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Recent advances in essential oils as sustainable food preservatives: Antimicrobial mechanisms, delivery systems, food applications, and industrial challenges

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ABSTRACT: Increasing consumer concerns regarding synthetic preservatives have intensified the search for natural, safe, and effective substitutes. Essential oils (EOs), which are recognized for their broad-spectrum antimicrobial activity and general safety, hold significant potential. However, challenges such as volatility, instability, and a lack of complete mechanistic understanding limit their widespread applications. This review systematically highlights recent advances in the use of EOs as food preservatives. It comprehensively examined the antimicrobial mechanisms of EOs, including bacterial membrane disruption, virulence factor suppression, and biofilm formation. Additionally, advanced delivery systems designed to enhance the stability, solubility, and controlled release of EOs have been explored. Practical considerations for industrial applications, such as sensory compatibility and regulatory aspects, are also discussed. EOs exhibit significant antimicrobial activity against major foodborne pathogens and spoilage microorganisms through multiple mechanisms, including cell membrane disruption, enzyme inhibition, and virulence factor suppression. Advanced delivery systems have significantly improved the stability, bioavailability, and controlled release of EOs within complex food matrices. These innovations have demonstrated high efficacy in practical applications, particularly in enhancing the preservation and shelf life of perishable foods. Future research should prioritize standardization and chemotype characterization of essential oils, food matrix-specific optimization of delivery systems, development of smart and sustainable formulations, and sustainable scaling with regulatory integration, thereby facilitating the commercial use of EOs as natural preservatives.

Keywords: Essential oils, food preservation, antimicrobial mechanisms, delivery systems, application, industrial challenges

1. Introduction

Rising living standards have intensified consumer demand for nutrient-rich foods; however, effective preservation remains challenging owing to the high susceptibility of raw materials to physical damage, pest infestation, and microbial decay. In 2024, global food waste amounted to approximately 1.05 billion tons, representing nearly 20% of the total food production, majorly contributed by inadequate preservation technologies. Although synthetic preservatives are commonly used and effective, they are increasingly resisted by consumers due to health concerns, such as potential allergenicity, cytotoxicity, and unresolved

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long-term safety issues^[1]. According to a survey by the International Food Information Council Foundation (IFIC), nearly half of the consumers actively avoid products containing synthetic preservatives, whereas approximately 40% prefer preservation methods based on natural ingredients. Furthermore, synthetic preservatives pose ecological concerns owing to their environmental persistence, potential to disrupt microbial ecosystems, and nonrenewable production processes. Regulatory compliance is becoming increasingly complex, necessitating rigorous safety and environmental impact assessments under frameworks such as those established by the FAO/WHO Joint Expert Committee on Food Additives (JECFA). These challenges highlight the urgent need to develop effective, safe, and sustainable natural alternatives, particularly those derived from plants.

In this context, essential oils (EOs) represent a promising natural alternative to synthetic preservatives because of their complex chemical composition and multi-target antimicrobial mechanisms. The diverse bioactive compounds in EOs, such as phenolics, terpenes, and aldehydes, simultaneously disrupt microbial membranes, inhibit enzymes, and interfere with genetic material, thereby reducing the potential for resistance development^[2]. Their broad-spectrum antimicrobial properties are complemented by antioxidative and anti-inflammatory effects, which further delay lipid oxidation and food spoilage^[3, 4]. EOs are generally recognized as safe (GRAS) under the conditions of their intended use in food, positioning them as suitable candidates for clean-label applications, and exhibit increased efficacy when used in synergistic combinations, thus offering a sustainable strategy for integrated food preservation.

EOs offer a scientifically validated and sustainable alternative to synthetic preservatives, effectively reducing food waste and enhancing safety while complying with increasing consumer and regulatory demands for natural products. Compared with many synthetic preservatives, EOs contain multiple active constituents that can target different microbial sites, potentially lowering resistance risks^[5]. Current research is focused on optimizing extraction methods, identifying bioactive constituents, elucidating antimicrobial mechanisms, and evaluating safety profiles to facilitate industrial applications (Fig. 1 A). Despite these promising advancements, scaling up from laboratory to industrial-scale food preservation presents challenges, including issues related to sensory compatibility, matrix interactions, and the stability of the scalable formulations. The primary limitation is the disparity between the antimicrobial concentrations required for efficacy and those that are acceptable sensorially. Moreover, food matrices can significantly influence EO activity, as lipid content, pH, protein interactions, and water activity can reduce bio accessibility and antimicrobial performance, necessitating tailored formulations for each application^[6]. Finally, EOs present significant stability challenges for industrial applications. High volatility leads to the loss of active compounds during thermal processing, whereas light exposure accelerates degradation^[7]. These issues result in reduced antimicrobial effectiveness, inconsistent quality, and reduced shelf life, hindering their reliable application in food preservation.

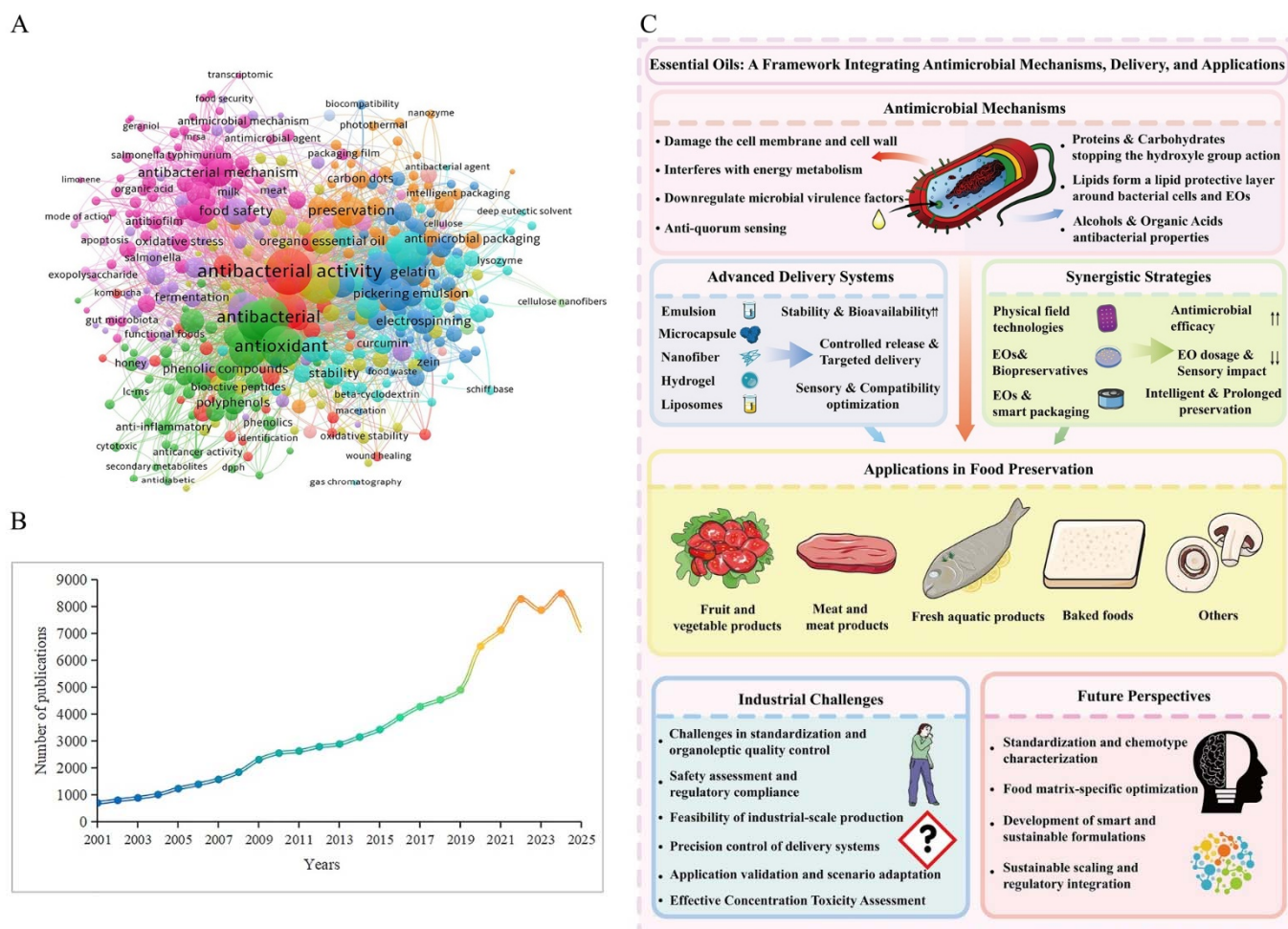


Fig. 1 Keyword co-occurrence map (A). Number of publications per year (B). Framework Diagram (C).

Although extensive research has been conducted on the antimicrobial properties of EOs, systematic reviews that effectively integrate their compositional characteristics with their practical applications in food systems do not exist. Therefore, this review proposes a comprehensive framework that connects the chemical composition and antimicrobial mechanisms of EOs, including membrane disruption, virulence regulation, and biofilm inhibition, with advanced delivery systems, such as microencapsulation and nano emulsions (NEs), as well as their practical implementation in various food matrices (Fig. 1 B). The most recent research advances published within the past three years are emphasized to ensure a timely synthesis of current knowledge. By critically examining these interconnected aspects, this review not only provides mechanistic insights but also offers practical strategies to overcome existing challenges related to volatility, solubility, and modes of action that currently impede industrial adoption. Ultimately, this study aims to expedite the translation of EOs from experimental research to commercial-scale applications in food preservation, promoting the development of effective natural alternatives to traditional preservatives.

2. Antimicrobial mechanisms

2.1 Effects on cell membrane and cell wall

EOs represent an important class of natural antimicrobial agents whose antibacterial effects are not mediated by a single mechanism but are determined by their specific chemical composition and targeted

microbial species. The antimicrobial activity of EOs primarily stems from their hydrophobic nature, which allows them to penetrate microbial cell walls and interact with lipid bilayers. Bioactive compounds accumulate in the phospholipid bilayer, compromising the membrane integrity and increasing its permeability, leading to leakage of cellular contents, disruption of membrane proteins, and loss of membrane potential, ultimately resulting in cell death (Fig. 2 A). This membrane-disrupting effect was directly observed using scanning electron microscopy (SEM), which showed the characteristic morphological collapse of the treated microbial cells. Notably, gram-negative bacteria exhibit lower intrinsic susceptibility to essential oils than gram-positive bacteria, primarily due to the presence of an outer membrane that limits the penetration of hydrophobic EO components. This outer membrane barrier necessitates the use of membrane permeabilizers to enhance the antimicrobial efficacy of essential oils against gram-negative pathogens^[8]. In contrast, gram-positive bacteria, which lack the outer membrane, are generally more susceptible to essential oils, as demonstrated by the effective inhibition of common foodborne gram-positive pathogens such as *S. aureus*, *L. monocytogenes*, *B. cereus*, *E. faecalis*, and *E. faecium*^[2, 9]. For gram-negative bacteria like *E. coli*, *S. Typhimurium*, *S. abony*, and *P. aeruginosa*, essential oils alone show limited activity, and their antimicrobial effects are significantly enhanced when combined with outer membrane permeabilizers or when delivered via appropriate delivery systems^[10]. Moreover, essential oils also possess antifungal activity against foodborne fungi, as exemplified by their efficacy against *C. albicans*^[9]. In contrast, the lipopolysaccharide-containing outer membrane of gram-negative bacteria forms a hydrophilic barrier, providing intrinsic resistance to hydrophobic antimicrobial agents^[11]. These structural differences provide crucial insights into the selective antimicrobial activities of EOs and offer theoretical guidance for the development of novel antibacterial agents.

