

A comprehensive review of oregano (*Origanum vulgare* L.) essential oil: Physicochemical properties, antimicrobial activities, and applications in food safety

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ABSTRACT

Oregano (*Origanum vulgare* L.) essential oil (OEO) has attracted growing attention as a natural antimicrobial agent for modern food safety applications. This interest is driven by rising consumer demand for clean-label preservatives and the need to control foodborne pathogens. The OEO exhibits broad-spectrum antibacterial activity, primarily due to its high content of phenolic monoterpenes such as carvacrol and thymol. These compounds disrupt microbial cell membranes and metabolic functions, leading to leakage of cellular contents and cell death, even at relatively low concentrations. The physicochemical properties of OEO, with strong aroma, hydrophobicity, and volatility, enhance its antimicrobial activity but also present challenges in formulation and food compatibility. The OEO has been successfully incorporated into various food preservation strategies, including edible films and coatings, antimicrobial packaging, and vapor-phase treatments, to inhibit microbial growth and extend shelf life. However, its practical application is limited by sensory impacts at effective concentrations and instability caused by evaporation or degradation. To overcome these challenges, recent innovations have focused on controlled-release delivery systems like nano-encapsulation, emulsions, and biodegradable polymers to improve stability and performance. This review summarizes the antimicrobial mechanisms of OEO, evaluates its applications across diverse food systems, and discusses current limitations, innovative formulation strategies, and future directions for its application to enhance food safety.

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1. Introduction

Foodborne microbial contamination remains a serious public health threat and a significant challenge for the food industry. Bacterial pathogens are responsible for the majority of foodborne illness outbreaks and cases (Olsen et al., 2000), leading to substantial health and economic consequences. While conventional chemical preservatives and chlorine-based sanitizers are used to reduce microbial loads, they may produce toxic by-products (e.g., chlorinated organics) and face consumer resistance due to concerns over synthetic additives. Therefore, interest in natural antimicrobials from herbs and spices has increased, offering safer and more acceptable alternatives to enhance food safety (Oussalah et al., 2007). Essential oils, the aromatic and volatile plant extracts, have gained attention for their strong antimicrobial properties and potential use as food preservatives. Among them, OEO is widely studied for its effectiveness against foodborne pathogens.

Oregano (*Origanum vulgare* L.), from the mint family (Lamiaceae), produces essential oil rich in phenolic terpenoids (Leyva-López et al., 2017). The OEO typically contains high levels of carvacrol (60 - 80%) along with thymol, p-cymene, and γ -terpinene (Adebayo et al., 2013; Cattelan et al., 2018). Carvacrol is the major active component and is classified by the U.S. FDA as Generally Recognized as Safe (GRAS) (Fraj et al., 2019). Thymol, a structural isomer of carvacrol, also contributes to the oil's antimicrobial and antioxidant effects. The main antimicrobial mechanisms involve membrane disruption, leakage of cell contents, and enzymatic inhibition (Kolypetri et al., 2023). Numerous studies have confirmed OEO's antibacterial effects (Kim et al., 1995; Oussalah et al., 2007) and demonstrated

its effectiveness in vapor-phase systems (Chang et al., 2017; Kwon et al., 2017). It also inhibits fungi like *Aspergillus*, *Botrytis*, *Penicillium*, and *Z. bailii* (Hernández et al., 2023). However, OEO's volatility, poor water solubility, and strong aroma limit its direct use in foods (Santos et al., 2022). Encapsulation and delivery technologies have been investigated to overcome these issues (Liu et al., 2019; Hernández et al., 2023; Sirati et al., 2024), thereby enhancing OEO's stability, release control, and overall functionality in food preservation. This review distinguishes itself from prior works on oregano essential oil (OEO) by providing a comprehensive synthesis of its physicochemical properties, antimicrobial mechanisms, and practical applications in food safety, with a particular emphasis on recent advancements in delivery systems and their implications for overcoming formulation challenges. While previous reviews have explored OEO's phytochemistry, biological activities, and antimicrobial properties, they often focus on specific aspects, such as chemical composition or in vitro efficacy, with limited integration of practical food safety applications. This manuscript uniquely bridges these domains by critically evaluating OEO's role in diverse food systems, meat, seafood, produce, and active packaging, while addressing current limitations like sensory impact and matrix interactions. Furthermore, it highlights cutting-edge innovations, such as nanoemulsions, biopolymeric nanoparticles, and smart release systems, which enhance OEO's stability and efficacy, offering insights into scalable solutions for clean-label preservation. By incorporating recent studies and providing a holistic perspective on OEO's potential, this review serves as a timely resource for researchers and industry professionals aiming to advance natural antimicrobial strategies in food safety.

