Review

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Review

Mechanistic Insights on Antibacterial Property of Essential Oil Components and Their Utility in Preserving Food Items

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Abstract

Foodborne diseases and food poisoning caused by bacterial pathogens is a significant global health as well as economic concern. While synthetic compounds are widely used as preservatives to ensure food safety, growing concerns regarding their potential health risks and the rise of antimicrobial resistance have driven the search for natural alternatives. Essential oils (EOs) and their individual bioactive constituents, known as essential oil components (EOCs), have emerged as promising, eco-friendly candidates for food preservation due to their robust broad-spectrum antibacterial properties. This review provides comprehensive mechanistic insights into how individual EOCs exert their antibacterial effects, detailing the disruption of bacterial cell membranes, inhibition of vital metabolic enzymes and ATP synthesis, modulation of virulence gene expression, and the prevention and eradication of biofilms. Furthermore, the review explores the practical applications and limitations of EOCs in food systems, addressing challenges such as chemical instability, toxicity at high doses, and adverse organoleptic effects. It also highlights advanced formulation strategies, such as micro/nano-encapsulation, nano-emulsions, and chemical derivatization, which significantly enhance EOC stability, bioavailability, and overall preservative efficacy. Ultimately, understanding the multifaceted mechanisms of individual EOCs paves the way for their optimized and sustainable use, ensuring global food safety.

Keywords: essential oil; essential oil components; food preservation; food safety; antimicrobial activity

Introduction

Food safety refers to all those hazards which make the food unsafe to human consumption. Unsafe food contributes to a vicious cycle of disease and malnutrition, impacting people of all ages, especially children, the elderly, and those who are ill (Chaudhuri, 2015). Foodborne diseases are significant contributors to increasing rate of morbidity and mortality (Bintsis, 2017; Kohli and Garg, 2015; Srikumar and Fuchs, 2011). Food-poisoning bacteria, fungi, and yeasts are major contributors to food spoilage; among them, bacteria contribute far more to food poisoning than fungi. Bacterial pathogens are among the most common causes of food borne illness, with bacteria like *Staphylococcus aureus*, *Salmonella* spp, *Clostridium perfringens*, *Campylobacter* spp, *Listeria monocytogens*, *Vibrio parahemolyticus*, *Bacillus cereus* and entero-pathogenic *Escherichia coli* being responsible for a significant majority of cases (Li et al., 2023; Lorenzo et al., 2018; Muhammad et al., 2020; Rathod et al., 2022). Bacterial growth in certain food matrices encourages metabolism of certain pathways that are related to pathogenesis, virulence, and antibiotic resistance (Bhalerao et al., 2025; Chen et al., 2021; Pracser et al., 2025; Srikumar and Fuchs, 2011), which not only bestows upon them faster proliferative ability and survival within it but also enhances their capacity to pose a global threat to it. Each year, around 600 million people worldwide—nearly one in ten—become ill from foodborne pathogens (Zhao and Talha, 2022). It has been observed that low- and middle-income countries are mostly affected because of food safety issue, with an annual estimated cost of 110 billion USD in productivity losses, trade-related losses, and rise in medical treatment costs due to the consumption of unsafe foods (Jaffee et al., 2019). Moreover, the globalization of the food supply chain increasingly exposed to various threats, such as emerging pathogens, existing pathogens with new virulence traits and the development of antimicrobial resistance (AMR) in foodborne pathogens (Gizaw, 2019; Rafiq et al., 2022). Food safety, nutrition and food preservation are closely linked. Unsafe food due to improper preservation creates a vicious cycle of disease and malnutrition, which in turn creates both economical and societal burden to any country ("Food Safety," n.d.). Food preservation encompasses a range of techniques aimed at controlling internal and external factors that lead to spoilage, primarily by inhibiting microbial growth, with the main goal of extending shelf life.

Throughout history, essential oils (EOs) are important phytochemicals that have been widely employed in medical care including cosmetics as well as in the preservation of foods and beverages (Bolouri et al., 2022; Hyldgaard et al., 2012). Advancements in science have heightened researchers' interest in the medicinal properties of essential oils, owing to their low toxicity, diverse pharmacological activities, and cost-effective solution in food preservation (Falleh et al., 2020; Raveau et al., 2020). EOs are plant secondary metabolites that play a significant role in plant adaptation and defense mechanisms against a myriad of environmental threats, primarily from pathogens, pests, herbivores, and extreme climatic conditions (Bennett and Wallsgrove, 1994). Almost all EOs are volatile, slightly miscible in water, colorless, having characteristic odor, optically active and are characterized by high refractive index (Burt, 2004; Chouhan et al., 2017a; Dima and Dima, 2015; Hyldgaard et al., 2012; Kalemba and Kunicka, 2003). Research has shown that EOs can be a promising means to combat food safety concerns. The EOs comprise of active pharmaceutical compounds often called essential oil components (EOCs) that are mostly low molecular weight with a great structural diversity (Wink, 2015). The majority of EOCs seem to be safe for human consumption and are generally recognized as safe (GRAS) by the Food and Drug Administration (FDA) for their usage as food additives and in food preservation (Davis et al., 2022; Nisar et al., 2021). Given the membrane penetration potential, many EOCs are known to have bacteriolytic property (Davis et al., 2022; Nisar et al., 2021). With these attributes antimicrobial activities of EOCs have garnered particular attention (Angane et al., 2022), besides other biological activities (Ali et al., 2020; Ćavar Zeljković et al., 2022; Ilić et al., 2022; Zuo et al., 2020) as well as an increasing emphasis on environmentally sustainable solutions to control microbial propagation in food matrices (Jackson-Davis et al., 2023). Although, EOCs endowed with intrinsic antimicrobial traits, are a promising means to combat food borne pathogens; however, there is a lack of detailed knowledge about the mechanism of the individual essential oil components which thus attributes to our superficial understanding of governing synergy and antagonism in real time application.

The purpose of this review is to provide an overview of current knowledge regarding the components of essential oils, their antimicrobial properties, their mechanisms of action, and plausible effective food preservation strategies. Furthermore, the review explores the practical applications of these plant-derived compounds in food preservation, addressing key considerations such as dosage, stability, sensory properties, and regulatory requirements.