Traditional methods for evaluating the antimicrobial properties of EOs include standardized methods, such as agar/disk diffusion, broth dilution, E-test, and time-kill assays. The recent integration of these conventional approaches with multiomics technologies has significantly enhanced mechanistic investigations, enabling comprehensive analyses of the genomic regulation of metabolic perturbations. Contemporary studies employing this combined strategy have systematically revealed the membrane-disruptive effects of EOs through the simultaneous assessment of cellular damage and omics-level responses, providing unprecedented resolution in elucidating antibacterial mechanisms. Metabolomic studies have consistently shown that EOs from *Zanthoxylum bungeanum* cause membrane damage, as indicated by nucleic acid and protein leakage and disrupted lipid metabolism. Transcriptomics (RNA-seq) has revealed the downregulation of peptidoglycan and fatty acid biosynthesis genes, impairing structural integrity^[12]. The combined application of transcriptomics and metabolomics, where the former reveals the gene expression regulatory network under antibacterial stress through whole transcriptome analysis and the latter systematically monitors the dynamic changes and interaction patterns of the metabolome, complement each other and provide key evidence for elucidating the target sites and molecular mechanisms of antibacterial compounds. Although multiomics approaches have proven valuable for elucidating antimicrobial mechanisms, they have several limitations.

Current methodologies exhibit insufficient temporal resolution to differentiate primary antimicrobial effects from secondary adaptive responses, and GC-MS-based metabolomics preferentially detects polar metabolites. To advance this field, future studies should incorporate lipidomics for comprehensive membrane analysis, implement time-series multiomics to establish causal relationships, and develop standardized protocols to enhance cross-study comparability and clinical relevance.

2.2 Disrupts energy metabolism

EOs can disrupt proton dynamics, alter ATPase conformation, and suppress the expression of ATPase-associated subunits, thereby inducing cell membrane damage. Omics studies have confirmed that the bioactive compounds in EOs can impair mitochondrial function by inhibiting dehydrogenases involved in ATP biosynthesis.

EOs primarily exhibit antimicrobial effects by disrupting energy metabolism, with their specific mechanisms depending on their chemical composition and microbial targets. This variability is highlighted in several mechanistic investigations focusing on various EOs and microbial species. Noni fruit (*Morinda citrifolia* L.) EO (NEO) exhibits a dual antibacterial effect on *Staphylococcus aureus* through membrane disruption and direct inhibition of TCA cycle enzymes^[13]. Notably, clove EO (CIEO) and oregano EO (OEO) suppress *Salmonella* Derby biofilm formation by significantly downregulating energy pathways and virulence factors, with CIEO specifically impairing ribosomal function^[14]. EOs disrupt energy metabolism through distinct yet overlapping mechanisms, including direct enzyme inhibition, membrane destabilization, and transcriptional reprogramming, with effects shaped by both the pathogen's physiological state and the specific chemical composition of the EO. Proteomics and transcriptomics are valuable for mapping broad metabolic disruptions, while metabolomics provides direct evidence of specific metabolic perturbations, though it often lacks the spatial resolution needed to localize these changes within cells. A key limitation of current research is its reliance on in vitro models, which do not capture the complexity of host-microbe interactions in vivo, and the presence of compensatory metabolic pathways in pathogens suggests potential adaptive resistance mechanisms that could undermine the long-term efficacy of EOs. This has led to ongoing debate about whether energy disruption is a direct primary effect of EOs or a secondary consequence of membrane damage. To clarify these causal relationships, future studies should integrate multi-omics approaches and structure-activity analyses to link specific EO components with precise enzyme-level interactions, while investigating EO combinations or adjuvants to counteract microbial adaptability. Ultimately, validating these mechanisms in in vivo infection models will be essential for translational applications.

2.3 Anti-quorum sensing (QS)

QS is a communication mechanism dependent on cell density, allowing bacteria to synchronize collective behaviors by producing and detecting diffusible signaling molecules. When bacterial populations reach a critical threshold density, the accumulated autoinducers activate specific genetic programs that regulate collective behaviors, including formation of biofilm, production of virulence factors, and modulation of bioluminescence. Among the emerging biofilm control strategies, EOs have garnered considerable

attention because of their environmental compatibility and broad-spectrum antimicrobial properties. EOs can effectively inhibit the initial stages of biofilm formation and disrupt the structure of mature biofilms by interfering with the synthesis, accumulation, or receptor binding of QS signaling molecules^[15]. Complementary research has revealed that black pepper EO exerts its antiviral effects by modulating quorum-sensing networks, specifically by inhibiting *lasR* and *cviR* expression, which subsequently suppresses the production of exopolysaccharides and flagellar motility proteins in *P. aeruginosa* and *C. violaceum*^[16]. Notably, these transcriptional changes occurred at sub-inhibitory concentrations, suggesting that EOs primarily function as virulence attenuators rather than bactericidal agents. These findings establish EOs as a novel class of antiviral agents that disrupt QS-mediated gene expression, providing a strategic alternative to conventional antibiotics that reduce the selective pressure for resistance. EOs exert dual antipathogenic effects by suppressing bacterial virulence factors and enhancing host immunity. Their multi-target mechanisms, including interference with QS signal synthesis and receptor binding, further identifies EOs as promising biofilm inhibitors and potential tools for managing microbial hazards in food systems.

2.4 Downregulation of microbial virulence factors

Harmful pathogens pose a major threat to food safety and can result in substantial economic losses. Biofilm formation, a typical microbial survival strategy, is closely associated with the expression of bacterial virulence factors. Virulence factors are functional components derived from pathogens, including adhesins, invasins, toxins, extracellular enzymes, and QS signaling molecules^[17], which synergistically promote bacterial colonization of the host, immune system evasion, and increase pathogenicity. Due to their high heterogeneity and widespread inherent resistance characteristics, virulence factors have become key targets for the clinical management of bacterial infections.

Related research is of great significance for the optimization of treatment strategies. Antitoxic therapy strategies offer an innovative treatment approach for the prevention and control of bacterial diseases by specifically interfering with bacterial virulence mechanisms rather than by directly killing microorganisms. Existing research has indicated that EOs can effectively inhibit the expression and function of bacterial virulence factors through multiple target regulatory effects. EOs can down-regulate the expression of bacterial virulence-related genes, thereby reducing the potential of pathogens. *Citrus microcarpa* oil (CAEO) inhibits biofilm formation and suppresses key virulence genes in *S. aureus*, showing a multitarget mechanism against pathogenic bacteria^[18]. This multitarget action effectively controls bacterial growth and maintains food freshness. Moreover, this mechanism has been systematically verified using modern omics technologies. Transcriptomic analysis revealed that cinnamon EO (CiEO) inhibits *A. flavus* by down regulating genes involved in ergosterol biosynthesis as an essential process for fungal membrane integrity, and aflatoxin production as a major virulence factor, as well as inducing ROS-mediated cell death^[19]. These findings provide strong scientific evidence for the efficacy of antitoxic therapeutic strategies.

2.5 Food matrix effects

Although extensive *in vitro* studies have investigated the antibacterial properties of plant EO components against specific bacteria in culture media, *in vivo* data indicate that their activity depends not only on the interaction between EO and bacteria but also on the biomolecules present in the food system in which the EO exerts its effects. Research has shown that food constituents, such as proteins, lipids, and carbohydrates, can bind to EO components (EOCs) through physical or chemical interactions, thereby affecting their antibacterial efficacy (Fig. 2 B).

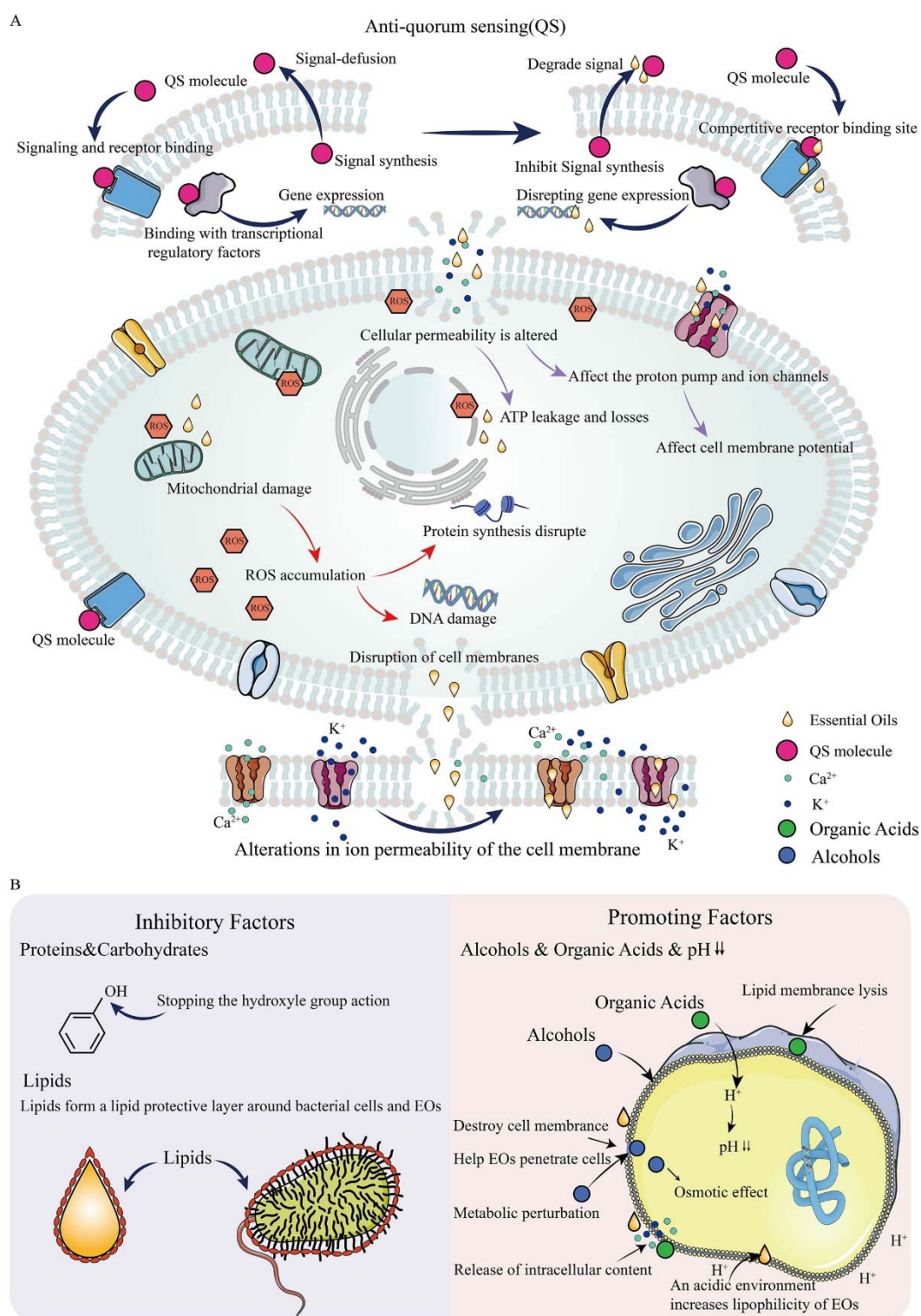


Fig. 2 Antimicrobial mechanism of essential oils (A). Impact of food matrix on antibacterial efficacy of essential oils (B).