2. Physicochemical Properties of Oregano Essential Oil

OEO is a volatile, aromatic, and hydrophobic oil rich in monoterpenoid compounds, particularly phenolic monoterpenes like carvacrol and thymol (Fraj et al., 2019; Santos et al., 2022). Carvacrol is typically the dominant component, comprising 50 - 70% of the oil, while thymol is the second major phenolic (Noshirvani et al., 2017; Radünz et al., 2021). In *O. vulgare*, a composition with 68.7% carvacrol has been reported, along with 12.5% p-cymene, 4.7% γ -terpinene, and minor compounds such as trans-caryophyllene (5%) and β -myrcene (de Almeida et al., 2023). These components contribute to OEO's strong antimicrobial and antioxidant properties. However, other oregano chemotypes may be thymol-dominant, depending on genetics, origin, and environmental factors.

A commercial oil containing 67% carvacrol confirmed this variability (Božik et al., 2017). Due to its volatility and hydrophobicity, OEO requires careful handling to preserve bioactivity. Although it can impart a slight tint to transparent films or gels, its color effect is minimal at food-safe concentrations ($\leq 1\%$) (Pan et al., 2024). Table 1 highlights how OEO's potent natural activity also presents formulation challenges, as even small changes in the carvacrol-to-thymol ratio can influence efficacy, stability, and sensory impact. The discrepancy between the broader 20 - 75% carvacrol range in Table 1 and the 60 - 80% range in some introductions stems from this variability, where the wider range accounts for diverse oregano sources (e.g., wild vs. cultivated, different species like *Poliomintha longiflora*), while the narrower range reflects standardized, high-carvacrol chemotypes used in commercial or therapeutic applications.

Table 1. Physicochemical parameters of oregano essential oil¹

Parameter	Value/Description
Density (20°C)	0.90 - 0.95 g/mL
Color	Colorless to light yellow or brown, depending on fractionation
Odor	Strong, pungent, herbaceous; softer in terpenic fractions
Refractive index (20°C)	1.49 - 1.50
Major constituents	Carvacrol (20 - 75%), thymol (0 - 20%), p-cymene (5 - 15%), γ -terpinene (5 - 30%), β -caryophyllene ($\leq 5\%$)
Boiling points	Carvacrol: 236°C; thymol: 232°C; p-cymene: 177°C; γ -terpinene: 183°C
Solubility in water	Practically insoluble; hydrophobic
Appearance & aroma	Clear pale yellow to amber oil; strong herbaceous, spicy aroma
Stability	Good thermal stability up to 230°C; antioxidant-rich, but prone to volatilization

¹Sources: Kim et al. (1995); Seydim & Sarikus (2006); Liu et al. (2019); Mora-Zúñiga et al. (2022).

3. Antimicrobial Mechanisms of Oregano Essential Oil

The OEO exhibits a multifaceted mode of action against microorganisms, targeting both structural components and physiological processes of cells. Its broad-spectrum efficacy is largely attributed to the presence of phenolic terpenoids (especially carvacrol and thymol) which can penetrate microbial cell envelopes and disrupt vital functions.

