸

Studies have demonstrated that carvacrol's hydrophobicity leads to the removal of polysaccharides from the membrane and an increase membrane permeability.^{30, 37} Microorganisms develop adaptive mechanisms against the harmful effects of cytotoxic components at low concentrations³⁸ such as the restoration of membrane fluidity, preservation of membrane integrity and the ability to expel foreign elements. An increase in carvacrol concen-

trations is associated with an accumulation of carvacrol in the membrane, leading to more severe damage.¹⁷

Another study reported that carvacrol alters the expression of several proteins in *E. coli* O157:H7:carvacrol increases the amount of heat shock protein 60 and strongly inhibits the synthesis of flagellin.³⁹

Thymol's mechanisms of action are very close to those of carvacrol.⁴⁰ Thymol is known to bind to the hydrophobic parts of membrane proteins in *P. aeruginosa* and *S. aureus* through hydrogen bonding. Thymol binding causes changes in the bacteria's permeability characteristics.⁴⁰ Another study showed that carvacrol and thymol cause a decrease in intracellular ATP concentration, leading to disruption of the cell membrane in *E. coli* and *S. typhimurium*.⁴¹ The action of thymol has also been studied in artificial membranes.⁴² Thymol's effectiveness was found to depend on the membrane's composition and charge. Upon entering the cytoplasmic membrane, thymol alters the membrane's permeability, resulting in the loss of intracellular material. A transmission electron microscopy (TEM) study reported that the use of thymol on *L. monocytogenes* cells resulted in decreased cell size, an altered bacterial cell wall and lack of cytoplasm.⁴³

Eugenol

Another phenolic compound is eugenol, the major component of clove oil (approximately 75 to 85%).

Currently, few studies have examined the mechanisms of eugenol action. It has been reported that this antimicrobial agent inhibits the production of enzymes such as amylases and proteases⁴⁴ in *B. cereus*. Eugenol also causes cell wall degradation, resulting in inhibition of membrane-bound ATP synthases.⁴⁵

A study reported that eugenol exhibits a lower antibacterial activity than carvacrol. This difference can be attributed to eugenol's lower hydrophobicity, which is due to its ortho methoxyl group.⁴⁶

It has been demonstrated that the hydroxyl groups in eugenol can bind and inhibit proteins such as histidine decarboxylase in *Enterobacter aerogenes*.⁴⁷ A study reported that eugenol has bactericidal effects on *L. monocytogenes*, acting as an ion transporter and preventing the accumulation of intracellular ATP.⁴⁸ Another study showed that *E. coli* and *S. aureus* bacteria treated with eugenol exhibit altered membrane permeabilities due to potassium ion leakage.⁴⁹ Inhibition of histidine decarboxylase in *E. aerogenes* has been recorded in the presence of high eugenol concentrations. The authors suggest that eugenol inhibits histidine decarboxylase synthesis, directly affecting the cell's metabolic energy.⁴⁷

Combination of Phenol Actives

To maximize the antibacterial potential of phenolic compounds, one must maximize the number of bacterial species affected by these compounds. We have seen that these antibacterial agents have many mechanisms of

action, including insertion between fatty acids in the bacterial membrane, attachment to proteins and membrane enzymes, inhibition of DNA/RNA synthesis, inhibition of proteins and polysaccharides and chelation of trace elements (e.g., iron).⁵⁰ Considering that a microorganism could be resistant to a particular antimicrobial agent, it would be interesting to assess the activities of mixtures of different antimicrobial agents. It has been shown that when microorganisms are exposed to a combination of antimicrobial agents, the risk of resistance development is significantly limited.²⁶

Interactions between various EO components may also affect antibacterial activity, as combining components can result in synergistic, additive or antagonist effects.^{18, 51, 52} For example, the effectiveness of thyme EOs against *S. aureus* and *P. aeruginosa* is due to the synergy between its major components, carvacrol and thymol.⁴⁰

A number of studies have tested the inhibitory effects of natural antibacterial mixtures (carvacrol, thymol, eugenol) or synthetic antimicrobial agents against several bacteria.^{25, 53-55}

For example, a study by Garcia-Garcia⁵⁶ showed that among binary and ternary mixtures of carvacrol, thymol and eugenol tested against *L. innocua*, the ternary mixture exhibited the highest antimicrobial activity,⁵⁶ while the least effective mixture was carvacrol-eugenol. In addition, this study demonstrated that carvacrol is the most effective antimicrobial agent against *L. innocua* compared to thymol and eugenol. Another study demonstrated that binary combinations of carvacrol, thymol or eugenol with potassium sorbate effectively inhibited growth of *L. innocua*, *S. typhimurium* and *E. coli*.⁵⁵ The natural antimicrobials were more effective than potassium sorbate.