In protein-rich environments, EO constituents form stable complexes with food proteins through multiple molecular interactions, particularly hydrophobic forces and hydrogen bonding, which effectively sequester the bioactive phenolic hydroxyl groups responsible for the antimicrobial activity, as demonstrated in with bovine serum albumin (BSA)^[20]. Lipid components in food matrices are another major modifying factor, as they can physically encapsulate hydrophobic EO molecules within lipid droplets or micellar structures, creating a diffusion barrier that limits access to bacterial targets. Carbohydrate interactions differ, with reducing sugars such as lactose forming specific hydrogen bonds with phenolic compounds such as vanillin, whereas polysaccharides exert steric interference through their bulky molecular structures. In contrast, components such as organic acids and ethanol may synergistically enhance the effects of EOCs by compromising bacterial membrane integrity or reducing the intracellular pH^[6, 21], thereby potentiating antimicrobial efficacy. Multiple studies have confirmed the aforementioned mechanism. One study found that the acidic microenvironment of *Actinidia arguta* enhances antimicrobial efficacy of daisy EO (DEO) by promoting protonation of its phenolic compounds, thereby increasing their hydrophobicity and membrane permeability^[22]. Another study showed that cherry tomato organic acids may improve the antibacterial effects of OEO by disrupting bacterial membranes and lowering intracellular pH, synergizing with carvacrol's membrane-damaging effects. Additionally, ultrasonic cavitation may facilitate the co-penetration of organic acids and EO components^[23]. This combination results in potent antimicrobial effects, particularly in acidic food matrices, thereby optimizing EO-based preservation strategies.

Current research, although limited, has unequivocally demonstrated the crucial role of food matrix composition in the antimicrobial efficacy of EOCs. Preliminary evidence indicates that food components can substantially interfere with the accessibility of EOCs' active sites through multiple molecular mechanisms and that such interactions directly govern antimicrobial performance of EOCs in real food systems. Given the nascent stage of this research field, in-depth exploration of food matrix-EOC interaction patterns holds significant theoretical importance while providing crucial scientific foundations for developing high-efficiency, stable food preservation technologies.

3. Delivery technology

Hydrophobic bioactive compounds such as EOs have garnered significant attention from food chemists because of their multifaceted benefits, including antioxidant, antimicrobial, and enzyme-inhibitory activities. Their inherent instability and volatility make them prone to rapid degradation upon exposure to light and oxygen^[7]. In addition, their poor dispersibility in water significantly limits their practical application in food products. To address these challenges, advanced delivery technologies have been developed to enhance the solubility and stability of hydrophobic compounds (Fig. 3). Notably, controlled-release systems that encapsulate EO components within active films or coatings offer dual advantages of effectively protect food products from fungal contamination while mitigating the strong, often unpleasant odors associated with EOs. Encapsulation prevented rapid volatilization of the primary active constituents of EOs, thereby achieving

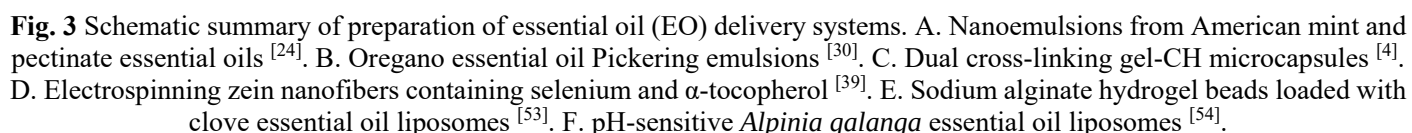


Table 1: Comparative summary of different types of essential oil delivery systems.

Category	Nanocarrier Type	Advantages	Limitations	EE(%)	Release Profile	Stability	Typical Applications	Reference
Nano emulsion	O/W	antioxidant and antimicrobial activities ↑ Solubility ↑ Stability ↑ slow release	High volatility of LEO Potential alteration of meat flavor Sensitivity to processing conditions	74.66	Slow release rate ($k < 0.1$)	Stable for 14 days at 4 °C No delamination or demulsification observed	chilled pork	[79]
	O/W	hydrophobicity of EOs ↑ stability and permeability ↑ Prevents oxidation Masks odors	May produce spicy odor at high oregano oil concentration requires optimized surfactant ratio for stability	NR	NR	Stable particle size after 15-day storage at 4 °C	grass carp fillets	[25]
Pickering Emulsion	ZCP/C-CNC stabilized CEO	High encapsulation efficiency pH/temperature-responsive	Particle size variability Flocculation at 80 °C	91-95	Controlled release	20-day room temperature stability Stable below 60 °C	Food, pharmaceuticals, cosmetic	[107]
	CNCs stabilized clove essential oil (CEO) emulsion	Surfactant-free Superior stability against coalescence Biocompatibility and renewability	Potential phase separation at high emulsion concentrations Reduced film continuity at excessive loads	NR	Gradual release	Stable at 25 °C for 30 days pH stability Thermal stability (20-60 °C) Maintains activity over 18-day storage at 4 °C	Grape preservation	[32]
Microcapsules	Chitosan/TiO ₂ -l loaded OEO microcapsules	Antimicrobial efficacy ↑ Non-contact preservation mode	UV penetration depth may limit scalability	NR	Accelerated release under UV		Ready-to-eat chicken breast	[108]
	MEL-A-based microcapsules	Solubility and applicability ↑ antioxidant and antibacterial activities ↑ Good dispersibility	Slightly reduced thermal stability due to essential oil loading	NR	NR	Good thermal stability	Food	[109]
Electrospun fibers	OSS/PUL fibers	Green fabrication High porosity Tunable fiber diameter	Limited electrospinnability for high Bead formation at low polymer concentrations	CEO loading rate: 2.64-3.02 g/g	Not quantitatively analyzed	Mechanical stability Structural integrity maintained after CEO loading	Active food packaging	[110]

Hydrogel	Zein electrospun fibers	Tunable release properties Biodegradable, odorless, hydrophobic	Limited efficacy for climacteric fruits	96.2-98.3	Not quantitatively analyzed	High thermal stability Crystallinity ↑	Non-climacteric fruits	[42]
	Chicken protein hydrogel	Biocompatibility, biodegradability, and bio-stability Enhanced crosslinking via MTG enzymes High WHC	Weak mechanical properties Low thermal stability	NR	potential sustained release	Low thermal stability Water leakage under centrifugation	High-moisture foods	[111]
	PVA-PVP/EO	Excellent sustained release Water-holding capacity No direct fruit treatment required; Biodegradable. Good biocompatibility and biodegradability	Higher T40 concentrations may induce phytotoxicity and accelerate fruit decay; Firmness ↓	NR	Anomalous diffusion	Thermal stability ↑	Blueberry preservation	[112]
Liposomes	BEOLβ-CL-EL	Good biocompatibility and biodegradability Controlled release properties Synergistic antibacterial and antioxidant effects	Morphology and stability influenced by core materials	>90 (Loading Efficiency)	Sustained release over 48 h	Good storage stability (30 days at 4 °C) Centrifugal and thermal stability Stable storage for 7 days at 4 °C	Aquatic products	[113]
	Lps-SEO	Colloidal stability ↑ Sustained release properties Bioavailability ↑	Particle size and PDI influenced by SEO concentration	57.39 (Lps-SEO-80)	Sustained release over 48 h	Reduced phospholipid oxidation	white mushrooms	[114]

3.1 Emulsions

Emulsification is an effective strategy to enhance the solubility and stability of hydrophobic compounds in aqueous systems. Oil-in-water (O/W) emulsions significantly improve the dispersibility of EOs in both food and non-food matrices while concurrently enhancing their stability, enabling controlled release kinetics, and optimizing their antimicrobial efficacy^[24]. Emulsions are categorized by the emulsifier type into molecular emulsifier-stabilized systems and particle-stabilized emulsions (commonly termed Pickering emulsions, PEs). Molecular emulsifiers, typically surfactants, function by adsorbing at oil-water interfaces to reduce interfacial tension. In contrast, particle-based emulsifiers are amphiphilic solid particles irreversibly anchored at the interface, providing mechanical barrier stabilization. Emulsion preparation methods are primarily divided into high- and low-energy approaches. High-energy methods, including high-pressure homogenization (HPH), ultrasonic emulsification, and micro fluidization, employ mechanical devices that provide external energy to disrupt macroscopic droplets. In contrast, low-energy techniques utilize the system's natural emulsification characteristics, such as the phase inversion temperature (PIT), phase inversion composition (PIC), and emulsion inversion point (EIP).

3.1.1 NE

NEs are colloidal systems characterized by dispersed-phase droplets with diameters generally between 10 to 100 nm and are also known as mini-emulsions, ultrafine emulsions, or submicron emulsions. EO-based NEs can be classified as oil-in-water (O/W) or water-in-oil (W/O). In O/W NEs, oil droplets are stabilized in the aqueous phase by hydrophilic emulsifiers, whereas in W/O NEs, water droplets are dispersed in the oil phase by lipophilic emulsifiers. The aqueous phase of NEs consists of emulsifiers and co-emulsifiers, preferentially with food-grade ingredients, such as whey protein isolate, due to food safety concerns. To prepare NEs of EOs, a coarse emulsion is typically obtained by ultrasonic emulsification or homogenization, followed by ultrasonication to reduce the droplet size to the nanoscale range^[24].