3.1. Disruption of microbial cell membrane integrity

The hydrophobic components of OEO can integrate into bacterial lipid membranes, increasing membrane fluidity and permeability, which disrupts integrity and causes leakage of vital intracellular contents (Santos et al., 2022). Exposure to OEO or carvacrol leads to the release of ions, ATP, and nucleic acids, collapsing the proton motive force and resulting in cell death. Carvacrol disrupts the outer membrane of Gram-negative bacteria by releasing lipopolysaccharides and increasing cytoplasmic membrane permeability (Burt & Reinders, 2003; Seydim & Sarikus, 2006). In vitro studies have confirmed carvacrol's potent membrane-disruptive effects, including cell lysis and leakage of cellular material (Kim et al., 1995). These effects are largely due to interference with the phospholipid bilayer by compounds like carvacrol and thymol. A mechanistic study by Oussalah et al. (2007) showed that Spanish oregano oil severely damaged the membranes of *E. coli* O157:H7 and *Listeria monocytogenes*, supporting membrane disruption as the main bactericidal mechanism (Oussalah et al., 2007). Generally, Gram-positive bacteria are more susceptible to OEO than Gram-negatives, due to the latter's outer membrane acting as a barrier

(Oussalah et al., 2007; Delcour, 2009). However, OEO at sufficient concentrations can still permeabilize Gram-negative cells (Seydim & Sarikus, 2006). For example, *E. coli* O157:H7 and *Salmonella typhimurium* showed higher MICs than *Staphylococcus aureus* (Oussalah et al., 2007). In tuna applications, OEO significantly reduced bacterial growth and biogenic amine formation, confirming its preservative potential in seafood products (Wang et al., 2022).

3.2. Interference with cellular metabolism and homeostasis

Beyond damaging microbial membranes, OEO also disrupts metabolism and cellular homeostasis. Once membrane integrity is lost, OEO can dissipate the proton gradient and membrane potential, reducing ATP synthesis and triggering an energy collapse. Even at sub-lethal concentrations, OEO components may penetrate cells and interfere with intracellular targets. These constituents inhibit enzymes involved in energy production, such as those in the TCA cycle and ATP synthesis, and affect macromolecule biosynthesis (Kim et al., 1995). This enzymatic disruption leads to toxic intermediate accumulation or loss of vital metabolites. Oregano phenolics also impair respiratory chain enzymes and those involved in cell wall synthesis, reducing growth and viability (Kim et al., 1995). OEO further disturbs pH balance and ion homeostasis, causing cytoplasmic acidification and protein dysfunction. Cells exposed to carvacrol often alter membrane fatty acid composition, indicating stress responses and homeostatic disruption (Santos et al., 2022). Some OEO components may even damage DNA or interfere with nucleic acid synthesis (Kim et al., 1995). As shown in Table 2, OEO exerts broad antimicrobial effects on Enterobacteriaceae.

Its multi-targeted actions, ATP depletion, biosynthesis inhibition, oxidative stress, make resistance development difficult (Bharadwaj et al., 2022) and explain its continued efficacy against antibiotic-resistant strains (Selim, 2011). OEO's efficacy stems from its ability to disrupt microbial cell membranes, increasing permeability and causing leakage of cellular contents, with carvacrol's hydrophobic nature enabling deep penetration into lipid bilayers, leading to proton motive force collapse and cell death. Thyme oil, rich in thymol, shares similar membrane-disruptive properties but is slightly less effective against Gram-negative bacteria due to lower carvacrol levels, while cinnamon oil, driven by cinnamaldehyde, targets microbial enzymes and cell wall synthesis, offering consistent inhibition

but less pronounced membrane disruption than OEO, and clove oil, with eugenol as its primary component, disrupts membrane integrity and inhibits energy metabolism but shows moderate activity, less potent than OEO's broad-spectrum effects (Peñalver et al., 2005; Oussalah et al., 2007). OEO's additional mechanisms, such as quorum sensing inhibition and biofilm disruption, particularly against *Pseudomonas* and *Listeria*, further enhance its superiority, as seen in niosome-encapsulated formulations that amplify anti-biofilm effects by 2 - 4 times (Sirati et al., 2024). These comparative insights highlight OEO's multifaceted antimicrobial action, making it a leading candidate for food safety applications compared to other essential oils.