Studies describing the activities of polyphenols against a variety of microorganisms showed that eugenol has a significantly lower antimicrobial activity compared to other EO components.⁵⁷ A study evaluating combinations of thymol/eugenol, thymol/carvacrol and carvacrol/eugenol demonstrated a synergistic effect against *E. coli*. The best synergistic effect was observed for a combination of eugenol with thymol or carvacrol, which decreased the MIC against *E. coli* from 1600 mg/L to 400 mg/L.⁵⁴

Another study showed that an appropriate ratio of carvacrol/thymol maximizes the synergistic antibacterial effects of the compounds against lactobacilli.⁵⁸

However, it is difficult to anticipate the effects of combinations of antimicrobial agents against bacterial strains. Despite the fact that there is very little scientific knowledge regarding the agents' mechanisms of interaction, many synergistic combinations have been observed.

ENCAPSULATION OF PHENOLIC COMPOUNDS EXTRACTED FROM EOs

Eos and their major components are very poorly soluble in water, and injection of unmodified EOs into the

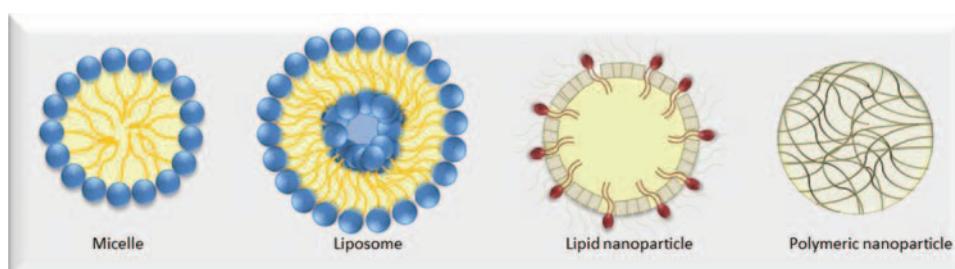


Figure 6. Representation of different types of nanoparticles.

bloodstream is impossible. In most cases, EOs must to be administered orally. Unfortunately, EO components tend to bind to hydrophobic components in food, decreasing the components' bioavailability and antimicrobial activity.⁵⁹ Additionally, facilitated degradation and consequent loss of chemical reactivity is an additional drawback to EOs.⁵⁹

The EO characteristics described above necessitate a delivery system with appropriate hydrophilic characteristics. Thus, encapsulation of EOs, especially phenols, could be a viable alternative to increase antimicrobial effectiveness.

Nanoparticles have many advantages over other delivery systems, including incorporation of both hydrophilic and lipophilic agents, protection of encapsulated drugs from degradation and a potential for sustained release. Nanoparticles also allow for high drug carrier capacity, improve drug bioavailability, eliminate drug toxicity and target the specific site of action. Moreover, encapsulation allows for controlled release of EOs and their major components.⁶⁰ Currently cyclodextrins (cyclic carbohydrates derived from starch) are used for EO encapsulation.^{60–62}

Different types of encapsulation with phytophenols have already been tested, including emulsions, liposomes, micelles and solid or lipid particles made of proteins, carbohydrates or crystallized lipids (Fig. 6). Among these nanocarriers, nanoparticles are the most commonly used method to demonstrate antibacterial activity (Fig. 7).

Nanoparticles range from 10 to 1000 nm in diameter and can encapsulate various therapeutic agents such as drugs, radionucleotides or DNA. Ideally, an optimal delivery system would target the antibacterial agent directly to the site of infection. Encapsulation of phenols in a nanoparticle system is a viable and effective approach to increase the stability of lipophilic bioactive components. Additionally, some studies have reported no loss of antibacterial efficacy after encapsulation^{63–65} (Fig. 8).