Antibacterial Activity of EOs and Their Components

Over the past few decades, essential oils (EOs), such as cinnamon, clove, oregano, and thyme, have been extensively used as natural preservatives to control food spoilage (Mith et al., 2014). All EOs have also demonstrated antimicrobial activity against a number of foodborne bacteria, including *Escherichia coli*, *Campylobacter*, *Clostridium perfringens*, *Listeria*, *Salmonella*, *Bacillus cereus*, *Shigella*, and *Staphylococcus aureus* (Table 1). Since essential oils (EOs) contain diverse components in varying proportions, their antimicrobial efficacy differs among bacterial species. For example, cinnamon essential oil consists of cinnamaldehyde (more than 70%), linalool (7%) and trace amount of eugenol, cinnamyl acetate, and safrole (Alizadeh Behbahani et al., 2020; Guo et al., 2024); whereas, major constituent of clove essential oil is eugenol (45–90%), followed by eugenyl acetate, β-caryophyllene, and α-humulene (Haro-González et al., 2021; Pires Costa et al., 2025). According to previous studies, clove oil exhibits stronger antibacterial activity than cinnamon oil (Falleh et al., 2020); however, antibacterial efficiency varies with the presence of the food components, pH of the food matrices etc. (Falleh et al., 2020; Wang et al., 2024). Since EOs present a diverse composition of EOCs, there have been multifaceted challenges in their utilization and in understanding their mechanism of action (Dima and Dima, 2015; Hyldgaard et al., 2012). There are also issues related to the standardization of essential oil formulations, determining the potential synergistic or antagonistic interactions among their components, and variations in terms of their efficacy against different bacterial strains, thus encouraging the necessity for further research to optimize their utility potential (de Sousa et al., 2023; Hüsnü et al., 2007; Simoben et al., 2023; Thomford et al., 2018). Therefore, it is more advantageous to study individual components (EOCs) in detail instead of focusing solely on essential oils as complex mixtures.

The bioactive constituents of EOs (EOCs) demonstrate a wide range of antibacterial effects, a favorable toxicity profile, and the ability to interfere with diverse bacterial pathways (Khwaza and Aderibigbe, 2025). The antimicrobial effects of EOCs are closely related to their physicochemical properties, such as lipophilicity, partition coefficient, and hydrogen bonding characteristics, which are attributed to similar structural arrangements and functional groups present in these compounds (Marinelli et al., 2018). Indeed, the effects of individual EOC varies across microorganisms due to differences in membrane thickness, composition, and metabolic activity among various bacterial species (Maurya et al., 2021).

For a long time, EOCs have demonstrated competence in hampering bacterial growth in controlled laboratory settings and living organisms (Almuzaini, 2023). It has been revealed that the EOCs ascribing to phenolic and aromatic aldehydes exhibit robust antibacterial properties, followed by ketones, alcohols, ethers, and other hydrocarbons, mostly due to their efficient permeability across cell membranes (Bai et al., 2022; Falleh et al., 2020; Kalemba and Kunicka, 2003; Zhou et al., 2007). In fact, majority of EOCs effective against food poisoning bacteria are phenolic monoterpenoids and phenylpropenes namely eugenol, trans-cinnamaldehyde, carvacrol and thymol (Ben Jemaa et al., 2018; Dhifi et al., 2016; Gutiérrez-del-Río et al., 2018).

Insights into Mode of Action

The antibacterial activity of antimicrobial agents is primarily attributed to their capacity to chemically disrupt the synthesis or function of essential biomolecules within bacteria, such as proteins, nucleic acids, cell membrane components, or metabolic pathways. This interference ultimately impairs bacterial growth, replication, or survival, leading to the inhibition or eradication of bacterial infections. Several studies indicated that individual components of essential oils have multiple target sites within bacterial cells (Table 2). This represents different susceptibility patterns across the strains of same genera and at varied surrounding environments (Hyldgaard et al., 2012). For instance, trans-cinnamaldehyde has been found to inhibit ATP synthase enzyme activity in *Salmonella* apart from cell membrane disruption (Silva et al., 2018). The same has also been observed to play a role in down-regulating carbohydrate metabolism and transport and amino acid metabolism (Kollanoor Johny et al., 2017).

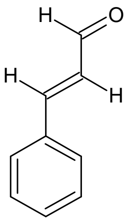
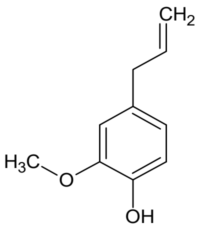
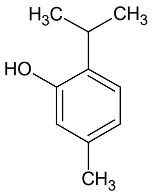
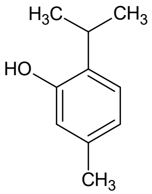
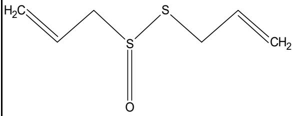
Table 1. Antibacterial attributes of commonly used essential oils in food preservation.

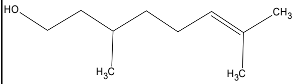
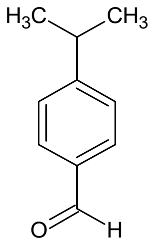
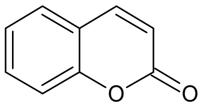
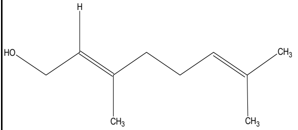
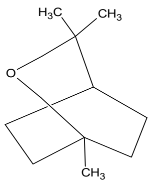
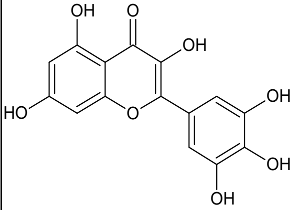
Essential oil plant origin	Scientific name	Major Components	Use in food preservation	Effectiveness on Bacterial species	Reference
African basil	*Ocimum gratissimum, Ocimum basilicum, Ocimum canum*	Eugenol (7.42–74.83%) estragol (43.0–44.7%), linalool (24.6–29.8%), carvacrol (12.0–30.8%), p-cymene (19.5–26.2%), thymol (28.3–37.7%) and γ-terpinene (12.5–19.3%)	Meat, fish, spaghetti sauces and cheese bakes	*Staphylococcus aureus*, *Bacillus cereus*, *Listeria monocytogenes*, *S.* Typhimurium, *Escherichia coli*	(Mith et al., 2016; Ueda et al., 2021)
Cinnamon	*Cinnamomum verum, Cinnamomum loureirii, Cinnamomum cassia Cinnamomum zeylanicum*	Trans-cinnamaldehyde (66.28–81.97%), Linalool (7.00%), Eugenol (4.6%)	Semi-skimmed UHT milk, bakery foods, dairy products	*Listeria innocua, Staphylococcus aureus, Salmonella* Enteritidis and *Bacillus cereus*	(Alizadeh Behbahani et al., 2020; Hyldgaard et al., 2012; Li et al., 2013; Zhang et al., 2022)
Clove	*Eugenia caryophyllus*	Eugenol (76.8%), β-caryophyllene (17.4%), α-humulene (2.1%), and eugenyl acetate (1.2%)	full-fat and low-fat soft cheeses, UHT milk, sea food, Fruits and vegetables	*S. enterica, Escherichia coli, Staphylococcus aureus*, *Listeria monocytogenes*	(Cui et al., 2018; Jirovetz et al., 2006; Nuñez and D' Aquino, 2012)
Garlic	*Allium sativum*	Allicin (57.1%)	Meat and poultry products, seafood, sauces and dressings	*Salmonella* Typhimurium, *Escherichia coli, Listeria monocytogenes, and Staphylococcus aureus*	(Belguith et al., 2010; Sallam et al., 2024)