Recent advances in the NE technology have significantly improved the functionality of EOs by enhancing their stability, bioavailability, and targeted delivery. Currently, EOs from various botanical sources have been successfully integrated into edible films using NE technology, demonstrating enhanced functionality across different applications. For instance, *Origanum vulgare*/*Litsea cubeba* EO NEs developed via high-pressure microjet technology significantly inhibited microbial spoilage in fish fillets while maintaining physicochemical stability under stress conditions^[25]. Encapsulating citrus EOs in NEs enhances their properties; low-concentration root application on peppers improves preservation and extends shelf life to 40 days through enhanced microbial interaction^[26]. Moreover, the gelatin-chitosan edible film incorporating kesum essential oil nanoemulsion enables matrix-synergistic delivery, wherein the release kinetics and total release amount are substantially enhanced by the presence of salts, particularly NaCl, and ethanol in food simulants, thereby allowing controlled and accelerated release tailored for high-salt and high-fat food matrices^[27]. Notably, nanoemulsions serve as a universal preservation strategy that is highly synergistic with different food matrices. They uniformly coat and penetrate surface microstructures, restricting the exchange of

water and gases. This physical modulation reduces oxidative metabolism within the matrices; in aquatic and meat products, it inhibits lipid autoxidation and aerobic spoilage bacteria^[25, 28]; in fruits, it suppresses ethylene biosynthesis and polyphenol oxidase activity^[29], thereby reducing browning. Furthermore, the coating reduces moisture loss in a matrix-dependent manner. Collectively, these studies demonstrated that NE technology optimizes EO performance in food preservation by improving stability, bioavailability, and antimicrobial precision. By integrating these delivery systems with edible coatings, the food industry can develop more efficient, sustainable, and consumer-friendly preservation methods. Future research should focus on scaling up the production and evaluating the long-term safety of NE-based coatings for commercial applications.

3.1.2 Pickering emulsion

As unique emulsion systems, PEs have attracted significant attention in recent years owing to their distinctive characteristics and broad application potential. In the case of EOs, PEs have demonstrated advantages over conventional emulsions. Unlike traditional emulsions stabilized by surfactants, PEs rely on solid particles adsorbed at the oil-water interface to form a robust “particle-stabilized interfacial film,” which effectively prevents destabilization through droplet coalescence and flocculation^[30]. Solid particles derived from polysaccharides, proteins, nanofibers, silica, and titanium dioxide are used to prepare PEs. These particulate stabilizers, typically having micro- or nano-scale dimensions, exhibit irreversible adsorption characteristics at the interfaces, endowing PEs with exceptional stability^[31]. PEs, stabilized by the irreversible adsorption of solid particles at oil-water interfaces, significantly enhance the sustained-release properties and antimicrobial activity of EOs, demonstrating their multifaceted application potential in food preservation.

Recent studies have highlighted the effectiveness of PE-based films in improving the sustained release and antimicrobial performance of EOs in food packaging applications. Cellulose nanocrystal-stabilized CEO PEs (CCPE) were incorporated into pectin-konjac glucomannan films to enhance EO delivery. This approach improved the tensile strength of the film by 51.54% and reduced the water vapor permeability, while maintaining the sustained release of antimicrobial eugenol. The films showed effective inhibition of *S. aureus* (38.77 mm) and *E. coli* (29.03 mm), which was attributed to the stable emulsion system and hydrogen bonding interactions within the polymer matrix^[32]. Similarly, a chitosan-based composite film was developed using bacterial-cellulose-stabilized CEO PEs to enhance EO delivery. The film exhibited improved mechanical properties (51.24% higher tensile strength and 28.79% greater elongation) and antibacterial activity (50-65% inhibition against *E. coli* and *S. aureus*). When used for walnut preservation, it effectively suppressed enzymatic browning, delayed lipid oxidation, and reduced microbial growth by 1.9 log CFU/g, demonstrating its potential for active food packaging^[33]. In addition to conventional PEs, stimuli-responsive PEs have emerged as a promising alternative for active food preservation. For instance, a temperature responsive PEs was developed using a chitosan-grafted poly microgel to encapsulate cinnamon essential oil^[34]. Similar to nanoemulsions, PEs also exert their preservative effect by forming a physical barrier on the food surface, thereby limiting gas and moisture exchange and inhibiting microbial invasion. A chitosan sodium alginate-thyme essential oil PEs was developed to preserve refrigerated pork. The emulsion synergized with

the pork matrix by forming such a barrier on the meat surface, which suppressed water migration, inhibited microbial proliferation and lipid oxidation, and extended shelf life by 4-6 days^[35]. These findings collectively demonstrate that the PE technology can effectively enhance the functional properties of biopolymer films through improved EO stabilization and controlled release, offering promising solutions for active food packaging applications.

3.2 Microencapsulation

Microencapsulation involves using physical, chemical, or physicochemical methods; to enclose core materials (such as EOs and bioactive compounds) within a natural or synthetic polymer shell to create a miniature encapsulation system. The size of the particles is usually at the micron level; the structure consists of two parts: the core and the wall material. The core material can be in liquid, solid, or gaseous form, whereas the wall materials are mostly natural or synthetic polymers that exhibit film-forming, biocompatible, and protective properties. For food-grade microencapsulation, wall materials often include polysaccharides and proteins, is mainly gelatin and chitosan^[4]. Microencapsulation techniques can be classified into physical (e.g., spray drying and freeze drying), chemical (e.g., interfacial polymerization), and physicochemical methods (e.g., emulsion-solvent evaporation). EOs, which are characterized by volatility, hydrophobicity, and chemical instability (susceptibility to degradation by light, heat, and oxygen), require microencapsulation to enhance their stability and application potential. Microcapsule wall materials form a physical barrier through encapsulation, effectively inhibiting the volatilization of EOs and minimizing their contact with the external environment.

The synergistic application of microencapsulation technology and EOs presents an innovative approach for food preservation. However, their antimicrobial efficacy is influenced by technical compatibility multiple constraints. Microencapsulation significantly enhances the synergistic antimicrobial efficacy of EOs (e.g., juniper berry and ginger) by enhancing their stability and controlled release, effectively inhibiting pathogens such as *B. cereus* and *S. enterica*^[36, 37]. However, limitations such as thermal degradation, particle inconsistency, high-energy requirements, and insufficient validation in complex food systems restrict wider applications. Optimizing the processing conditions and wall materials remains critical for maximizing the functional performance. In this context, low-pressure cold plasma (CP) was applied to modify pea protein isolate (PPI) before complexing it with gum Arabic (GA) to form wall materials for cinnamon essential oil microcapsules. CP treatment enhanced PPI-GA interactions and improved the stability of the resulting capsules under various environmental stresses, while preserving antimicrobial activity and gastric structural integrity. This non-thermal approach offers a mild strategy for developing plant-based delivery systems with enhanced robustness^[38]. However, in these studies, microencapsulation technology is still primarily used to achieve sustained or controlled release of essential oils, whereas research on the interplay between food matrices and capsule performance remains limited. This lack of evaluation raises concerns regarding the broader applicability of such delivery systems. Research efforts should prioritize the development of energy-efficient production methods while optimizing wall materials to improve environmental stability and

reduce overall production costs. Furthermore, comprehensive evaluations across diverse food systems are required to validate their performance under various processing and storage conditions, which will significantly advance the commercial viability of these encapsulation technologies for industrial food applications. Further investigation into these areas is critical for translating laboratory success to real-world application in the food industry.

3.3 Nanofiber

Nanofibers are characterized by their high specific surface area, adjustable porosity, and superior biocompatibility, are ideal carriers for EOs. Among various fabrication techniques, electrospinning has emerged as one of the most widely employed technique for producing nanofibers^[39]. In the presence of an electric field, the droplet at the needle's tip transforms from a spherical shape into a conical structure (known as the "Taylor cone"), and a jet is then ejected from the tip of the cone. This jet elongates to form ultrafine fibers, which solidify as the solvent evaporates or cools, yielding fibers with diameters ranging from a few micrometers to a few nanometers^[40]. Electrospinning is one of the most widely used techniques for the fabrication of nanofibers owing to its high aspect ratio, large specific surface area, tunable porosity, and excellent mechanical properties. Nanofibers are ideal carriers of EOs owing to their high specific surface area, controllable porous structure, and biocompatibility.

Electrospinning integrates EOs into nanofibers through two main approaches. First, by directly dispersing the EOs into the polymer solution, where encapsulation is achieved through hydrogen bonding or hydrophobic interactions between the polymer and EOs. The polyvinyl alcohol (PVA)/chitosan composite physically encapsulated CEO through hydrogen bonding and dipole interactions. Although this method preserves bioactivity and simplifies preparation, it requires a careful balance of the components; excessive CEO disrupts film integrity, whereas high PVA hydrophilicity may cause premature release. Optimal component ratios are critical for maximizing the retention and mechanical strength^[41]. Second approach involves a core-shell coaxial electrospinning. Electrospun zein fibers incorporating savory EO (SEO) demonstrated high encapsulation efficiency (96-98%), improved thermal and mechanical properties, and significant antibacterial activity. However, uneven fiber morphology at high SEO loadings hinders controlled release. Although suitable for non-climacteric fruits, the fibers accelerate spoilage in climacteric varieties. Industrial scalability remains challenging due to cost and stability concerns^[42].

The synergistic integration of EOs and electrospun fibers improves material functionality, however, key factors such as encapsulation efficiency, controlled release kinetics, and polymer-EO compatibility critically influence their antimicrobial and antioxidant efficacy. Electrospun cellulose acetate fibers loaded with 50% cinnamon and CLEOs effectively inhibited *Staphylococcus* and *E. coli* while enhancing antioxidant activity and maintaining antimicrobial efficacy in the produce for 40 days. The fibers reduced EO release by 30% over 60 days compared to spray-coated methods and extended the shelf life by 25 days^[43]. Moreover, nanofibers play a multifaceted role in food preservation by synergistically interacting with diverse food matrices. They modulate key parameters such as gas permeability, moisture retention, and controlled release of bioactive

compounds, while also providing tailored protection against matrix specific spoilage mechanisms. For instance, in high-moisture fresh-cut bamboo shoots, nanofiber stabilized essential oil emulsions reduce oxygen permeability and enable sustained oil release, thereby suppressing lignification^[44]. In small berries, nanofiber mats embedding cyclodextrin/essential oil inclusion complexes provide adequate gas permeability and controlled release, achieving dual antifungal and anti-insect functions^[45]. In protein and fat rich meat products, nanofiber reinforced films incorporating essential oils enhance antimicrobial activity against common pathogens^[46]. Thus, nanofibers do not act merely as passive barriers; they actively regulate release kinetics, improve barrier properties, and adapt to the specific deterioration pathways of each food matrix, thereby achieving efficient and targeted preservation. However, challenges remain regarding the hydrophobic nature of EOs, which may lead to inconsistent fiber formation and their volatility could affect flavor profiles. These limitations may be addressed by optimizing the polymer concentration or incorporating surfactants to further enhance the stability and release characteristics of the core shell structures.

3.4 Hydrogel

Hydrogels are three-dimensional polymer networks formed by the physical or chemical cross-linking of hydrophilic polymers. They can absorb and retain large amounts of water, while maintaining a macroscopic solid structure. These materials typically have high water content, softness, and biocompatibility, and their network structures are created through ionic, hydrogen, or covalent bonds, or physical entanglement. Hydrogels are typically prepared in three steps: dissolving monomers, initiators, and crosslinkers in a solvent to form a prepolymer solution; creating a three-dimensional network through physical (non-covalent) or chemical (covalent) crosslinking; and finally, washing and drying the product^[47]. Based on the raw material source, hydrogels can be classified into protein-, polysaccharide-, and synthetic polymer-based types. EOs have extensive potential applications in the fields of food and biomedicine owing to their antimicrobial and antioxidant properties. However, poor water solubility, volatility, and chemical instability limit their direct use. Hydrogels based on natural polymers such as alginate and chitosan, which exhibit biocompatibility, degradability, and ease of functional modification, have become ideal carriers for EOs. The three-dimensional network structure of hydrogels encapsulates the EOs through physical or chemical interactions, thus reducing their evaporation and enhancing their stability.