In addition, due to their subcellular size, nanoparticle systems should increase the biological activity of phenols and therefore their antimicrobial activity by activating passive cellular uptake mechanisms.⁶⁶ Furthermore, encapsulation of phenols protects the phenols against the environment (e.g., oxygen, light, moisture, pH).⁶⁷

Emulsions and Nanoemulsions

Emulsion systems are the most frequently used encapsulation system. These systems ensure a uniform distribution of partially or completely hydrophobic components in a hydrophilic medium.³⁶ Emulsions are thermodynamically unstable and tend to break down over time; therefore, emulsions must to be carefully formulated to remain stable for as long as possible. The functionality of emulsions is influenced by the concentration and size distribution of the droplets. Thus, the choice of a suitable emulsifier is critical to achieving a stable emulsion. Traditionally, emulsions have droplet sizes above 100 nm.

Several studies have demonstrated the suitability of EO encapsulation in emulsions stabilized by proteins, polymers and polysaccharides.^{68–70}

The use of an oily solid emulsion reduces the volatility of antimicrobial agents trapped in the oil-crystallized structure, and this system is capable of protecting agents against environmental factors. For example, the encapsulation of juniper oil by solid lipid micro-particles reduces the volatility of the antimicrobial agent.⁷¹

Recently, a new class of emulsions with finer particles has gained interest. These systems, called nanoemulsions, consist mainly of droplet dispersion with diameters between 10 and 100 nm. Production of nanoemulsions has become possible by using techniques for high-pressure homogenization, such as ultrasonication or microfluidization as well as the phase inversion temperature (PIT) method.^{72, 73} The main phenomenon that can affect the stability of nanoemulsions is Ostwald ripening. This phenomenon causes migration of the smaller droplets to the larger droplets through the continuous phase. Migration occurs when the oil phase has an appreciable solubility in the aqueous phase. This phenomenon results in an increase in average droplet size.⁶¹ However, previous studies have shown that this phenomenon can be inhibited by incorporating into the droplets sufficient levels of oils that are highly insoluble in the aqueous phase.⁷⁴

Encapsulation of phenols from EOs inside oil-in-water (o/w) emulsions or nano-emulsions has been performed.^{36, 61, 75} Chang⁶¹ used thyme oil nano-emulsions against the yeast *Zygosaccharomyces bailii*, showing that the oil phase had an appreciable antimicrobial activity.