Oregano	*Origanum vulgare*	Carvacrol (63.97%), p-cymene (12.63%) and linalool (3.67%), α-terpineol (2.54%), (-)-terpinen-4-ol (2.24%), thymol (1.93%)	Pasteurized milk, meat and poultry, seafood, fruit juices and beverages	*Salmonella enterica, Escherichia coli, Staphylococcus aureus, Brochothrix thermosphacta, P. fluorescens*	(Ghosh et al., 2024; Liu et al., 2026; Martucci et al., 2015; Mith et al., 2014; Özkan et al., 2017; Tejada-Muñoz et al., 2024)
Menthol	*Mentha piperita* L.	Menthol (36.02%), menthone (24.56%), menthyl acetate (8.95%), and menthofuran (6.88%)	Tzatziki (cucumber and yogurt salad), taramosalata (fish roe salad) and pâté	*Salmonella enteritidis* and *Listeria monocytogenes*	(Desam et al., 2019)
Savory	*Satureja thymbra* *Satureja montana*	Carvacrol (42.7%), o-cymene (17.98%), linalool (9.65%), caryophyllene oxide (5.25%), γ-terpinene (4.22%), caryophyllene (2.73%) and (-)-borneol (2.24%)	Meat, fruit	*S.* Enteritidis, *S.* Infantis, *S.* Kentucky, *S.* Typhimurium, *E. coli, L. monocytogenes, S. aureus, Clostridium perfringens*	(Hyldgaard et al., 2012; Özkan et al., 2017)
Thyme	*Thymus vulgaris*	Thymol (47.23%), p-cresol (20.37%) and 2,6-dimethylphenol (16.26%)	semi-skimmed UHT milk, meats and meat products, Apple juice	*S.* Typhimurium, *Staphylococcus aureus, Brochothrix thermosphacta, P. fluorescens*	(Ben Jemaa et al., 2017; Mith et al., 2014; Morshdy et al., 2022)
Vietnam Coriander	*Polygonum odoratum*	Dodecanal (55.5%), decanal (11.6%)	Meat, Salami, Bakery	*Escherichia coli, Bacillus cereus, Bacillus subtilis, Vibrio cholerae, Staphylococcus*	(Fujita et al., 2015; Řebíčková et al., 2020)

				aureus and *Salmonella* choleraesuis	
Cumin	*Cuminum cyminum L*	Cuminaldehyde (27.10%), beta-pinene (25.04%) and gamma-terpinene (15.68%)	Cheese, meat products	*S.* Typhi, *Clostridium perfringens*, *Staphylococcus aureus*	(Fathy et al., 2025; Hassanien et al., 2014; Petretto et al., 2018; Sharifi et al., 2021; Wongkattiya et al., 2019)
Rosemary	*Rosmarinus officinalis*	Genkwanin (26%), camphor (28%), endo-borneol (13%), alpha-terpineol (12%), and hydroxyhydrocaffeic acid (13%)	Yogurt, mayonnaise, refined vegetable oil	*Salmonella* Spp., *Escherichia coli*, *Staphylococcus aureus*	(Manilal et al., 2021; Yang et al., 2023)

Table 2. Mechanism of action of different EOCs.

Essential oil components	Structure	IUPAC Nomenclature	Mechanism	Reference
Trans-cinnamaldehyde		(E)-3-phenylprop-2-enal	-Targets ATP synthase alpha chain protein and causes the reduction level of ATP. - Antibiofilm effect -Downregulate several metabolic and biosynthetic pathways	(Doyle and Stephens, 2019; Anup Kollanoor Johny et al., 2010a; Silva et al., 2018)
Eugenol		2-methoxy-4-prop-2-enylphenol	- Alters the membrane permeability followed by leakage of ions. -Down-regulate several metabolic pathways -Inhibit virulence gene expression of T3SS (Type 3 Secretion System)	(Ahmed Khalil et al., 2017; Devi et al., 2010; Anup Kollanoor Johny et al., 2010a; Zhao et al., 2022)
Carvacrol		2-methyl-5-propan-2-ylphenol	-Damages the enzyme for ATP synthesis. - Rendering the membranes and mitochondria more permeable and disintegrating the outer cell membrane.	(Imran et al., 2021; A. Kollanoor Johny et al., 2010; Sharifi-Rad et al., 2018)
Thymol		5-methyl-2-propan-2-ylphenol	-Damages the enzyme for ATP synthesis. -Disrupt the membrane integrity.	(Chauhan and Kang, 2014; Escobar et al., 2020; A. Kollanoor Johny et al., 2010; Marchese et al., 2016; Sharifi-Rad et al., 2018; Tian et al., 2021)
Allicin		3-prop-2-enylsulfinylsulfanylprop-1-ene	-Inhibit the RNA synthesis	(Belguith et al., 2010; Feldberg et al., 1988)

Citronellol		3,7-dimethyloct-6-en-1-ol	-Loss of membrane integrity	(Guimarães et al., 2019; Victoria et al., 2012)
Cumin aldehyde		4-propan-2-ylbenzaldehyde	-Disrupt the cell membrane integrity and enter into the cytoplasm, where it interacts with nucleic acid and stops the growth.	(Li et al., 2023)
Coumarin		9-methoxyfuro [3,2-g]chromen-7-one	-It binds to the B subunit of DNA Gyrase in *Salmonella* and inhibits DNA supercoiling by blocking the ATPase activity.	(Basile et al., 2009; Feng et al., 2020; Lončar et al., 2020; Thakur et al., 2020)
Geraniol		(2E)-3,7-dimethylocta-2,6-dien-1-ol	-Inhibit the mobility, adhesion, and invasiveness of *Salmonella*.	(Ekonomou et al., 2022; J. m. Kim et al., 1995; Mączka et al., 2020)
1,8-cineole		1,3,3-trimethyl-2-oxabicyclo [2.2.2]octane	-Disrupt the structure of cell wall and membrane	(Cai et al., 2021; Sun et al., 2018)
Myricetin		3,5,7-trihydroxy-2-(3,4,5-trihydroxyphenyl)chromen-4-one	-Inhibit the type III secretion system by downregulating the pathogenic island I gene regulatory pathway	(Imran et al., 2021; Q et al., 2021)

EOCs are widely recognized for their effectiveness against various pathogens, which is attributed to the specific chemical properties of these compounds.