Recent advances in hydrogel-based encapsulation systems have resulted in significant improvements in the sustained release and antimicrobial activity of EOs for food preservation applications. The thermal stability of *Fructus Ligustri Lucidi* EO (FEO) was significantly improved by encapsulation within sodium alginate (SA)/gelatin (Ge) hydrogel beads formed through electrostatic interactions and hydrogen bonding. The composite beads exhibited a high swelling ratio in alkaline environments, enabling the sustained release of FEO^[48]. Similarly, pectin-chitosan composites encapsulate coffee EOs through electrostatic interactions and ionic crosslinking. High-methoxyl pectin (HMP) enhances EO retention and antioxidant activity but exhibits rapid release due to its loose structure. Low-methoxyl pectin (LMP) forms a tight "egg-box" gel, which delays release but EO-induced electrostatic disruption reduces its mechanical strength. Chitosan

improved the acid stability, but excessive concentrations hindered EO diffusion. Optimizing crosslinking density and EO polarity is crucial for balancing controlled release and bioactivity^[49]. Hydrogels exhibit matrix-specific synergy with essential oils in food preservation. In humidity sensitive blueberries, a humidity-responsive hydrogel pad released thyme oil at higher rates under increased humidity, keeping fruit mold free for 20 days^[50]. In aquatic products, a hydrophilic hydrogel loaded with cinnamon oil absorbed exudates and enabled long-lasting release through gradual disintegration, extending fish fillet shelf life from 7.4 to 12.0 days^[51]. For ready to eat foods, a humidity-responsive hydrogel film containing lemongrass oil accelerated oil release as relative humidity rose, delivering adaptive antimicrobial protection^[52]. These examples demonstrate how hydrogels leverage their water absorption, responsiveness, and tunable release to achieve targeted preservation across diverse food matrices. Although these hydrogels enhance EO stability and antimicrobial efficacy, challenges remain, including inconsistent release profiles under varying pH conditions, the reduced mechanical integrity of EO-loaded gels, and potential diffusion limitations at high polymer concentrations. Future research should focus on tailoring the hydrogel crosslinking density and polymer-EO interactions to achieve precise release kinetics while maintaining structural stability, thereby maximizing their potential in active food packaging and preservation.

3.5 Liposomes

Liposomes are amphiphilic structures composed of phospholipid layers that can encapsulate both water- and fat-soluble drugs and control their release rates^[53]. The primary components of liposomes are phospholipids, including phosphatidylcholine and phosphatidylethanolamine, which are typically derived from natural sources such as soybean or egg yolk. Liposomal stability is influenced by the thermotropic phase behavior of phospholipids and can be enhanced by incorporating regulators that increase membrane rigidity and reduce permeability. Furthermore, liposome preparation methods, include thin-film hydration^[54], reverse-phase evaporation, ethanol injection, and advanced techniques such as supercritical fluids and microfluidics^[55]. Liposomes are effective delivery systems in food science, protecting functional ingredients from environmental degradation, while enhancing their bioavailability. In liposome-EO systems, lipophilic EO components are embedded within the hydrophobic region of the phospholipid bilayer, whereas hydrophilic constituents are encapsulated in the aqueous core of vesicles, forming stable nano delivery systems. Liposomes significantly improve the functional properties of EOs via multiple mechanisms.

For example, hydrophobic interactions between phospholipid bilayers and lipophilic EO components enable the formation of stable nanostructures that facilitate controlled release. Eucalyptus oil liposomes (76.6% EE) extend the shelf life of shrimp from 3 to over 7 days through sustained antioxidant and antimicrobial release^[56]. Liposome-based delivery systems offer versatile solutions for food preservation by combining extended antimicrobial activity and quality protection through precisely engineered release mechanisms. In addition, some liposomes can be modified by polymers to achieve environmentally triggered release and enhance the efficacy of EOs in plants. For example, the pH-responsive γ -polyglutamic acid-modified liposomes (Lip-PHEO) demonstrated intelligent release of *Alpinia galanga* EO under acidic

conditions, where polymer chain curling disrupted phospholipid bilayers. This triggered release enhanced the antioxidant activity by 30% and significantly improved the antibacterial effects against foodborne pathogens in chilled pork preservation, effectively reducing microbial counts and lipid oxidation while targeting spoilage-induced pH changes. Such a responsive release mechanism targets the microenvironmental changes in pH during food spoilage, enabling the precise release of EOs to enhance efficacy while minimizing unnecessary waste^[54]. Liposomes can also achieve functional enhancement through multilayer synergistic effects. Notably, CLEO was encapsulated in a liposome-hydrogel hybrid system, achieving sustained release through combined liposomal permeation and hydrogel degradation. This hierarchical structure significantly inhibits volatilization and maintains effective fumigant toxicity while preventing direct contact with food^[53]. These multilayer structures, through electrostatic deposition, responsive release, and composite systems, significantly enhance the stability and antimicrobial efficacy of the EOs.

EO delivery systems exhibit both advantages and limitations. NEs provide high encapsulation efficiency, but are less stable than particle-stabilized PEs. Microcapsules offer strong environmental protection, whereas liposomes exhibit excellent biocompatibility and dual-compound encapsulation. Electrospun fibers provide high surface-area release and hydrogels allow swelling-controlled release, although both suffer from limited mechanical strength in water.

Among the systems discussed, nanoemulsions appear particularly promising for high-salt or high-fat matrices due to their salt-accelerated release, while humidity-responsive hydrogels and nanofibers show greater potential for high-humidity fresh produce and fresh-cut vegetables. Edible films are relatively more suitable for refrigerated meat products based on their moisture barrier function. Microcapsules, however, lack sufficient evidence for matrix specific superiority. Nevertheless, current research on essential oil encapsulation has largely focused on sustained or controlled release or environmentally triggered release, whereas studies that rationally design delivery systems according to specific food matrix characteristics remain scarce. However, hybrid systems that combine these strengths to improve performance are emerging. Recent research has proposed a carrier adaptation strategy for polysaccharides that matches carriers to compound properties and application needs^[57], a logic that could be extended to design matrix tailored essential oil delivery systems for food preservation beyond simple triggered release. Future research should prioritize the development of intelligent hybrid delivery systems that integrate the complementary advantages of existing platforms, to achieve multifunctional EO encapsulation tailored to diverse food matrices. Such systems are expected to leverage engineered responsive mechanisms and multilayered architectures to significantly improve bioactivity, stability, and controlled-release profiles, thereby facilitating scalable applications in food preservation and related sectors.

4. Synergistic strategies

4.1 Synergistic effects with physical field technologies

The combination of EOs and physical field technologies represents a promising strategy for overcoming the inherent limitations of each system. EOs possess broad-spectrum antimicrobial activity but have

limitations such as poor water solubility, volatility, sensitivity to degradation, and negative effects on organoleptic properties at effective concentrations. Conversely, non-thermal physical fields (e.g., cold plasma and pulsed light) offer rapid, residue-free microbial inactivation but can oxidatively damage food components, exhibit inconsistent treatment, and require high energy inputs for efficacy^[58]. The integration of these technologies capitalizes on their complementary mechanisms of action, often yielding a synergistic effect that permits the use of reduced EO concentrations and milder physical processing parameters. This synergy not only enhances microbial safety but also preserves food quality and extends shelf life.

Intense light pulses (ILPs) possess antibacterial activity and can act synergistically with EOs to enhance overall antimicrobial efficacy. Recent research has found that sequential application of ILPs and lemongrass EO (LgEO) in the vapor phase significantly enhances the inactivation of *Salmonella* on sunflower and quinoa seeds^[59]. Furthermore, ultrasound (US) can act synergistically with EOs to enhance antimicrobial efficacy. A notable example is its synergy with nano emulsified basil oil, which synergistically inactivates *Salmonella* through irreversible cellular damage, while maintaining food quality^[60]. Moreover, high-voltage electrostatic field (HVEF) enhances the antimicrobial performance of EOs through a synergistic interaction. A study showed that the synergistic effect of HVEF and CiEO significantly enhanced minced pork preservation by disrupting microbial membranes and inducing oxidative stress, while maintaining sensory qualities^[61].

The integration of physical field technologies with EOs exhibits a marked synergistic effect, significantly enhancing the antimicrobial performance beyond the efficacy of either treatment alone. This combination facilitates a substantial reduction in the EO dosage required for effective microbial inhibition, while concurrently improving functional stability and mitigating adverse sensory impacts on food products.

4.2 Synergistic effects of bio preservatives and EOs

Biocontrol agents and EOs have gained considerable attention as natural antimicrobials for food preservation; however, there are inherent limitations. For instance, nisin, a widely used bacteriocin, exhibits potent inhibitory effects against gram-positive bacteria^[62]. Similarly, lysozyme is effective against gram-positive bacteria but shows limited efficacy against gram-negative species^[63]. In contrast, EOs exhibit broad-spectrum activity, but their high effective concentrations often impart undesirable sensory attributes to foods and exhibit poor chemical stability. Recent studies have demonstrated that a combination of biocontrol agents with EOs can produce synergistic antimicrobial effects. This strategy not only reduces the required dosage of each component, mitigating negative impacts on food quality, but also extends the antimicrobial spectrum, offering a promising approach for designing efficient, low-concentration, natural preservation systems.

The synergistic effects of EOs and biocontrol agents have been demonstrated in various practical applications, particularly in enhancing the preservation of highly perishable foods. A composite film incorporating perilla EO, nisin, and chitosan effectively suppressed *S. aureus* growth and reduced the total volatile basic nitrogen content in ready-to-eat fish balls^[64]. The results highlight the application potential of combining EOs with biocontrol agents, such as nisin, to develop effective antimicrobial packaging systems for

aquatic products that are highly susceptible to spoilage. In addition to nisin, other biocontrol agents exhibit promising synergies with EOs. Combining lysozyme with oregano or thyme EOs (TEOs) significantly enhanced antimicrobial efficacy against both gram-positive and gram-negative bacteria. The Lys-OEO emulsion, optimized by ultrasonic treatment, extends the antimicrobial spectrum and improves physicochemical stability, whereas Lys-modified TEO liposomes exhibit superior thermal, acid, and salt stability^[65, 66]. These synergistic approaches offer effective strategies for natural food preservation that leverage complementary mechanisms of action. In addition, the antimicrobial interactions between EOs and bioactive peptides are complex and system-dependent, potentially yielding synergistic effects. Although chitosan/furcellaran NEs co-loaded with oregano EO and peptides showed enhanced broad-spectrum activity and stability, the peptide-EO interaction was not universally positive. In chitosan-based microemulsions, peptide addition reduces the efficacy against certain gram-negative bacteria. Significant synergy appeared to rely primarily on the intrinsic EO components, indicating that the role of bioactive peptides is constrained by the delivery system and target microorganisms, highlighting both the potential and limitations of peptide-EO combinations in antimicrobial formulations^[7]. Similar conclusions were drawn by other scientists^[67].