| Nano-system delivery | Advantages | Phenols | Composition | Size (nm) | Bacterial strain | References |
|----------------------|-------------------------------------|---------------------------|---|---------------|---|------------|
| Micro-emulsion | Nanometer size | Eugenol | Tween-20 (polyoxyethylene) Micellar solution | 8 nm | <i>Staphylococcus aureus</i> <i>Escherichia coli</i> | [90] |
| | Promotion of active stability | | | | <i>Pseudomonas aeruginosa</i> | |
| | Reduction of toxicity | | | | <i>Salmonella typhimurium</i> | |
| | Biodegradability | | | | <i>Listeria monocytogenes</i> | |
| | Promotion of active bioavailability | | | | | |
| | Protection of active degradation | | | | <i>Bacillus cereus</i> | |
| Nano-emulsion | Targeting specific cells | Carvacrol | Tricetylglyceride (Miglyol 812N) | 80 nm–3000 nm | <i>Escherichia coli</i> | [36] |
| | | Eugenol | Tween 80 | | <i>Listeria innocua</i> | |
| | | Carvacrol | Tween 20 | 123 nm–293 nm | <i>Saccharomyces cerevisiae</i> | [67] |
| | | | Glycerol monooleate | | <i>Escherichia coli</i> | |
| | | | Lecithin | | <i>Lactobacillus delbrueckii</i> | |
| | | | Pea proteins | | | |
| Liposome | | | Sugar ester | | | |
| | | Carvacrol | Phosphatidylcholine | / | <i>Staphylococcus aureus</i> | [79] |
| | | Carvacrol/ Cholesterol | Cholesterol | | <i>Staphylococcus epidermidis</i> | |
| | | Thymol (6:1) | | | <i>Staphylococcus mutans</i> | |
| | | | | | <i>Staphylococcus viridans</i> | |
| | | | | | <i>Pseudomonas aeruginosa</i> | |
| Micelle | | | | | <i>Escherichia coli</i> | |
| | | Carvacrol | Surfynol 465 and 485 W | 3 nm–17 nm | <i>Listeria monocytogenes</i> | [87] |
| | | Eugenol | | | | |
| | | Thymol | Zein | 200 nm | <i>Escherichia coli</i> | [92] |
| | | | Sodium Caseinate | | <i>Salmonella</i> | |
| | | Thymol | Zein | 50 nm–328 nm | <i>Escherichia coli</i> | [93] |
| Nanoparticle | | Carvacrol | Ethylcellulose/ methylcellulose | 865 nm | <i>Escherichia coli</i> | [95] |
| | | Thymol | Chitosan | 40–80 nm | <i>Pseudomonas aeruginosa</i> | |
| | | | Tween 60 | | <i>Staphylococcus aureus</i> | |
| | | Carvacrol | Sodium Tripolyphosphate | 220 nm–260 nm | <i>Escherichia coli</i> | [65] |
| | | Thymol | Chitosan | 20 nm–190 nm | <i>Staphylococcus aureus</i> | [63] |
| | | Eugenol | Sodium Tripolyphosphate | | <i>Escherichia coli</i> | |
| | | Thymol | Chitosan | | <i>Staphylococcus aureus</i> | [111] |
| | | | | | <i>Escherichia coli</i> | |
| | | Eugenol | Protein isolate (WPI) | 130 nm–315 nm | <i>Staphylococcus aureus</i> | |
| | | | Maltodextrin (MD) | | <i>Escherichia coli</i> | |
| | | Carvacrol | poly(DL-lactide-co-glycolide) | 210 nm | <i>Escherichia epidermidis</i> | [101] |
| | | | Phosphatidylcholine | | | |
| | | Eugenol | poly(DL-lactide-co-glycolide) | 170 nm–185 nm | <i>Salmonella enteritidis</i> | [100] |
| | | | poly(vinyl alcohol) | | <i>Salmonella typhimurium</i> | |
| | | | | | <i>Listeria monocytogenes</i> | |
| | | | | | <i>Listeria innocua</i> | |
| | | | | | | |
| | | | | | | |

Figure 7. Encapsulation of phenols by different nanodelivery systems.

Another study conducted by Ziani⁷⁵ reported the use of thyme oil-in-water nano-emulsions stabilized by nonionic, cationic, anionic surfactants ((Tween 80, lauric alginate (LAE), sodium dodecyl sulfate (SDS)) against four strains

of acid-resistant spoilage yeasts. However, the results showed that the combinations of antimicrobial oil (thyme oil) and antimicrobial ionic surfactant (SDS, LAE) had an antagonistic impact on antimicrobial efficacy.

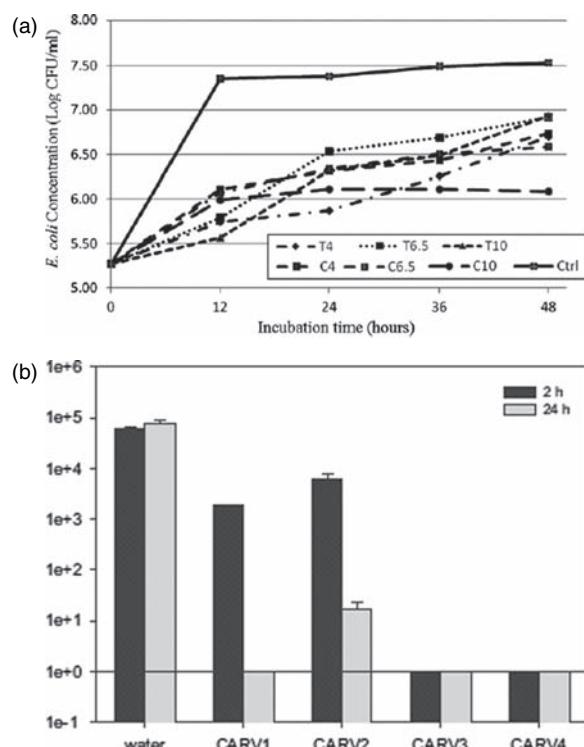


Figure 8. Growth curves of *E. coli* exposed to nanosystem deliveries.