***Disruption of cell membrane*:** The breakdown of bacterial cell membranes by essential oil constituents is a complex process that includes hydrophobic and/or hydrophilic interactions. The hydrocarbon backbone of EOCs is lipophilic, allowing them to interact with lipid-based structures in bacterial cells, while their hydrophilic functional groups enable interaction with aqueous environments (Kalemba and Kunicka, 2003; Koroch et al., 2007; Marchese et al., 2017; Marinelli et al., 2018). Several EOCs such as eugenol, carvacrol and thymol are the potent cell membrane disruptors. The principal mode of action of these compounds at bactericidal doses is cytoplasmic membrane rupture, which increases non-specific permeability (Figure 1). This hyperpermeability is accompanied by ion leakage, a significant loss of other cellular components, such as intracellular proteins, and eventually, cell death (Ahmed Khalil et al., 2017; Devi et al., 2010; Sharifi-Rad et al., 2018; Zhao et al., 2022). A study conducted by Di Pasqua et al., in 2007 revealed that exposure of cells to five EOCs, namely eugenol, carvacrol, thymol, trans-cinnamaldehyde, and limonene for two hours led to a significant decrease in unsaturated fatty acids and an increase in saturated fatty acids (Di Pasqua et al., 2007). A high level of saturated fatty acids (SFAs) in the membrane lipid bilayer is associated with reduced membrane fluidity, leading to increased rigidity (Bayer et al., 2000). The change in the fatty acid composition of the organism is perhaps because of the adaptive mechanism of the organism where cellular reaction to membrane damage takes place which results in the reduction of unsaturated fatty acids and increase in the saturated fatty acid. This observation suggests that these compounds potentially interacted with the membrane lipid profile, inducing structural alterations in the bacterial cell (Di Pasqua et al., 2007). The individual and combined effects of eugenol, carvacrol, and thymol have been shown to induce cell membrane disruptions and reduce biofilm mass on the food matrix surface (Miladi et al., 2017). Several analytical techniques like scanning electron microscopy (SEM) and transmission electron microscopic (TEM) analyses confirm the changes in the cell membrane upon EOC treatment (Chauhan and Kang, 2014; Di Pasqua et al., 2007; Miladi et al., 2017; Sun et al., 2018).

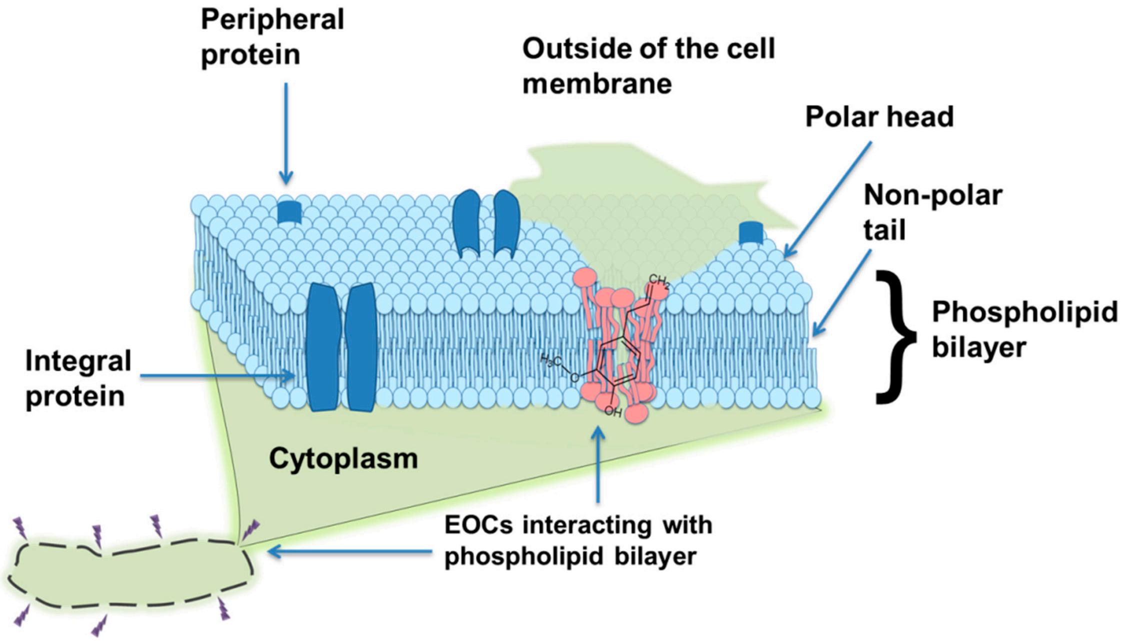


Figure 1. Illustration of cell membrane destabilization by EOC.

***Modulating expression of important genes*:** The impact of slight exposure of various essential oil components on several bacterial species has revealed significant effects on genes essential for survival as well as virulence and colonization (Ananda Baskaran and Venkitanarayanan, 2014; Giovagnoni et al., 2020;

Kollanoor Johny et al., 2017; Sun et al., 2018; Wagle et al., 2019). The transcriptomics profiles of the pathogens following exposure of EOCs provided insights into their effects at the genetic level (Ananda Baskaran and Venkitanarayanan, 2014; Kollanoor Johny et al., 2017; Sun et al., 2018). Trans-cinnamaldehyde, eugenol, thymol and carvacrol at their sub-MIC level are able to down-regulate genes responsible of carbohydrate and amino acid metabolism and their transport, and vitamin B_{12} biosynthesis of *Salmonella* Enteritidis PT8 and *Salmonella* Typhimurium (Giovagnoni et al., 2020; Kollanoor Johny et al., 2017). Trans-cinnamaldehyde, eugenol and carvacrol also downregulate expression of genes related to stress response and cell surface modifying enzymes in *Campylobacter jejuni* (Wagle et al., 2019).