Despite the promising synergy between EOs and biological preservatives, key challenges, including interactions with food matrices, sensory impacts, and regulatory requirements, impede their commercial application. Future research should focus on advanced delivery systems to improve the stability and release, along with sensory and toxicological studies. Addressing these barriers is crucial to harness their potential as natural antimicrobial agents.

4.3 Combination of EOs and smart packaging

The direct incorporation of EOs into packaging is limited by their high volatility, oxidative degradation, and negative effects on polymer properties. To overcome these issues, smart packaging systems have been developed for the controlled, stimulus-responsive release of EOs. This enables on-demand delivery and enhances the preservation efficiency and functionality.

Stimuli-responsive antibacterial packaging materials are novel smart materials that can respond to various stimuli produced by food or the external environment, including pH, temperature, oxygen, moisture, and light, to control the release of functional ingredients^[68]. By incorporating EOs into responsive matrices, it is possible to achieve targeted and timely release, thereby enhancing antimicrobial efficacy while minimizing the premature loss of active compounds. This synergistic approach not only extends the shelf life of packaged products, but also contributes to the development of more efficient and sustainable packaging solutions. The soy lipophilic protein-hydroxypropyl methylcellulose (LP-HPMC) bilayer film with TEO and shikonin, and the electrospun polyvinyl alcohol (PVA) film containing CiEO in poly(ethylene glycol)-poly(ϵ -caprolactone) (PEG-PCL) micelles and blueberry anthocyanin (BA), both demonstrate synergistic effects between EOs and stimulus-responsive components. Encapsulation of EOs (in NEs or micelles) enhances their stability and enables sustained antimicrobial release. Natural pigments (shikonin or BA) provide visible pH/ammonia-responsive color changes for real-time freshness monitoring^[69, 70]. These combinations integrate

long-acting antibacterial activity with intelligent spoilage indicators, offering a dual-function strategy for advanced food packaging.

Advanced material designs and multi-layer architectures are critical for the practical applications of these responsive systems. By employing multilayer designs, the two functional packaging systems can integrate EOs with biopolymer matrices to achieve synergistic preservation and monitoring. OEO in a konjac glucomannan-based emulsion layer provides sustained antibacterial activity, while a carrageenan indicator enables real-time NH_3 sensing^[71]. Similarly, savory oil (SEO) encapsulated in electrospun PVANFs imparts antioxidant properties, complemented by a gelatin-eggplant extract indicator for visual freshness detection^[72]. Despite the differences in matrix materials and fabrication techniques (emulsion casting versus electrospinning), both designs leverage the complementary roles of EO-containing active layers and intelligent indicator layers, highlighting a versatile and synergistic strategy for enhancing food preservation and spoilage detection in bilayer packaging systems.

In summary, the integration of EOs into advanced packaging systems marks the transition from conventional active materials to intelligent multifunctional platforms. These systems use engineered release mechanisms, responsive material designs, and layered architectures to enhance the stability and efficacy of the EOs, thereby improving food preservation and enabling real-time quality monitoring. Future developments require tailored activation thresholds and scalable safety-compliant systems.

5. Application

EOs are promising natural antimicrobials for food preservation. However, their efficacy is strongly influenced by their interactions with the food matrix. Proteins, lipids, and carbohydrates can adsorb or bind to bioactive compounds, thereby altering their antimicrobial activities^[6]. To overcome these limitations, encapsulation technologies and rational formulation designs are being developed to enhance EO stability, enable controlled release, and minimize sensory impact. These advances have facilitated the development of highly effective clean-label preservation systems suitable for modern food products with reduced additives, demonstrating significant potential for commercial translation and broader industrial adoption (Fig. 4 and Table 2).

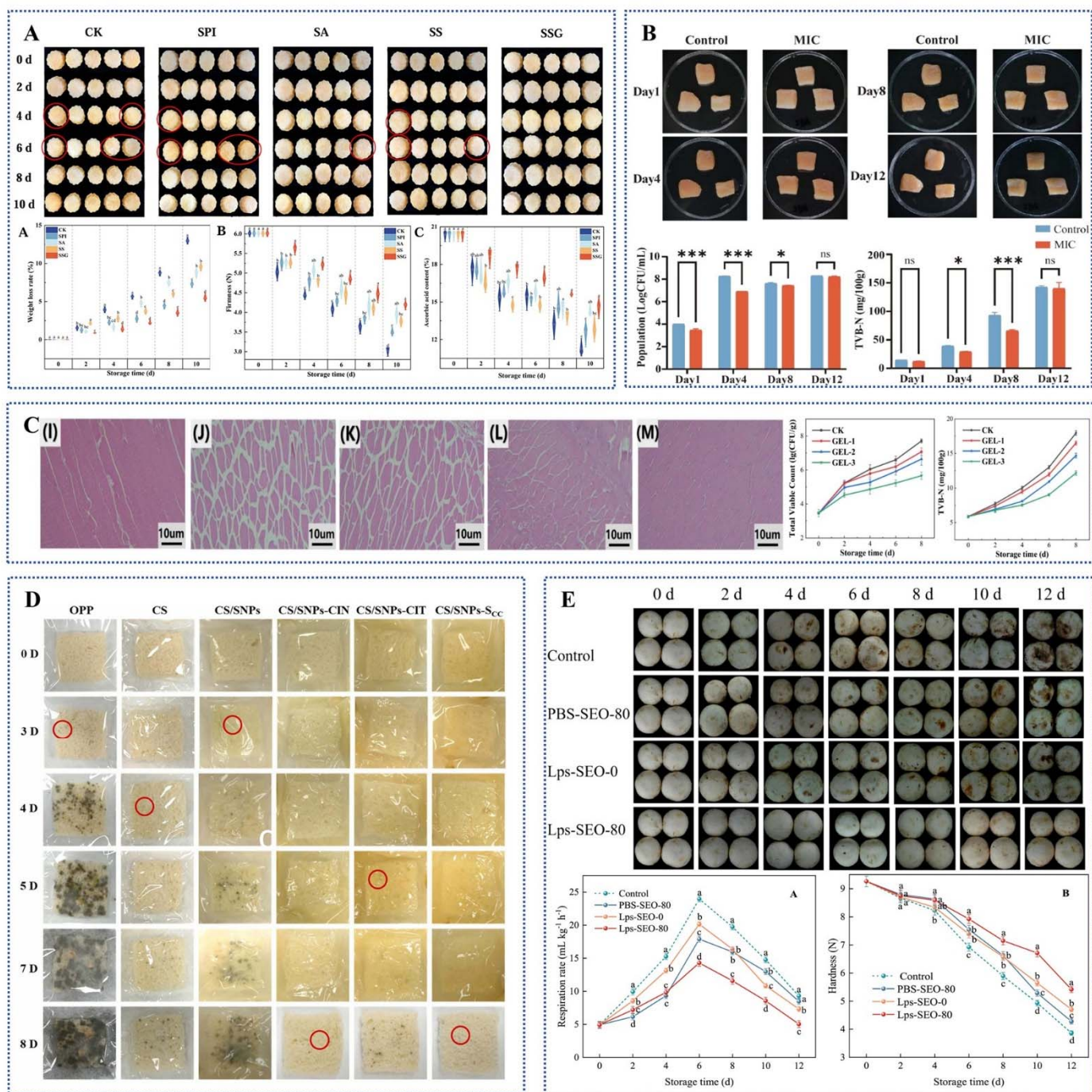


Fig. 4 Applications of essential oils in food preservation. A. Effects of different emulsion coatings on the appearance and morphology of fresh-cut cantaloupe [73]. B. Application of calamansi essential oil in chicken preservation [117]. C. Oregano essential oil/β cyclodextrin microcapsules for chilling preservation of grass carp fillets [80]. D. Application of chitosan/shellac nanoparticles-essential oil pickering emulsion in bread preservation [85]. E. *Salvia officinalis* essential oil nano-liposomes in postharvest preservation of *Agaricus bisporus* [114].

Table 2. Application of essential oils in food preservation

Food Category	Specific Preserved Food	Preservation System	Essential Oils	Target Microorganisms	MIC/MBC	Applied Concentration	Reference
Fruits & Vegetables	Fresh-cut carrots	Emulsion coating	LEO,GEO	<i>S. aureus</i> , <i>E. coli</i>	MIC:50-100 mg/mL MBC:50-100 mg/mL	10% oil phase	[75]
	Apple	PWEO	PWEO	<i>B. dothidea</i> <i>S. Aureus</i> ; <i>E. coli</i> <i>P.citrinum</i>	MIC: 2.00 mL/L	128.00 mL/L	[115]
	Strawberries	Chitosan/Silk Fibroin + CEO Microemulsion	Cinnamon Essential Oil	<i>A. niger</i> ; <i>M. Recemosus</i> <i>T. viride</i> ,	NR	3% (v/v) in film-forming solution	[116]
	Chicken breast	Refrigerated storage (4 °C)	CAEO	<i>S. aureus</i>	MIC: 1 mg/mL MBC: 2 mg/mL	1/2 MIC (0.5 mg/mL) and MIC (1 mg/mL)	[117]
Meat and meat products	Chilled pork	FEO/HP- β -CD inclusion complex	FEO	General spoilage microorganisms	NR	1% (w/w)	[118]
	Pork sausage	Ar-CP treated PBS/TPS film coated with MEO	MEO	General spoilage microorganisms	NR	80 % (v/v)	[119]
Fresh seafood	Sea bass	KGM/GEL/BC composite film	GEO REO	<i>S. aureus</i> , <i>E. coli</i>	GEO: 7.8 (alone) REO: 7.8 (alone) GEO: 0.97 (combined) REO: 1.95 (combined)	0.8% (w/v) (3:1 GEO:REO ratio)	[120]
	Pacific white shrimp	Electrospun PVA/chitosan (PVA-CS) film	CEO	<i>S. Aureus</i> ; <i>E. coli</i> <i>B subtilis</i> <i>Salmonella typhi</i> <i>Klebsiella pneumonia</i> <i>P aeruginosa</i> <i>B pumilus</i>	MIC:3.13% (v/v) against Lv-SSOs	10% (v/v) CEO in film-forming solution (actual loading: 25.26 $\pm$ 0.77 μ g/mg film)	[41]
	Bread	Direct incorporation into dough	LEO	<i>A. flavus</i> <i>P. crustosum</i>	Free LEO: 30 μ L/mL Fibers: 20 mg/mL MFC: 330 μ L/mL (Free LEO)	0.0017 μ L LEO/mg dough; 0.0009 mg fibers/mg dough	[86]
Baked goods	Bread	Coaxial electrospun film (CS/PVA shell, β -CD@EEO core)	EEO	<i>E. coli</i> <i>S. aureus</i>	NR	β -CD : EEO molar ratio = 1:1; EEO concentration range: 0.5% - 3.0% (w/v);	[121]

Others	Toast bread	Solvent-cast PVA-Ch composite film with nanoemulsions	Basil essential oil, carvacrol, and their combination (1:1 wt)	<i>E.coli</i> <i>S. Aureus</i> <i>A. niger</i>	NR	optimal: 2.5% Nanoemulsion addition: 1 g / 100 g total polymer (1% w/w); oil phase concentration in nanoemulsion: 6 g/100 g	[122]
	Milk (whole, low-fat, skim)	Nanoencapsulation (pectin:whey protein concentrate, 75:25 w/w) Sodium caseinate/HPCD nanoemulsion	Carvacrol	<i>B. cereus</i>	Nanoemulsion MIC: 0.15 mg/mL MBC: 0.30 mg/mL; Free carvacrol MIC: 0.19 mg/mL, MBC: 0.38 mg/mL	0.075-0.20 (free & encapsulated) 0.15 mg/mL	[123]
	<i>Agaricus bisporus</i> (white mushroom)	Nano-liposomes (thin-film dispersion + ultrasonic hydration; lecithin:cholesterol = 4:1 w/w)	SEO	<i>Pseudomonas</i> sp.	NR	Lps-SEO-80: 4:1 (SEO:lipid suspension)	[114]
	Fresh eggs	Gellan gum-rice bran oil (GG-RBO) emulsion + basil essential oil (BEO)	BEO	Total aerobic bacteria	NR	0.50% (v/v)	[124]

5.1 Fruit and vegetable products

The synergistic effect of the targeted antimicrobial activity of EOs and their delivery systems provides innovative solutions for fruit and vegetable preservation through a multidimensional mechanism of action. The active ingredients in EOs exert antimicrobial effects via multiple mechanisms, while the delivery system significantly enhances bioavailability by improving EO stability, controlling the release rate, and enhancing tissue permeability.