Terjun and al.³⁶ focused on nano-emulsions made from Miglyol 812 N (triacylglyceride) and Tween 80 containing various concentrations of eugenol and carvacrol. The results showed that emulsions with large droplet sizes (3000 nm) were more effective at inhibiting the growth of *L. innocua* than emulsions with smaller droplets (80 nm), as eugenol and carvacrol concentrations decreased with droplet size. In addition, the results showed that, in contrast to the carvacrol-loaded emulsion, the eugenol-loaded emulsion did not inhibit *L. innocua* growth at the concentrations tested.

A another study reported systems composed of biocompatible components such as chitosan⁷⁶ and calcium alginate.⁷⁷ These systems were used to control EO release in the mouth (chitosan) or small intestine (calcium alginate).

Liposomes

Liposomes are nanocarriers whose structure is similar cell membranes.⁷⁸ Liposomes are spherical particle consisting of amphiphilic molecules (e.g., phospholipids, cholesterol, sphingomyelins) arranged in one or several lipid bilayers enclosing an aqueous compartment.

Studies have shown that liposomes enhance the antimicrobial activity of *Origanum dictamnus*,⁷⁹ extracts of lemon,⁸⁰ extracts from myrtus⁸⁰ and *Artemisia arborescens* EOs.⁸¹

It has been shown that for certain concentrations, thymol and carvacrol inhibit the peroxidation of phospholipid

liposomes, suggesting that these agents are strong antioxidants.⁸² Similarly, the inhibition of EO oxidation in *Origanum* plants is highly dependent on the concentration of carvacrol and thymol.⁸³

Liolios⁷⁹ showed that carvacrol and thymol incorporated into liposomes (made from phosphatidyl choline) possessed higher antibacterial power than the non-encapsulated actives against *L. monocytogenes*.

Micelles and Microemulsions

Micelles are spontaneously formed when amphiphilic molecules (with adapted Hydrophilic Lipophilic Balance values) are inserted in water. Micelles are composed of an inner core of interacting hydrophobic segments surrounded by an outer hydrophilic corona, which serves as a stabilizing interface with the external aqueous environment.⁸⁴ Micelles are generally between 5 and 100 nm in diameter, depending on the nature of the amphiphilic molecules (e.g., small molecules, polymers or other macro molecules).

Studies have shown that micellar based systems increase the antimicrobial activity of eugenol and carvacrol.^{35, 85-87} One of the studies demonstrated growth inhibition of four strains of *E. coli* and *L. monocytogenes* by using carvacrol and eugenol solubilized in non-ionic micelles with Surfynol 465 and 485 W surfactants.⁸⁵ The results showed that the antimicrobial activity of Surfynol 485 W micelle is higher with eugenol compared to carvacrol.

Studies realized by Perez-Conesa^{88, 89} showed that a micellar nonionic surfactant Surfynol 485 W solution containing eugenol and carvacrol was effective against biofilms containing *L. monocytogenes* and *E. coli*. *L. monocytogenes* strains were more resistant to these antimicrobial systems than *E. coli* strains.

In another study, inhibition of *L. monocytogenes* and *E. coli* O157:H7 was tested with eugenol encapsulated in micellar solutions at different pHs (pH 5, 6 and 7) and different temperatures (10 °C, 22 °C and 32 °C). Antibacterial effectiveness decreased when pH increased but was not affected by temperature.⁸⁶

Microemulsions correspond to ternary systems in a thermodynamic equilibrium state composed of water or oil-loaded micelles. These systems maintain their structure as long as system temperature and composition are unchanged. A study by Hamed⁹⁰ demonstrated that eugenol microemulsions (prepared using Tween 20) possessed higher antioxidant activity than clove EO microemulsions. Moreover, eugenol microemulsions seemed more effective against *S. aureus*, *E. coli*, *P. aeruginosa*, *S. typhi* and *B. cereus* than clove EO microemulsions.

Microemulsion systems enhance the activity of phytophenols,⁸⁶ and these systems are known to possess a complex micellar topology. However, these systems may have some disadvantages, including a lack of physical stability after dilution, undesirable interactions with food and the degradation or loss of particular components.