***Reduction in biofilm formation and biofilm disrupting effect*:** Recent studies have highlighted the potential of EOCs to disrupt and prevent biofilm formation. Antibiofilm potential leverages great potential of EOCs in their utility in food preservation, as EOCs can be applied directly to the surface of food or incorporated into packaging, where it migrates and inhibits microbial activity. Phenolic monoterpenes, such as thymol and carvacrol, are among the most potent agents, in disrupting EPS, a potent structural component of biofilm. These EOCs can penetrate the EPS matrix, thereby eradicating existing structure (Touati et al., 2025). More recently, thymol and oregano demonstrated to be more effective in inhibiting biofilm formation by *E. coli* than carvacrol (Tadevosyan et al., 2025). However, carvacrol and thymol showed higher activity against *Salmonella* biofilms than oregano did (Tadevosyan et al., 2025). EOCs like cinnamaldehyde has ability to modify protein composition in biofilms, weakening structural integrity; whereas, thymol reduces biofilm synthesis by lowering glutamine, glutamate, and uridine diphosphate levels, impairing EPS production. Linalool, on the other hand, inhibits biofilm formation through microcolony disruption. Thymol reduces thickness and density of biofilm matrix in food poisoning *E. faecalis* (Touati et al., 2025). The presence of both thymol and carvacrol in *L. origanoides* EO exerts greater effectiveness in dispersing *S.* Enteritidis biofilms (Touati et al., 2025). In a study carried out by Purkait et al., eugenol and trans-cinnamaldehyde individually lowers established biofilm of *S.* Typhimurium by 51% and 54%, respectively (Purkait et al., 2020). A combination of both the compounds enhances the efficacy to 69% (Purkait et al., 2020). It has been revealed that trans-cinnamaldehyde is also effective in disrupting *S.* Typhimurium biofilms on solid surfaces, providing promise towards its utilization in food packaging industry (Silva et al., 2018). The proteomics analyses revealed that there is differential expression of proteins associated with energy metabolism, highlighting potential mechanisms by which cinnamaldehyde disrupts biofilm formation and promotes antibacterial effects (Silva et al., 2018). Linalool is recognized as another effective EOC with anti-biofilm activity in many food-spoilage bacterial species (Prakash et al., 2019). Recent study indicates that linalool interacts with quorum-sensing ComP receptor in *Bacillus amyloliquefaciens* (Shen et al., 2023). Menthol, on the other hand, reduces the AHL-dependent production of violacein, virulence factors, and biofilm formation, indicating broad-spectrum anti-quorum sensing activity (Tadevosyan et al., 2025). Figure 2 illustrates the general mechanism of anti-biofilm activity of EOCs against bacteria.

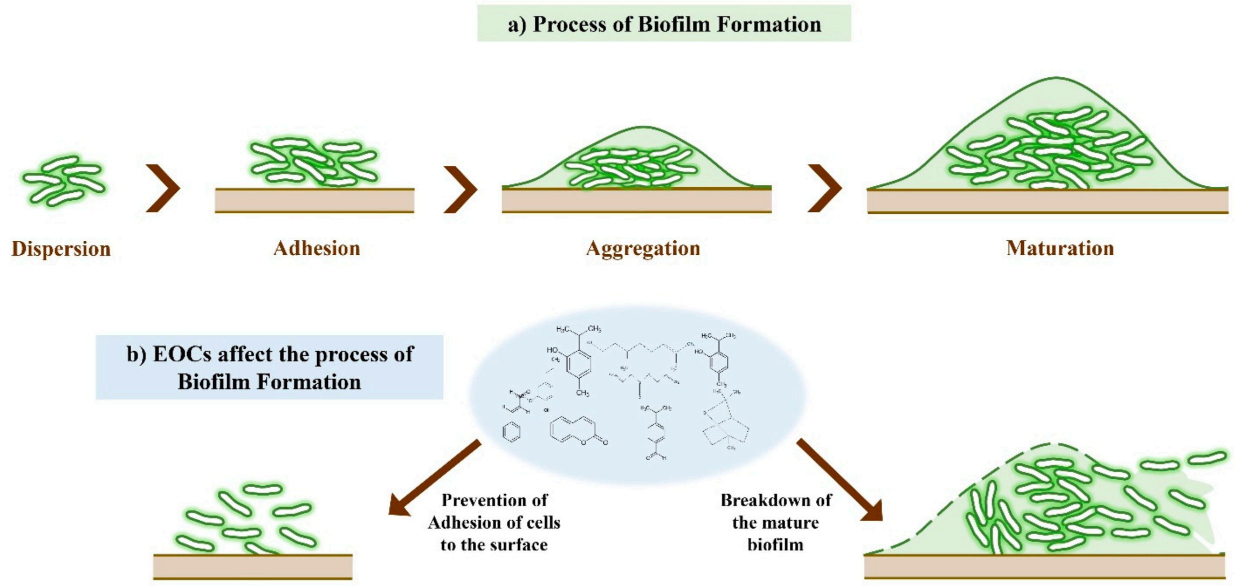


Figure 2. Illustration of anti-biofilm activity of EOCs.

Inhibition of important metabolic activity**:** EOCs exhibit varying effects on a diverse array of enzymes depending on their functional groups.

Both EO and EOCs have been demonstrated to inhibit various enzymes involved in cellular processes such as protein and nucleic acid biosynthesis, ATP synthesis, amino acid metabolism, the citric acid cycle, and glycolysis aiming to inhibit pathogen growth. The EOCs present in cloves, cinnamon, sage, and nutmeg oils inhibit histidine, ornithine and lysine decarboxylase, where cinnamaldehyde and eugenol exhibit the highest effectiveness against these enzymes in *Enterobacter aerogenes* (Wendakoon and Sakaguchi, 1995). A recent study by Vimal et al. indicates that eugenol is effective against L-Asparaginase of *Salmonella* Typhimurium (Vimal et al., 2018).

EOCs were studied on the inhibition of ATP synthase activity of *E. coli* where thymoquinone, quercetin, and resveratrol were shown to be more potent inhibitors than other components (Issa et al., 2019). The inhibition mechanism as well as the potency of the EOCs varies depending on the interaction between residues of the enzyme and functional groups of the compounds (Ahmad et al., 2013; Issa et al., 2019). For instance, the effect of structural modulation of polyphenolic compounds on the inhibition of *E. coli* ATP synthase was studied by Ahmad et al. in 2012. Their findings indicate that structural modifications of polyphenols can inhibit *E. coli* ATP synthase to varying degrees (Ahmad et al., 2012). These modifications resulted in augmented inhibition with both natural and modified polyphenols showing inhibitory effects on ATP synthesis in *E. coli* (Ahmad et al., 2012) (Figure 3).