Table 2. Antimicrobial activity of essential oils against *Enterobacteriaceae*

Essential oil	Most effective against	MIC range (μL/mL)	Antimicrobial effectiveness
Oregano	<i>E. coli</i> , <i>Salmonella</i> spp., <i>Proteus</i> spp.	0.25 - 1.0	Most potent; carvacrol-rich; broad-spectrum inhibition
Thyme	<i>E. coli</i> , <i>Enterobacter</i> spp.	0.5 - 1.0	Strong antimicrobial; high thymol content
Cinnamon	<i>Klebsiella</i> spp., <i>Salmonella</i> spp.	0.5 - 1.5	Effective; consistent inhibition
Clove	<i>E. coli</i> , <i>Proteus</i> spp.	1.0 - 2.0	Moderate activity; eugenol as main compound
Rosemary	Limited strains	2.0 - 4.0	Least effective; low activity against most strains

Source: Peñalver et al. (2005). MIC: minimum inhibitory concentration.

3.3. Inhibition of quorum sensing and biofilm formation

A key factor in microbial persistence in food environments is biofilm formation and quorum sensing (QS) communication. Oregano essential

oil has shown strong anti-biofilm activity, partly due to its ability to disrupt QS signaling and inhibit biofilm development. It interferes with the expression of genes involved in bacterial adhesion and exopolysaccharide production.

For example, a niosome-encapsulated OEO formulation enhanced anti-biofilm efficacy by 2 - 4 times and downregulated key biofilm-related genes (Sirati et al., 2024). OEO likely blocks QS receptors or inhibits the synthesis of QS molecules. In practice, OEO vapors reduced bacterial contamination on food-contact surfaces, particularly polypropylene, with decreasing effectiveness on stainless steel and glass (Pinto et al., 2024). Sirati et al. (2024) showed that niosome-delivered OEO not only prevented biofilm formation but also reduced existing biomass, confirming its role in QS

disruption (Sirati et al., 2024). OEO’s membrane-disrupting action may also facilitate antimicrobial penetration into biofilms. Additionally, its phenolics may oxidize or inactivate signaling molecules. Though the exact quorum-quenching mechanisms are still under study, OEO has been effective against *Pseudomonas* spp. and *Listeria* (Selim, 2011; Sirati et al., 2024). Biopolymeric nanoparticles loaded with OEO demonstrated strong antimicrobial activity, supporting its promise in food preservation and medical applications (Table 3) (Romero-Montero et al., 2024).

Table 3. Essential oil-loaded biopolymeric nanoparticles for microbial control

Nanoparticle type	Essential oil	Target pathogens/ biofilms	Results
Chitosan-based NPs	Oregano, Cinnamon	Tea, <i>E. coli</i> , <i>S. aureus</i> , <i>L. monocytogenes</i>	Strong antimicrobial and anti-biofilm activity; biodegradable and mucoadhesive
Alginate-based NPs	Thyme, Clove	<i>Pseudomonas</i> , <i>Candida</i> spp.	Controlled release; enhanced stability; effective against mixed-species biofilms
Lipid-based NPs (Nanoliposomes, Niosomes)	Oregano, Citral	<i>L. monocytogenes</i> , <i>P. aeruginosa</i>	Improved membrane interaction and delivery; reduced toxicity
Hybrid polymeric NPs	Various essential oil combinations	Multidrug-resistant strains	Synergistic antimicrobial effects; potential for food and biomedical use

Source: Romero-Montero et al. (2024).

Importantly, the anti-biofilm property of OEO enhanced food safety by targeting the modes of growth that often protect pathogens from cleaning processes and preservatives. By preventing biofilm formation, OEO makes microbial contaminants more susceptible to removal and inactivation in food processing environments.

4. Applications of Oregano Essential Oil in Food Safety

Oregano essential oil’s broad-spectrum antimicrobial activity has spurred extensive research into its use as a natural preservative in foods. Researchers have evaluated OEO in a variety of food systems and preservation

strategies, including direct incorporation into foods, surface treatments, and active packaging. It has demonstrated effective inhibition of many foodborne microbes, but its practical application must balance microbial efficacy with sensory and regulatory considerations. This section reviews the evidence on OEO's antimicrobial performance in food-relevant contexts, organized by application area.