Nanospheres-Nanocapsules

There are two main types of nanoparticle that can be used to encapsulate lipophilic compounds. The first type corresponds to lipidic or polymeric systems, where the entire nanoparticle structure is cohesive (matrix systems). The solid lipid nanosphere (SLN) is an important member of this group. The second type corresponds to nanocapsules composed of an oily core (or aqueous core in some cases) surrounded by a cohesive polymeric or lipidic shell (nano-capsules). Lipid nano-capsules (LNCs) are the most used system in this category. LNC shells can consist of polymer and/or lipids in different proportions, with sizes in the 10 to 200–500 nm range.

Polymeric nanoparticles are usually prepared from hydrophobic synthetic polymers or copolymers such as polylactide/polyglycolide (PLA/PLGA) or natural polymers such as albumin, gelatin, collagen, and chitosan. A variety of therapeutic agents including lipophilic or hydrophilic drugs can be encapsulated in such systems.

Several studies have reported the use of nanospheres to encapsulate antimicrobial agents. Parris⁹¹ used corn zein to produce nanospheres encapsulating oregano and thyme EOs. The aim of Parris's study was to target the release of each active to a specific site in order to optimize each compound's antibacterial properties. Another study explored the suitability of thymol-loaded zein-sodium caseinate (SC) nanoparticle-based films,⁹² finding antimicrobial activity against *E. coli* and *Salmonella* for a thymol-to-zein ratio of 30–40%. Wu⁹³ demonstrated the antioxidant and antimicrobial properties of carvacrol and thymol zein nanoparticles against *E. coli*.

Kavoosi⁹⁴ reported the antimicrobial and antioxidant properties of gelatin films incorporating thymol. The results showed the effectiveness of this system against *S. aureus*, *B. cereus*, *E. coli* and *P. aeruginosa*. Another study conducted by Wattanasatcha⁹⁵ investigated the encapsulation of thymol in ethylcellulose or methylcellulose spheres. Wattanasatcha et al. showed that the MIC and minimum bactericidal concentration (MBC) for pure thymol and its nano-encapsulated formulation against *E. coli* and *S. aureus* were comparable. Unfortunately, pure thymol was more effective than nano-encapsulated thymol against *P. aeruginosa*.

Several studies have explored the use of grafted chitosan nanoparticles.^{63,65,96,97} Grafting of chitosan, a biopolymer with antibacterial properties, to nanoparticles confers a positive charge to the nanoparticle. This positive charge facilitates interactions between the nanoparticle and the negatively charged bacterial cell wall. A study conducted by Chen⁶³ investigated formulations of eugenol-grafted and carvacrol-grafted chitosan nanoparticles. This study found antibacterial and antioxidant properties on *E. coli* and *S. aureus* for both the eugenol-grafted and carvacrol-grafted chitosan nanoparticles. In addition, the eugenol-grafted chitosan nanoparticles had a higher antibacterial

efficiency than the carvacrol-grafted chitosan nanoparticles. Chitosan nanoparticles therefore seem effective against both *E. coli* and *S. aureus*. Jung⁹⁷ also utilized eugenol grafted to chitosan to formulate a hydrogel with interesting antioxidant activity. Another study demonstrated the antibacterial activity of carvacrol-loaded chitosan nanoparticles against *S. aureus*, *B. cereus* and *E. coli*.⁶⁵

Many studies have demonstrated the use of PLGA (poly(DL-lactide-co-glycolide)) for phenol encapsulation. Indeed, a study revealed the ability of carvacrol to combat biofilm formation using a polymeric film composed by biodegradable PLGA. The results showed that only 0.1% carvacrol was necessary to significantly decrease biofilm formation by *E. coli* and *S. aureus*.⁹⁸ Another study, by Persico et al.⁹⁹ demonstrated the antimicrobial activity of carvacrol nanoparticles dispersed in films based on low-density polyethylene (oregano-modified montmorillonite was used as the filler) against *Brochothrix thermosphacta*, *L. innocua*, *Pseudomonas fragi*, and *Carnobacterium*. Another study showed the antimicrobial activity of PLGA nanoparticles encapsulating eugenol and trans-cinnamaldehyde with poly(vinyl alcohol) (PVA) used as surfactant,¹⁰⁰ which inhibited the growth of *Salmonella* (Gram-negative bacterium) and *Listeria* (Gram-positive bacterium). A study conducted by Iannitelli¹⁰¹ reported the production of carvacrol loaded PLGA nanocapsules. These nanocapsules are potential candidates for improving the effectiveness of antibacterial agents against biofilm-associated infections.