For instance, CiEO encapsulated within composite particles exhibits significant fresh-cut cantaloupe preservation efficacy, demonstrating strong antimicrobial activity and effectively maintaining postharvest quality by reducing weight loss, delaying respiratory metabolism, and preserving firmness and ascorbic acid content^[73]. Similarly, a composite film containing ginger essential oil significantly reduces the rot rate of grapes and maintains fruit firmness, ascorbic acid, and soluble solids, thereby effectively extending the storage life of grapes^[74]. A composite pectin/caseinate-based lemon/ginger EO emulsion effectively extended the shelf life of fresh-cut carrot shelf-life to 10 days by enhancing the antioxidant capacity, inhibiting microbial growth, and preserving key quality attributes^[75]. The active film containing ginger essential oil Pickering emulsion exhibited antibacterial effects against foodborne pathogens (*E. coli* and *S. aureus*) and spoilage bacteria (*P. aeruginosa* and *B. subtilis*), thereby delaying strawberry decay and maintaining fruit quality^[76]. However, within individual studies, direct comparisons between different delivery systems applied to the same fruit matrix are rarely conducted, which limits the ability to identify the most effective formulation for a given produce type. Additionally, most of the available studies report preservation effects over relatively short storage periods (typically up to 10-15 days), whereas longer-term safety, sensory acceptance, and economic feasibility remain underexplored. Therefore, future advances in the EO-based preservation of fruits and vegetables should prioritize the development of tailored delivery systems with enhanced biocompatibility, stimuli-responsive release behavior, and improved cost efficiency. Interdisciplinary efforts that integrate food technology, materials science, and horticultural science are crucial for simultaneously optimizing antimicrobial efficacy, phytocompatibility, and storage stability. Such innovations will support the scalable adoption of EO formulations as eco-friendly and effective solutions for extending the shelf life and preserving the quality of fresh produce.

5.2 Meat and meat products

EOs have significant potential for natural meat preservation owing to their antimicrobial properties. However, their efficacy is considerably influenced by their interactions with major food components, particularly proteins and lipids. Antimicrobial activity is substantially reduced when bioactive compounds form complexes with proteins or are sequestered by lipids, thereby decreasing their free and active concentrations^[6]. The extent of inhibition varies considerably among individual EOs depending on their specific chemical properties. Therefore, optimizing EO efficacy requires careful selection of the oil type and dosage based on the specific protein and lipid composition of the food matrix.

Lavender EO (LaEO), a natural plant extract, exhibits remarkable antioxidant and antimicrobial properties for meat preservation. Its active components, predominantly linalool and linalyl acetate, effectively inhibit lipid oxidation in lamb meat, and significantly suppress the growth of aerobic mesophilic bacteria, psychrotrophic bacteria, yeasts, and molds^[77]. Oregano essential oil encapsulated in ZIF-8 endowed the composite film with antimicrobial and antioxidant functions, effectively inhibiting microbial growth and oxidative deterioration in chilled beef and extending its shelf life to 12 days^[78]. Moreover, lemon EO (LEO) NEs embedded in a β -glucan-based edible film enhanced chilled pork preservation through sustained release, nanoencapsulation improves lipid compatibility and distribution, significantly extending the shelf life compared with that of untreated controls^[79]. Notably, while the interaction of EOs with meat proteins and lipids is acknowledged as a critical factor influencing efficacy, the reported studies do not quantitatively assess how this interaction affects the performance of each delivery system. Consequently, the extent to which encapsulation strategies actually overcome matrix induced activity loss remains unclear. However, the application of EOs in meat preservation requires a careful balance between antimicrobial efficacy and biocompatibility with the food matrix. Excessive concentrations can impair functional properties and induce an inconsistent distribution. When effectively integrated, EOs synergistically contribute to shelf-life extensions. However, their release kinetics and interactions with meat constituents such as proteins and lipids require further elucidation and optimization to enhance their practical utility in industrial settings.

5.3 Fresh aquatic products

Fresh aquatic products are vital sources of nutrition and are crucial to global food systems. However, the extended and complex seafood supply chain makes them highly susceptible to biological and chemical contamination, which can lead to nutrient degradation and increase consumer health risks. EOs offer a promising natural preservation strategy for aquatic products owing to their broad-spectrum antimicrobial and antioxidant properties, which can inhibit microbial spoilage microorganisms and oxidative reactions, thereby helping maintain product quality and safety.

For instance, EOs such as oregano, cumin, lemongrass, and Amomum tsao-ko extend the shelf life of fish, primarily by disrupting microbial membranes, however, their efficacy varies: encapsulated oregano oil targets *Pseudomonas* effectively, cumin, and lemongrass oils inhibit *V. parahaemolyticus* biofilms, and Amomum tsao-ko oil disrupts bacterial energy metabolism, offering the strongest preservation^[80-82]. Ginger stalk essential oil effectively delayed the increase in total volatile basic nitrogen, inhibited microbial growth, and slowed color and texture deterioration in salmon, demonstrating outstanding preservation performance^[83]. Similarly, EOs from *Arisaema fargesii* effectively inhibited microbial growth, lipid oxidation, protein degradation, and biogenic amine accumulation in salmon sashimi, thereby maintaining freshness and extending shelf life during chilled storage^[84]. In summary, EOs and their controlled-release technologies demonstrate promising application potential in aquatic product preservation. However, challenges remain in optimizing the volatility, sensory impact, and controlled release efficiency of EOs. Optimal results require matching EOs and delivery systems to the specific spoilage microbiota. Future research should focus on

integrating nanoencapsulation, composite film modification, and other advanced technologies to enhance the stability and targeted-release performance of EOs, thereby promoting their practical application in the food industry.

5.4 Baked foods

Baked goods provide an ideal microenvironment for fungal growth owing to their nutritional composition, suitable water activity, and near-neutral pH. EOs show strong antifungal activity against fungal proliferation in these products. However, the efficacy of EOs is strongly modulated by interactions with major food constituents: proteins bind phenolic compounds through complexation, lipids sequester hydrophobic EOs, reducing their bioavailability, and polysaccharides exhibit divergent effects. Notably, pectin enhances antifungal activity through hydrogel-assisted EO retention^[6]. Consequently, the application of EOs in bakery preservation requires careful selection and delivery strategies tailored to matrix composition to achieve optimal antifungal performance.

Recent studies have highlighted the effectiveness of EO-based delivery systems in extending the shelf life of baked products via distinct mechanisms and material interactions. This chitosan/shellac nanoparticle-EOPE film extends the shelf life of bread by 5 days via the vapor-phase release of EOs, which provides effective antifungal activity and moisture regulation^[85]. Similarly, cassava starch fibers loaded LgEO extended the shelf life of bread by 5 days and reduced fungal counts by 2-log through synergistic matrix interactions. Hydrophilic fibers regulate water activity, whereas hydrophobic LEO targets lipid phases, enhancing antimicrobial efficacy and enabling sustained release during storage^[86]. This finding underscores the necessity of tailoring EO delivery systems to specific food matrix properties, thereby achieving optimal synergy between green preservation strategies and quality maintenance of baked goods.

5.5 Others

EOs have emerged as promising natural preservatives not only for commonly studied food categories but also for various other food systems. Their application in preserving dairy products, cereal-based foods, edible fungi, and seeds has attracted growing research interest, particularly when incorporated into advanced delivery matrices to enhance stability, control release, and improve interfacial interactions with the food matrix. The strategic formulation of EOs within tailored encapsulation systems or active packaging has been pivotal in overcoming inherent limitations, such as volatility and low water solubility, thereby unlocking their full potential in these diverse applications.

A compound EO (CEO) from cinnamon and *Litsea cubeba* has demonstrated effective antibacterial activity by disrupting microbial cell membranes. When encapsulated in temperature-responsive PEs, it extended fresh noodles' shelf life by 3 days via controlled release, achieving 48.7% release at 4 °C through hydrogen bonding interactions^[87]. Furthermore, zein-encapsulated orange essential oil, primarily D-limonene, significantly inhibited *Fusarium* growth in agroecological maize seeds by disrupting fungal membranes and metabolic processes. Encapsulation enables sustained release, whereas hydrophobic and hydrogen-bonding interactions between the oil and seed matrix reduce oxidative damage and enhance preservation efficacy^[88]. In

dairy applications, TEO and Zn-based metal-organic frameworks (Zn-MOFs) were incorporated into carboxymethyl cellulose (CMC) films to preserve Iranian white cheese. The composite film demonstrated strong antioxidant activity, as evidenced by a DPPH radical scavenging rate of up to 56%, along with remarkable antifungal efficacy against common cheese spoilage molds, such as *P. digitatum* and *A. niger*. It effectively reduced moisture loss, maintained pH stability, and suppressed microbial growth, thereby extending the shelf life of the cheese from 5 to 30 days at 25 °C^[89].

These diverse applications highlight the adaptability of EOs in various food preservation contexts. Key success factors include appropriate delivery systems that enable controlled release, maintenance of EO stability, and enhancement of interactions with food matrices. However, the relative importance of these factors varies considerably across different food matrices and spoilage mechanisms, yet few studies have systematically compared their contributions under controlled conditions. Moreover, most reported successes are based on laboratory-scale trials with limited evaluation of industrial scalability, cost effectiveness, or long term sensory acceptance. Consequently, while the adaptability of EOs is well illustrated, a generalizable framework for selecting optimal delivery systems based on matrix specific requirements remains lacking.