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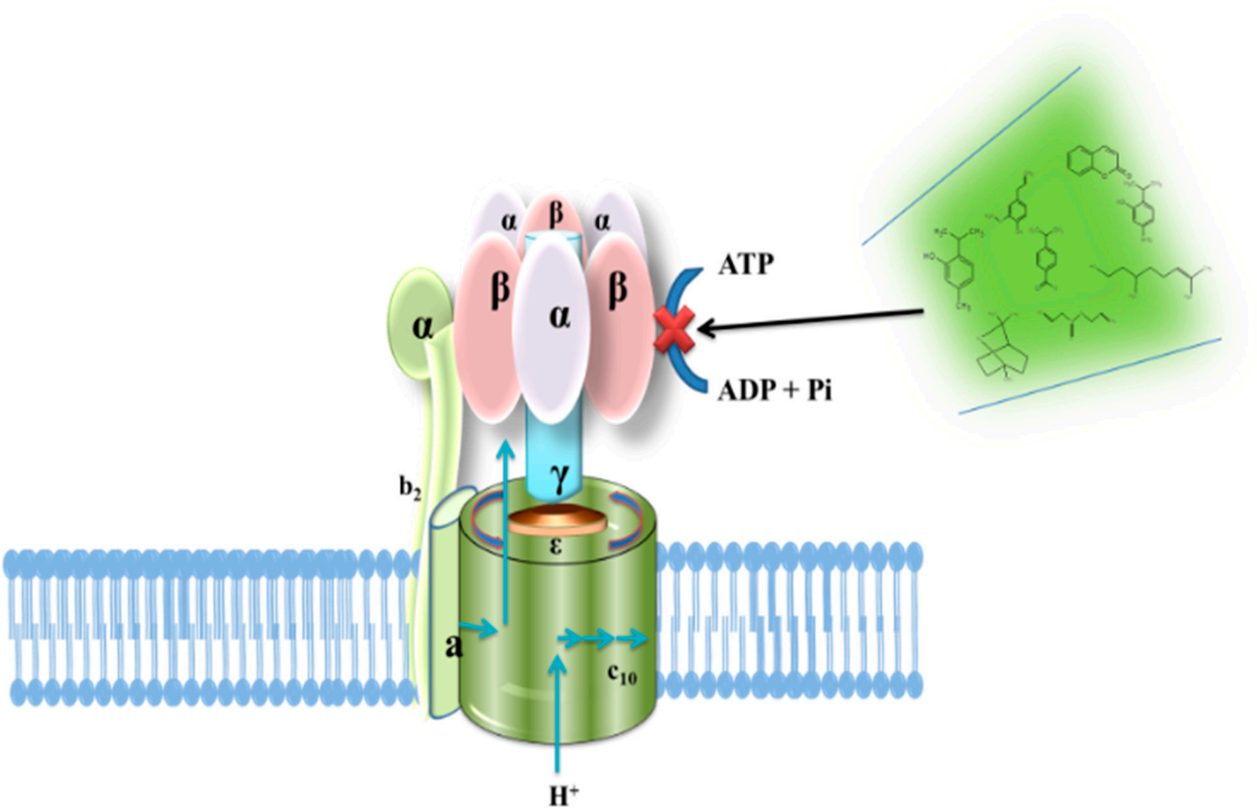

Figure 3. Illustration of ATP synthase inhibition by various EOCs.

Lately, after treated with linalool, a significant changes in metabolites attributed to amino acid metabolism, central carbon metabolism, lipid metabolism, nucleic acid metabolism were observed in *L. monocytogenes* (He et al., 2022). This result indicates a promise towards utilization of linalool preventing bacterial contamination by *L. monocytogenes* in the food industry (He et al., 2022).

A study by Medina et al. revealed that the essential oil components thymol and carvacrol interact with topoisomerase IV, a key enzyme in *Salmonella* essential for DNA replication, thereby disrupting critical cellular processes (Rochín-Medina et al., 2023). Earlier Cox et al had shown that when *E. coli* cells were treated with carvacrol, the glycolytic pathway was modified, glucose accumulated and there was a shift from respiration to fermentation (Cox et al., 1998). Later, subsequent exposure of *E. coli* to cinnamaldehyde induced the accumulation of stress-associated metabolites, including indole, alkanes, alcohols, acids, esters, and dimethyl disulfide (Hossain et al., 2013) Essential oil component from clove oil has been shown to inhibit DNA synthesis in *S. aureus* (Xu et al., 2016). Another study by Song et al. found that treatment with Mandarin essential oil from *Citrus reticulata* L. led to a decrease in protein concentration in *S. aureus*, indicating that essential oils and their components can significantly inhibit protein synthesis in bacteria (Song et al., 2020). Germacrene B, an essential oil component, has been shown to interact with the active sites of DNA and RNA polymerase, potentially disturbing the cell replication process (de Souza Moura et al., 2020). Essential oil from ginger has also been seen as a potential inhibitor of the expression of certain genes that play vital roles in bacterial energy metabolism, the tricarboxylic acid cycle, cell membrane-related proteins, and DNA metabolism (Wang et al., 2020). According to Cui et al., oregano essential oil can alter the structure of DNA, thus interfering with the replication process (Cui et al., 2019). Additionally, the main component of oregano essential oil, carvacrol, can form chimeras with DNA and inhibit the expression of the *pvl* gene, which is important for virulence in methicillin-resistant *Staphylococcus aureus* (MRSA) (Cui et al., 2019). Thymol causes

DNA intercalation and leads to the accumulation of reactive oxygen species, eventually causing damage to DNA structure and functionality (Khwaza and Aderibigbe, 2025; Liu et al., 2020).

Inhibition of flagella synthesis, Motility and Cellular Adhesion: EOCs are also involved in modulating virulence related gene expression. A thorough microarray-based gene expression study in *Salmonella* reveals significant downregulation of genes associated with chemotaxis, motility, and adherence to host cells by both eugenol and transcinnamaldehyde (Kollanoor Johny et al., 2017). It was also revealed that trans-cinnamaldehyde, eugenol, thymol and carvacrol at their sub-MIC level downregulate propanediol and ethanolamine utilization in *Salmonella* spp. (Kollanoor Johny et al., 2017). The aforementioned metabolisms have direct impact on *Salmonella* pathogenesis and virulence (Bhalerao et al., 2025; Jakobson and Tullman-Ercek, 2016; Prentice, 2021). In a study with *Campylobacter jejuni*, the transcinnamaldehyde has been shown to be effective in reducing the expression of genes coding for motility (*fliA*) and attachment (*cadF*). Whereas, carvacrol and eugenol reduce flagella motor function (*motA*) and surface attachment (*cadF*). Eugenol also reduces toxin production by reducing expression of the corresponding genes (*cdtA* and *cdtB*) in *C. jejuni* (Upadhyay et al., 2017). Transcinnamaldehyde inhibits type I fimbriae by suppressing transcription of *fimA*, *fimZ*, *fimY*, *fimH* and *fimW* in *Salmonella* Typhimurium (Yin et al., 2022). Transcinnamaldehyde also downregulates regulatory T1F of *Salmonella* and reduces the ability of the bacteria to adhere to the cells (Yin et al., 2022).

Carvacrol and thymol are shown to downregulate the genes related to motility (*fimH*), adherence and cellular aggregation (*csgD*), and exopolysaccharide production (*pgaC*) in *E. coli* and in *S. aureus* (Martínez et al., 2023). Carvacrol also induces Heat Shock Protein 60 (HSP60) in *E. coli* O157:H7 and inhibits flagellin synthesis (Burt et al., 2007). Differential proteomics analyses indicate down regulation of two proteins viz. FlaA and FliM, related to flagellum assembly in *L. monocytogenes* after treatment of thymol, a major component of thyme essential oil (Sarengaowa et al., 2019).