Shah¹⁰² proposed a new process for encapsulating eugenol inside nanodispersions consisting of isolated protein (WPI) and maltodextrin (MD) combined in different ratios. Nanoparticles created with this process were evaluated to determine their antimicrobial efficacy on different bacteria such as *E. coli* and *Listeria monocytogenes*.⁴¹ The results indicated no improvement in effectiveness when the bacteria are in the presence of a culture medium (MBC and MIC 0.25 g/L). This system is more effective against *E. coli* (Gram-negative) than *L. monocytogenes* (Gram-positive). There is no difference in efficacy between pure eugenol and nanoencapsulated eugenol.

Eugenol nanofibers have been used as antimicrobial microemulsions against *S. typhimurium* and *L. monocytogenes*. This nanocarrier system was more effective against *S. typhimurium* than *L. monocytogenes*.¹⁰³

Others products have been explored, such as metallic nanoparticles formulated with plant extracts. These metallic nanoparticles have been shown to have strong antibacterial activity.^{104–106} For example, the use of silver and gold nanoparticles combined with extracts of *Mentha piperita* plant was effective against *E. coli* and *S. aureus*.¹⁰⁵

Many studies have demonstrated the efficacy of nanoparticles in murine models. For instance, a study demonstrated that nitric oxide nanoparticles accelerated the healing of *Acinetobacter baumannii* infected wounds in a murine

model.¹⁰⁷ Another study showed the synergistic effects of combining chitosan and silver nanoparticles to treat a burn infected with *P. aeruginosa*: the survival rates of mice were 64.3% with silver-chitosan versus 0% with untreated mice.¹⁰⁸

Novel Phenolic Compounds Delivery System

Nanotechnologies have many advantages for encapsulating lipophilic actives such as phenols (Fig. 7), and encapsulated actives have an undeniable power against many MRBs. However, most of these vectors have many drawbacks, including a need for solvents or a significant energy demand for their manufacture. The use of solvents may promote the evaporation of phenols and/or alter their antibacterial activity. In light of these disadvantages, another type of nanoparticle, lipid nanocapsules (NCLs), may be suitable for the encapsulation of phenolic components. NCLs are composed of an oil core (e.g., triglyceride) for homogeneous distribution of the lipophilic active surrounded amphiphilic surfactants (e.g., polyethylene glycol). NCLs allow low complement activation. NCL preparation requires very little energy and no solvents. Moreover, the process is adaptable and may be conducted at a low temperature, avoiding degradation of phenols. In addition, antibiotics can be used in combination with phenols to decrease the effective dose of antibiotics on MRBs as well as the side effects of antibiotics. For instance, Fadli found synergies for 57 combinations between two EOs whose major component is carvacrol (*Thymus maroccanus* and *Thymus broussonetii*) and four antibiotics (ciprofloxacin, gentamicin, pristinamycin and cefixime). Carvacrol decreased the MIC of ciprofloxacin on Gram-negative bacteria by four-fold and the MIC of ciprofloxacin on Gram-positive bacteria by 8- to 16-fold.¹⁰⁹

An interesting study showed synergies between silver nanoparticles using plant extracts with antibiotics against *A. baumannii*, *P. aeruginosa* and *E. coli*. An 11.8-fold increase in the *E. coli* inhibition diameter around streptomycin was observed when the antibiotic combined with silver nanoparticles.¹¹⁰

CONCLUSION

The antibacterial effectiveness of phenols against Gram-negative or Gram-positive pathogenic bacteria is widely described in various studies. In light of the very specific behavior of EOs and their major components, encapsulation of EO components is an interesting treatment against MRB. Several studies underscore the success of encapsulation with different delivery system. These systems can be explored in combination with antibiotics in *in vivo* models.

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