4.1. Antimicrobial efficacy in model systems and *in vitro* studies

Initial studies demonstrated OEO's strong antimicrobial activity through *in vitro* assays. In a screening of 28 plant essential oils against *E. coli* O157:H7, *Salmonella* typhimurium, *Staphylococcus aureus*, and *Listeria monocytogenes*, oregano oil from *O. heracleoticum* and *O. compactum* ranked the most effective, with MICs $\leq 0.05\%$ (v/v) for all four pathogens (Oussalah et al., 2007). Carvacrol, OEO's main component, showed potent bactericidal effects against *E. coli*, *Salmonella*, *Listeria*, *Vibrio*, and more, outperforming other terpenoids (Kim et al., 1995). It completely killed *Salmonella* and *Vibrio* at 250 $\mu\text{g/mL}$, while other compounds like linalool were far less effective. Both carvacrol and thymol have been shown to inhibit numerous foodborne pathogens, including *B. cereus*, *S. aureus*, *Shigella*, and *V. cholerae* (Adebayo et al., 2013). The action is attributed to membrane disruption and proton gradient collapse. In lab media, even 0.25 - 0.5 mg/mL of OEO compounds can fully eliminate *E. coli* and *S. Typhimurium* (Kim et al., 1995). Though food matrices may reduce efficacy, baseline tests confirm OEO's exceptional antimicrobial potential, often rivaling thyme, clove, and cinnamon oils (Oussalah et al., 2007; Gutierrez et al., 2009).

4.2. Use of oregano essential oil in meat and poultry products

Meat and poultry products are highly prone to spoilage and pathogen contamination, making them ideal targets for oregano essential oil (OEO) as a clean-label antimicrobial. Direct application, such as marination or incorporation into ground meat, has shown promising results. For example, OEO (0.5 - 1.0%) significantly inhibited *E. coli* O157:H7 and Vancomycin-Resistant Enterococcus (VRE) in minced beef stored at 7°C over 14 days, reducing microbial loads compared to controls (Selim, 2011). Similarly, feta cheese treated with OEO showed reduced VRE and *E. coli* levels during storage. In trout fillets, a combination of 0.2% OEO, salt, and vacuum packaging extended shelf life by inhibiting spoilage bacteria like *Photobacterium phosphoreum* (Frangos et al., 2010). On meat surfaces, OEO effectively targets pathogens such as *Listeria monocytogenes* and *Salmonella* (Oussalah et al., 2007). While direct brushing or tumbling with OEO can reduce spoilage, strong flavors may limit doses (Santos et al., 2022). In minced pork, OEO at 0.02 - 0.04% (v/v) reduced *L. monocytogenes* by up to 2.5 log CFU/g (Guo et al., 2024). Encapsulated OEO in coatings or films, like chitosan-oregano wraps on chicken breast, suppressed *Campylobacter* and *Salmonella* during chilled storage (Fraj et al., 2019; Shen et al., 2022). These studies highlight OEO's versatility in meat preservation strategies.

4.3. Applications in seafood and fish products

Frangos et al. (2010) demonstrated that OEO could extend the shelf life of fresh fish, especially when combined with other preservation methods (Frangos et al., 2010). A recent study introduced niosome-encapsulated OEO, enhancing its antimicrobial and anti-biofilm activity against

fish-borne pathogens like *Aeromonas* and *Pseudomonas* spp., with a 2 - 4-fold increase in efficacy (Sirati et al., 2024). These 219 nm vesicles improved OEO's stability, dispersion, and release in aquatic environments. The formulation was also shown to be biocompatible and non-toxic to mammalian cells. Additionally, OEO effectively inhibited *Photobacterium phosphoreum* in fish broth and cold-smoked salmon when applied as a wash or dip (Mejlholm & Dalgaard, 2002).

4.4. Oregano oil in fruits, vegetables, and minimally processed foods

essential oil has gained attention as a natural antimicrobial for fresh produce, particularly minimally processed fruits and vegetables that often harbor *E. coli* O157:H7, *Salmonella*, and *Listeria* (Santos et al., 2022). Application methods include dipping, spraying, or incorporating OEO into edible coatings. In one study, iceberg lettuce dipped in oregano oil (alone or with rosemary oil) showed significant reductions in *L. monocytogenes*, *Y. enterocolitica*, and *A. hydrophila* (Xylia et al., 2021), while oregano-thyme mixtures also suppressed *E. coli* and spoilage flora on lamb's lettuce (Sirati et al., 2024). Combined with organic acids, OEO reduced *Salmonella* on tomatoes without compromising quality. Nanoemulsion washes and modified atmosphere packaging (MAP) with oregano oil and citral helped preserve lettuce and reduce pathogens like *E. coli* and *S. Typhimurium* (Hao et al., 2021). Hao et al. (2021) reported that 3 µL/L OEO vapor in modified atmosphere packaging decreased microbial growth and maintained lettuce quality for 10 days at 5°C (Hao et al., 2021). OEO also disrupts bacterial