Stability and Toxicity of EOCs

It is well documented that EOCs are known to be sensitive to light, temperature and other environmental factors once they deprived from their plant source which results into oxidation, chemical transformation and polymerization depending on their chemical nature (Dajic Stevanovic et al., 2020; Khwaza and Aderibigbe, 2025; Turek and Stintzing, 2013; Wang et al., 2024). Additionally, several challenges persist, including cytotoxicity at high concentrations, chemical instability, poor water solubility, and variable pharmacokinetics. Double-bonded compounds are more likely to undergo autoxidation due to the resonance-stabilized radicals produced by hydrogen atom abstraction (Dajic Stevanovic et al., 2020). Light enhances the breakdown of monoterpenes, catalyzes intramolecular isomerization events or trans-cis conversions in monoterpenes, and increases the rate of autoxidation and formation of alkyl radicals (Turek and Stintzing, 2013). Volatiles are thermally unstable and prone to rearrangement at high temperatures. Thermal degradation of terpenes is categorized into four types of oxidative reactions: breakage of double bonds, epoxidation, dehydrogenation to aromatic systems, and allylic oxidation to alcohols, ketones, and aldehydes (Dajic Stevanovic et al., 2020; Ingram, 1999). All these consequently reduce the quality of the EOCs. In a study, Michelies and co-workers examined the in vitro degradation and in vivo passage kinetics of four EOCs in the digestive tract of piglets. The four EOCs, namely carvacrol, thymol, eugenol, and trans-cinnamaldehyde were found to be stable in the stomach, even in an acidic environment, followed by minimal degradation in jejunal simulations and substantial degradation of eugenol and trans-cinnamaldehyde in caecal simulation studies (Michiels et al., 2008). The degradation of these two compounds may be due to microbial oxidation of the side chains to carboxylic acids prior to hydroxylation and cleavage of the benzene ring (Michiels et al., 2008; Shimoni et al., 2002). Perhaps, these compounds which were not degraded in the proximal areas of the intestinal tract of the piglets, must be absorbed in these areas (Michiels et al., 2008). Some portion of these compounds which was not absorbed in the stomach and small intestine is may be due to their interaction with organic matter (Michiels et al., 2008; Tavvabi-Kashani et al., 2024). In the above study, all the EOCs were mixed with the corn starch before feeding the piglets which suggests formulation can be made in such a way that it can increase the solubilization and bioavailability of the EOCs (Michiels et al., 2008).

Although, in vitro assays generally classify essential oils and their components as antioxidants, yet recent studies show that within eukaryotic cells, they can act as prooxidants, disrupting cell membranes and organelles (Bakkali et al., 2008). The high lipophilicity endows most EOCs with a remarkable ability to penetrate cellular components and other tissues (Akhmouch et al., 2022; Chi et al., 2023; Hou et al., 2021; Sadgrove and Jones, 2019). However, their effects vary with type and concentration, often leading to cytotoxicity at higher concentration and prolong exposure (Fujisawa and Murakami, 2016; Latorre et al., 2025).

Strategies to Enhance the Efficacy and Extended Shelf Life of EOCs

Although EOs and EOCs exhibit remarkable potential to serve as natural preservative in food systems, their practical application is constrained by intense aroma, high chemical reactivity, hydrophobicity leading to low solubility, poor stability, and potential adverse interactions with food components such as carbohydrates, fats, and fatty acids, which alter organoleptic properties. To overcome these limitations, several technological approaches have been developed to improve the preservative efficacy of the components (Maurya et al., 2021). Micro and Nano-encapsulation has become one of the promising strategies for increasing the overall efficiency of the EOCs. Encapsulation helps in decreasing volatility and provides protection from environmental interactions (e.g., light, oxygen, moisture, pH), thus enhancing physical stability of EOCs (Chouhan et al., 2017b; Ravi Kumar, 2000). Various encapsulating materials have been used and still research is currently in progress to check which material is more effective. Recently, use of cyclodextrins to encapsulate the essential oil and their components has been increasingly popular (Kfoury et al., 2019; Marques, 2010). Cyclodextrin is a cyclic carbohydrate derived from starch, which not only enhances the efficacy of the EOCs but also mask their unpleasant smell and taste (Marques, 2010). The formation of complex between cyclodextrin and the encapsulated molecule is done at molecular level with proper orientation as per the spatial requirement and in a lock and key manner (Marques, 2010). This complex has been shown to exhibit extended stability. Thymol, carvacrol and eugenol were encapsulated in the β-cyclodextrin by supercritical CO_2 technique resulted into reduced volatility, oxidation and degradation of the EOCs (Locci et al., 2004; Marques, 2010) (Figure 4). In another study, β-cyclodextrin forms inclusion complex with trans-cinnamaldehyde and thymol. Cinnamonaldehyde and thymol interact with β- cyclodextrin through hydrogen bonding and hydrophobic interactions, resulting in a stable inclusion complex (Ponce Cevallos et al., 2010). Furthermore, the controlled release of the EOCs can also be done by modifying their formulations with cyclodextrin (Ponce Cevallos et al., 2010). Eugenol and trans-cinnamaldehyde entrapped in poly (DL-lactide-co-glycolide) (PLGA) nanoparticles have shown to exhibit more enhanced antibacterial activity against *Salmonella spp.* and *Listeria spp.* with concentration ranging from 20 to 10 mg/ml (Gomes et al., 2011). Nanoparticles functionalized with EOCs is another alternative to entrapment strategy. These have shown enhanced antimicrobial activity against multidrug-resistant pathogens, attributed to improved chemical stability and solubility, reduced volatility, and protection against degradation of active components (Chouhan et al., 2017b). Carvacrol and eugenol-grafted chitosan nanoparticles have been shown to have higher antibacterial activity than the individual components. The encapsulated EOCs exhibit thermal stability, higher antioxidant activity and lower cytotoxicity as compared to those of the pure eugenol and carvacrol, underscoring greater potential to utilize as food preservative (Chen et al., 2009; Feyzioglu and Tornuk, 2016). Synthesis of EOC nano-emulsion has been carried out in order to address instability and volatility of EOCs. To address this issue, Anand Prakash et al. synthesized nano-emulsions of linalool, which demonstrated enhanced stability and efficacy. Their study revealed that the nano-emulsions of linalool exhibited a potency 12% greater than linalool alone (Prakash et al., 2019). Recently, chemical modification in various EOCs has been shown to enhance antibacterial potency against food spoilage bacteria and multidrug-resistant pathogens (Dong et al., 2024; Malheiro et al., 2019; Maurya et al., 2021; Swain et al., 2021; Vimal et al., 2018). Vimal and coworkers had shown that a derivative of eugenol (R)-1-((2-(4-allyl-2-methoxyphenoxy) ethyl) amino)-1-(2-chlorophenyl) propane-2,2-diol] is more effective against L-Asparaginase of *Salmonella* Typhimurium than eugenol alone (Vimal et al., 2018). Lately, several chlorinated and allyl phenyl ether derivatives have been studied for their effectiveness against various food poisoning bacteria (Pinheiro et al., 2018), accentuating their potential in using food preservation strategies.