biofilms, and its vapor form, released via sachets or coated films, offers sustained antimicrobial action with minimal sensory changes (Cho et al., 2020). This approach has been applied to cherry tomatoes and is suitable for other produce like salads and sprouts (Kwon et al., 2017). Effective concentrations in produce washes range from 0.1 - 0.5% (Frangos et al., 2010).

4.5. Active packaging and edible coating incorporating oregano oil

Oregano essential oil is promising for active food packaging, edible films, coatings, and encapsulation. Embedding 1 - 4% OEO into whey protein isolate films, Seydim & Sarikus (2006) found that ≥ 2% OEO fully inhibited *E. coli* O157:H7, *S. aureus*, *Salmonella enteritidis*, and *L. monocytogenes* in agar assays (Seydim & Sarikus, 2006). Compared to garlic or rosemary oil, the 2% oregano-oil film showed superior inhibition zones. A soybean polysaccharide film with OEO in a Pickering emulsion improved oil retention and extended antimicrobial activity against *E. coli* and *Staphylococcus* (Liu et al., 2019). Another film based on cassava starch-chitosan with OEO and citric acid blocked *Zygosaccharomyces bailii* yeast growth (Hernández et al., 2023). Shu et al. (2024) showed that OEO vapor prolonged kai lan shelf life under ambient and cold conditions (Table 4) (Shu et al., 2025). Guzmán-Pincheira et al. (2025) used alginate-chitosan films with OEO and observed enhanced activity against *L. monocytogenes* and *S. aureus*, with film thickness ranging from 37.7 - 38.2 µm (Guzmán-Pincheira et al., 2025). These findings support OEO-based packaging as an effective strategy for microbial control in vegetables.

Table 4. Effect of oregano essential oil vapor on kai lan shelf-life

Treatment condition	Storage temperature	Shelf-life extension	Results
OEO vapor (active packaging)	22°C (ambient)	Extended from 3 to 7 days	Reduced microbial load; maintained visual quality and texture
OEO vapor (active packaging)	4°C (refrigerated)	Extended from 5 to 14 days	Delayed yellowing and spoilage; suppressed microbial growth
Control (no OEO)	Both conditions	3 days (ambient), 5 days (cold)	Faster spoilage, discoloration, and higher microbial counts

Source: Shu et al. (2025).

Beyond edible films, OEO has been incorporated into synthetic packaging like LDPE and PVA. Active films with OEO microcapsules in a soybean protein isolate/cellulose matrix significantly inhibited *E. coli* and *S. aureus* (Wang et al., 2022). Kwon et al. (2017) embedded OEO into PVA films for passive vapor release and found that storing cherry tomatoes with 2 - 3% OEO films for 7 days at 4 and 22°C suppressed *Salmonella*, molds, and mesophilic bacteria without affecting quality. Encapsulated OEO in polycaprolactone nanocapsules retained carvacrol for 60 days (Fraj et al., 2019). Fan et al. (2024) applied OEO-loaded zein-pectin-chitosan nanoparticles to sausage and saw reduced lipid oxidation and bacterial growth over 20 days (Fan et al., 2024). Halloysite nanotubes exhibited better OEO delivery than diatomaceous earth, showing stronger antibacterial and antioxidant activity (Oun et al., 2022). Nguyen et al. (2025) found that OEO, cinnamon oil blends (ratios 8:2 and 9:1) had the lowest MICs against *S. aureus*, *B. cereus*, and *A. flavus*, while a 6:4 blend ratio was most effective against *A. flavus*, and cassava starch films with the blend fully inhibited fungal

growth in Vietnamese bread for at least 5 days. These applications confirm OEO as a powerful, natural solution for active packaging.