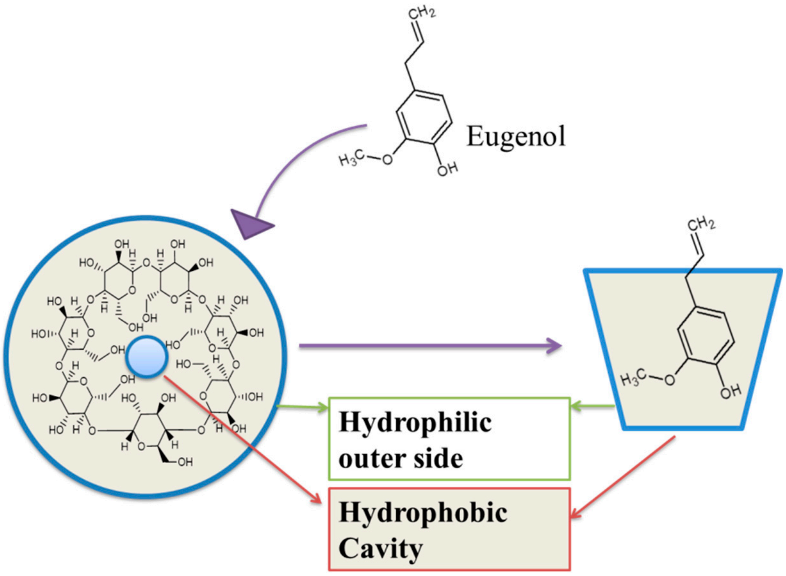

Figure 4. Illustration of β-Cyclodextrin encapsulation of Eugenol.

Comparison Between Synthetic Preservatives and EOC and Sustainable Practices

Synthetic preservatives, including benzoic acid, sorbic acid, propionic acid, nitrites, and sulfites remain integral to food preservation owing to their validated antimicrobial activity and cost-effectiveness (Carocho et al., 2014). Propionic acid suppresses microbial growth by lowering intracellular pH, whereas benzoic acid compromises cell membrane integrity and inhibits key metabolic enzymes (Jang et al., 2025). On the other hand, sorbic acid is extensively employed in the food industry to inhibit the growth of molds, yeasts, and other fungi (Jang et al., 2025). Nitrites, particularly sodium nitrite, serve as the primary preservatives in cured meats, specifically inhibiting the growth of *Clostridium botulinum* and preventing botulinum toxin production (Shakil et al., 2022). Sulfites are effective at controlling the growth of bacteria, yeasts, and molds and are employed in preserving beverages and wine (Dordevic et al., 2023). Although, synthetic molecules are approved and regulated by international regulatory systems such as the USA FDA, EU (Regulation (EC) No 1333/2008), and regulatory bodies of various Asian countries; however, there is ongoing debate concerning the potential health risks linked to long term consumer exposure to such molecules (Wang et al., 2024). It is suggested that use of synthetic chemical preservatives poses potential health risks through residue accumulation and migration in the body (Zhang and Rhim, 2022). Also, their prolonged use may contribute to the emergence of drug-resistant bacterial strains (Yang et al., 2023). The utilization of natural preservative agents, such as essential oils (EOs) and their components (EOCs) as substitutes for synthetic compounds has been encouraged in recent years; however, the use of natural antimicrobial agents is not devoid of limitations. A key limitation lies in the variability of their composition, which may result in inconsistent effectiveness and safety. Essential oils preservatives also exhibit allergenic properties, especially in individuals sensitive to plant-derived compounds, potentially causing adverse reactions (Türkmenoğlu and Özmen, 2021). Another limitation of natural antimicrobial agents is their narrow spectrum of activity, which can render them less effective than synthetic preservatives against specific microorganisms. Furthermore, determining the appropriate dosage of natural preservatives for effective use can be challenging, and excessive amounts may cause toxicity or adverse side effects (Bakkali et al., 2008; Sanchez Armengol et al., 2021). Additionally, EO and EOCs may reduce significantly organoleptic impact of the food matrix (Maurya et al., 2021). Therefore, when choosing between essential oil over synthetic agents, it is essential to consider factors such as the product's intended use, the preservative's efficacy and safety, and the sustainability of its source.

Future Directions

Essential oil components (EOCs) are increasingly acknowledged as promising natural substitutes for synthetic food preservatives, attributable to their broad-spectrum antimicrobial efficacy, antioxidant capacity, and antigenotoxic potential. This review highlights the antibacterial activity of EOCs, their mechanisms of action, toxicity and stability and strategies to enhance the efficacy and extended shelf life of EOCs. Nevertheless, several critical challenges persist with the practical application of EOCs, namely adverse sensory effects, stability limitations, compositional variability, regulatory constraints, and the risk of toxicity at elevated doses. Efficacy of the EOCs constantly diminishes in complex food matrices, where interactions with lipids, proteins, and carbohydrates hinder their bioavailability and compromise antibacterial activity (Diogo Gonçalves et al., 2025; Wang et al., 2024). Further, at higher concentrations, EOCs often impart undesirable organoleptic effects, as the altered profile excludes certain compounds that contribute to the food's sensory characteristics (Smith-Palmer et al., 2001), suggesting the need to optimize the combinational dosage between specific EOCs at varied food matrices. An AI-based mathematical modeling could be implemented to determine correct combination and dosages of EOCs in different types of food system (Wang, 2020). Although several strategies to enhance the efficacy and bioavailability of essential oil compounds, such as nano-emulsion formation and chemical derivatization have been reported, their application remains limited due to the absence of safety approvals and the insufficient characterization of allergenicity or toxicity profiles (Khan et al., 2023). Given their multitarget attributes and natural origin, the EOCs are unlikely to develop resistance development (Iskandar et al., 2025); however, a recent gene expression studies in *Salmonella* spp. revealed upregulation of the acridine efflux pump genes (*acrA* and *acrB*), and multiple antibiotic resistance protein (*mar*) genes upon treatment of transcinnamaldehyde and eugenol (Kollanoor Johny et al., 2017). The application of EO and EOCs as food preservative agents therefore must be regulated through defined concentration thresholds and labeling obligations, which could be guided by a comprehensive assessment of each option's risks and benefits, along with its impact on food quality and sustainability.

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