5. Safety, Regulatory Status, and Sensory Considerations

5.1. Toxicological assessment of oregano essential oil

Oregano essential oil, along with its key phenolic compounds carvacrol and thymol, is known for strong antimicrobial and antioxidant properties. Classified as GRAS by the U.S. FDA (Kim et al., 1995), OEO is widely used in food systems with low toxicity concerns at typical flavoring levels. Mansoori et al. (2019) found that carvacrol caused no significant harm even at high doses in animal models (Mansoori et al., 2019), and Santos et al. (2022) confirmed that oregano oil is well tolerated in minimally processed foods (Santos et al., 2022). Sirati et al. (2024) showed that OEO encapsulated in niosomes had no cytotoxicity in HFF cells at concentrations higher than food-use levels (Sirati et al., 2024). Edible films with OEO maintained

safety across various temperatures and humidity conditions (Hernández et al., 2023). OEO also showed strong anti-leishmanial effects *in vitro* and *in vivo*, reducing parasite loads without host toxicity (Tomiotto-Pellissier et al., 2022). Overall, oregano oil is considered safe when used in controlled-release systems at effective antimicrobial doses.

5.2. Sensory impact

A key challenge in using OEO in foods is its strong aroma and flavor, dominated by thymol and carvacrol, which can overpower food even at low levels. Frangos et al. (2010) found that trout fillets treated with 0.2% OEO remained acceptable to sensory panels, but at 0.4%, the aroma became too intense (Frangos et al., 2010). Mejlholm & Dalgaard (2002) also noted that effective EO concentrations for shelf-life extension often produce unwanted flavors (Mejlholm & Dalgaard, 2002). In meats and cheeses, 0.5 - 1% OEO can suppress bacteria, but often introduces strong herbal notes. Selim (2011) reported that while oregano-supplemented beef and feta had microbial benefits, sensory monitoring was essential. Cultural preferences and product types of influence acceptability, what works in sausages may fail in juice or dairy. In fresh-cut fruits, even effective antimicrobial doses may harm sensory appeal. Studies aim to find the highest OEO dose that reduces microbes without compromising taste (Jackson-Davis et al., 2023). Strategies like encapsulation, synergistic hurdles, or flavor masking help minimize OEO's sensory impact (Santos et al., 2022).

6. Challenges and Future Perspectives

6.1. Current limitations and challenges

Although OEO has proven antimicrobial

efficacy, several limitations hinder its full-scale use in food preservation. Sensory impact is a primary concern, concentrations effective against pathogens may exceed flavor acceptability thresholds. Frangos et al. (2010) showed that concentrations above 0.4% led to undesirable sensory effects. Furthermore, OEO's efficacy drops in complex matrices where fats and proteins bind hydrophobic compounds like carvacrol, reducing microbial contact. An OEO level that is bactericidal in lab tests may be ineffective in fatty foods. Another issue is batch variability, OEO's carvacrol and thymol levels can differ depending on subspecies and harvest time, affecting potency. Its volatility also limits stability, as heat, light, or oxygen can degrade active components. Protective delivery methods, such as encapsulation, are thus needed to preserve efficacy. Microbial variability also matters: Gram-negative bacteria may resist OEO, and sub-lethal exposure might trigger tolerance. Economically, OEO is costlier than synthetic preservatives, and large-scale use must balance effectiveness and price. Regulatory uncertainty around using OEO above flavoring levels further complicates adoption. Overall, addressing sensory, matrix, stability, and regulatory challenges is key to its broader application.

6.2. Future perspectives

Ongoing research is addressing the limitations of OEO to unlock its full potential in food safety. A major strategy involves advanced delivery systems like nanoemulsions, biopolymer nanocapsules, and liposomes/niosomes (Pontes-Quero et al., 2021; Sirati et al., 2024), which help stabilize OEO and control its release. Encapsulation protects volatile compounds during processing and allows gradual, sustained antimicrobial action without overwhelming

flavor. Smart release systems, such as pH-sensitive or heat-triggered carriers, can deploy OEO where microbial threats are greatest. Edible films and coatings using Pickering emulsions or microgel carriers are being developed to extend activity while reducing sensory impact (Liu et al., 2019). Synergistic preservation is another avenue: combining OEO with modified atmosphere packaging, high pressure, ultrasound, or UV light allows reduced OEO doses while maintaining microbial control. OEO’s antioxidant benefits further support food stability in modified atmosphere packaging. Pairing OEO with other natural antimicrobials like cinnamon oil, nisin, or thyme oil has shown promising synergy; for example, thyme oil plus oregano oil significantly lowered MICs (de Almeida et al., 2023). Such blends could enhance efficacy at sub-threshold flavor levels. Mechanistic insights, such as how carvacrol disrupts bacterial membranes, are driving innovations in delivery design. OEO’s antifungal and antiviral potential is also under study. Notably, it exhibited strong antifungal action against *Rhizoctonia solani* with an EC50 of 22.89 µg/mL, suggesting broader agricultural use beyond food safety (Wu et al., 2023) (Table 5).

Table 5. Antifungal effects of oregano essential oil against *Rhizoctonia solani*

Aspect	Results	Significance
Antifungal potency	22.89 µg/mL (stronger than carvacrol alone)	Demonstrates high efficacy of whole OEO
Cell morphology	Hyphae deformed, collapsed after OEO treatment	Indicates membrane disruption
Ultrastructure	Plasmolysis and organelle degradation	Confirms internal cell damage
Transcriptomics	887 upregulated, 1138 downregulated	Suggests stress and metabolic disruption
Oxidative stress	Increased ROS and lipid peroxidation	Leads to membrane damage
Membrane permeability	Higher leakage of nucleic acids & proteins	Confirms loss of membrane integrity
Hydrogen peroxide	Dose-dependent increase	Triggers oxidative damage
Antioxidant enzyme activity	Increased 2.3x after OEO treatment	Cell defense mechanism activated
Sclerotia formation	Completely inhibited at 50 µg/mL	Prevents survival structures of <i>R. solani</i>

Source: Wu et al. (2023).

The future for oregano essential oil in food safety lies in innovation at multiple levels: technological (encapsulation and packaging), combinatorial (synergies with other methods), and perceptual (managing sensory and consumer expectations). With these advancements, OEO's robust antimicrobial power can be more fully realized in keeping foods safe naturally. Oregano and other essential oils have steadily been moving from experimental studies into practical, effective tools for the food industry, such as incorporating OEO with gelatin-based edible films to inhibit effectively pathogens (Wu et al., 2023). As these hurdles are addressed, oregano essential oil is poised to play an increasingly important role in the future of food preservation as a sustainable, consumer-friendly solution.

7. Conclusions

Oregano essential oil offers a promising natural substitute for synthetic preservatives in food processing, drawing on its distinctive physicochemical attributes, volatile, hydrophobic, and abundant in phenolic monoterpenes such as carvacrol and thymol, to deliver robust antimicrobial and antioxidant effects. Numerous *in vitro* and *in situ* investigations have confirmed OEO's broad-spectrum activity against foodborne pathogens and spoilage agents, including *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Salmonella enterica*, and fungi like *Zygosaccharomyces bailii* and *Aspergillus* species. This versatility has enabled its successful integration into various food matrices, from meat and poultry to dairy, fresh produce, seafood, and baked goods. To overcome inherent drawbacks such as volatility, instability, and intense sensory profiles, researchers have turned to innovative delivery systems like edible films, nanoencapsulation, and vapor-phase

packaging, which facilitate controlled release and prolonged antimicrobial performance while preserving the sensory and nutritional integrity of foods. Nevertheless, hurdles persist, including sensory acceptability in certain products, interactions with complex food matrices, unclear regulatory guidelines for preservative dosages, and the need for consistent oil composition across batches. Looking ahead, investigations may prioritize synergistic combinations with other preservation techniques, assessments of consumer preferences, and scalable encapsulation approaches that balance efficacy with flavor masking. Achieving regulatory alignment and fostering public confidence will prove essential for broader adoption. In essence, OEO stands as a multifaceted, clean-label option for contemporary food preservation, with collaborative efforts across disciplines poised to realize its broader promise.

Conflict of interest

The authors declare that there is no conflict of interest.

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