6. Industrial challenges

Although significant advances have been made in research on EOs for food preservation, their transition to industrial applications remains at an exploratory phase, with notably few successful cases of large-scale production and commercial implementation. This gap between research and practice highlights the critical industrial challenges that must be addressed to unlock substantial development opportunities and market potential in this field. The following sections detail the major industrial bottlenecks and the potential pathways for overcoming them.

Challenges in standardization and organoleptic quality control: The industrial application of EOs is limited by their inherent compositional variability, which limits their standardization and sensory consistency. This variability stems from the genetic background, geographical origin, and environmental conditions, such as light and temperature. Commercial EOs often exhibit uniform profiles under controlled cultivation conditions, whereas wild populations exhibit significant chemotypic diversity. These differences can be quantified using marker compounds and multivariate analysis^[90, 91]. A comparative analysis of five commercial celery seed oils from China, the United States, France, and India exemplifies this challenge: despite identical labeling, limonene-D content differed markedly across brands, while the bioactive phthalide senkyunolide ranged from undetectable to 34.03% of the total profile^[92]. Moreover, the inherent chemical variability of EOs often leads to inconsistent aroma profiles between batches, sometimes producing harsh or overly intense odors^[93]. These variations complicate their use in flavor-sensitive applications. For instance, in fruits and vegetables, the typical acceptable concentration of essential oils in edible coatings or films is generally in the range of 0.1%-1.3% (w/v or w/w)^[94-96], and in meat products, the typical acceptable concentration of essential oils in direct surface treatments is generally in the range of 0.5%-2% (v/w)^[97-99]. Citrus essential oil (CEO) in pork preservation is optimally used at $\leq 2\%$, but the intrinsic citrus scent of CEO

can interfere with the natural meat flavor, and although encapsulation in a Pickering emulsion mitigates this effect to some extent, the oil concentration still needs to be carefully controlled to avoid undesirable sensory changes^[100]. Addressing this issue requires advanced analytical control and blending techniques. Balancing the need for such technological interventions with the consumer demand for unprocessed "natural" products presents an ongoing challenge to the industry.

2. Safety assessment and regulatory compliance: The commercialization of EOs as food preservatives is contingent on rigorous safety assessments within divergent international regulatory frameworks. The regulatory frameworks governing essential oil usage in food preservation vary substantially across major markets, with regions such as the European Union and the United States maintaining distinct authorization systems that complicate international standardization efforts. Critical concerns include the potential toxicity of specific constituents such as coumarins under long-term exposure, necessitating a systematic toxicological evaluation, particularly regarding the genotoxicity of minor components^[101].

This concern is exemplified in the nutmeg trade, where the adulterant species *M. argentea*, frequently substituted for authentic *M. fragrans*, accumulates the Group 2B carcinogen safrole at levels exceeding 20%, far surpassing the European Commission's daily intake limit of 5 µg/kg^[102]. To enforce regulatory compliance, GC-MS coupled with PLS-DA effectively discriminates authentic from toxicologically compromised samples via quantitative marker divergence. Further priorities include the development of matrix-specific migration testing methods and science-based human exposure assessments to establish safe levels of use. Overcoming the current regulatory fragmentation will require internationally coordinated efforts to advance validated analytical methodologies, transparent data sharing, and predictive safety models. Such integration is essential for aligning EO applications with global safety standards without compromising their natural status or commercial viability.

3. Feasibility of industrial-scale production: The industrialization of EOs for food preservation faces multiple technical challenges. From a production perspective, the efficiency and cost-effectiveness of extraction processes require significant improvement, and physicochemical stability issues further constrain their large-scale applications. To achieve commercial viability, key technological breakthroughs must focus on developing energy-efficient extraction and purification methods, constructing stable delivery carrier systems, and optimizing synergistic formulations with other natural preservatives. These innovations would substantially reduce production costs, while enhancing product performance and market competitiveness.

4. Precision control of delivery systems: Precision control of delivery systems is essential for overcoming the key challenges associated with the application of EOs in foods, particularly their volatility, thermal sensitivity, and tendency to form off-flavors during processing. Conventional incorporation methods result in the rapid loss of active aromas and their degradation under heat, severely limiting their functionality and sensory quality. To address these challenges, future studies should prioritize the development of precision delivery technologies. This includes designing stimuli-responsive carriers, establishing matrix-specific release protocols, and enhancing the compatibility with diverse food substrates. Such advanced systems

provide targeted protection, controlled release, and minimal thermal degradation, thereby significantly improving the stability, bioactivity, and consumer acceptance of EOs in complex food systems.

5. Application validation and scenario adaptation: The transition from laboratory research to industrial implementation requires systematic validation. Current priorities include strengthening efficacy verification across different food matrices, establishing standardized evaluation methodologies, and exploring practical application models for cold-chain logistics and retail distribution scenarios. Pilot-scale tests and industrial trials should be conducted to progressively refine the applied technology framework.

6. Effective Concentration Toxicity Assessment: As EOs gain increasing attention as natural food preservatives, their safety at effective antimicrobial concentrations remains insufficiently characterized. Although the US FDA classifies many EOs as “generally recognized as safe” (GRAS), this status is primarily based on historical use in flavors or at very low oral doses, and does not systematically consider the chronic, daily intake scenario when EOs are used at concentrations required to inhibit foodborne pathogens. In contrast, the European Commission, guided by EFSA risk assessments, has adopted a far more conservative stance: it has authorized only a few natural antioxidants (e.g., rosemary extract, ascorbic acid, tocopherols) as food additives and has not approved any EOs for human consumption beyond feed additive use^[103, 104]. Other major jurisdictions adopt similarly restrictive positions. In China, essential oils are included as natural flavors in the national standard GB 2760, which explicitly limits their use to flavoring purposes, with no provisions for their application as preservatives at antimicrobial concentrations. Japan permits them only as natural flavors under GMP without defined maximum limits; and the Eurasian Economic Union (EAEU), under TR CU 029/2012, includes EOs solely as flavoring substances. This regulatory discrepancy reflects a fundamental gap in the current evidence base—namely, the lack of comprehensive toxicological profiles for EOs, including repeated-dose oral toxicity data, genotoxicity, carcinogenicity, and reproductive toxicity (Table 3).

Table 3. Comparison of basic information on food additive/flavouring regulations in the EU, US, China, Japan, and EAEU.

	Core Regulations	Management Mechanism	Safety Assessment Body	Acceptable Daily Intake System Types	Limits for Undesirable Substances
European Union	No.1334/2008 (flavourings) No.1333/2008 (additives)	Mandatory approval system	EFSA (FAF Panel)	Numerical ADI: Explicit upper limit (0-X mg/kg bw/d); ADI “not specified”: Very low toxicity, no numerical limit, must be used under GMP; Group ADI: Single ADI shared by multiple related substances, total intake must not exceed the group ADI; Temporary ADI: Data incomplete, valid for a limited period, may become permanent or be withdrawn	Annex III Part B: specific mg/kg limits for methyleugenol, safrole, pulegone, etc.
United States (USA)	21 CFR Part 182 (GRAS)	Company self-determination of GRAS	FDA (company/industry experts)	Additives follow JECFA ADIs; GRAS substances have no ADI	No specific federal limits; 21 CFR 189 prohibits coumarin and safrole as additives
China	GB 2760-2024	Catalogue management administrative licensing	China National Center for Food Safety Risk Assessment (CFSA)	Follows JECFA: Numerical ADI, ADI “not specified”, Group ADI	Partially refers to GB 2762 or prohibition lists; No flavour specific limits
Japan	Food Sanitation Act; Specifications and Standards for Foods; Food Additives; Japan’s Specifications and Standards for Food Additives (JSFA)	Designated additives (mandatory approval); Existing additives (recognised by historical use); Natural flavourings and general food additives (use under GMP, no specific limits)	Food Safety Commission of Japan (FSCJ) risk assessment Ministry of Health, Labour and Welfare (MHLW) management	Designated additives: ADIs set following JECFA; Natural flavourings: no ADI (due to very low usage levels, used under GMP)	Negative list management: only prohibited substances are listed; natural flavourings generally have no specific limits. Adopts JECFA group ADIs and maximum food limits.
Eurasian Economic Union	TR CU 029/2012	Essential oils are regulated as flavorings. Natural flavorings must come from plant/animal sources via physical, enzymatic, or microbial processes	EEC Council (policy) EEC Technical Dept.and national bodies Apply to EEC for new substances	Policy: EEC Council. Technical assessment: EEC Technical Regulations Department + national bodies New substances: Apply to EEC for risk assessment.	Must comply with TR CU 021/2011 (heavy metals, pesticides, microbiology).

Recent toxicological assessments of citrus essential oil nano-emulsions confirm that at effective antimicrobial concentrations, these oils exhibit cytotoxicity, metabolism-dependent genotoxicity, and high predicted risks of skin sensitization and respiratory toxicity, while lacking chronic safety data or an established ADI-highlighting the inadequacy of GRAS status for food preservative applications^[105]. Even recent safety evaluations of individual EOs, such as the acute toxicity study of *Ligusticum jeholense* essential oil (LEO) in mice, reported no overt toxicity at single oral doses up to 1000 mg/kg, but such data are limited to acute exposure and lack repeated-dose, chronic, or reproductive toxicity endpoints, nor do they provide an acceptable daily intake (ADI)^[106]. Furthermore, no acceptable daily intake (ADI) has been formally established for most EOs when used as food preservatives, and critical endpoints such as cytotoxicity toward intestinal epithelial cells, skin sensitization potential, and risks associated with long-term low-dose exposure remain poorly characterized.

7. Conclusions and future perspectives

In summary, this review critically assessed the potential of EOs as next-generation antimicrobials for food preservation, addressing the fundamental mechanisms of action, recent technological advances in delivery, and persistent challenges in industrial applications. This review has systematically examined the potential of EOs as natural antimicrobial agents for food preservation by integrating a comprehensive framework encompassing "composition-mechanism-delivery technology-industrialization pathway," tracing the complete developmental chain from fundamental research to practical applications. Evidently, within this framework, while EOs hold great promise as sustainable alternatives to synthetic preservatives, their transition to industrial applications requires coordinated innovation across multiple disciplines.

1. Standardization and chemotype characterization: Establishing reliable standards for the consistency of raw materials is essential. This includes precise chemotyping of plant sources; controlling variations due to genetics, geography, and harvest conditions; and adopting advanced analytical methods (e.g., Gas chromatography-Mass spectrometry (GC-MS) combined with multivariate analysis) for quality assurance.

2. Food matrix-specific optimization: The antimicrobial behavior of EOs is highly dependent on the composition of the food (e.g., fat, protein, carbohydrate content, water activity, and pH). Future research should move beyond model systems to optimize EO formulations for specific food matrices. A fundamental understanding of how food components bind, release, or deactivate antimicrobial compounds is required for designing effective and targeted preservation strategies.

3. Development of smart and sustainable formulations: Future studies should explore stimuli-responsive release systems that enhance antimicrobial efficacy while minimizing organoleptic effects. Additionally, the environmental footprint of EO-based preservation, from cultivation to extraction and application, should be evaluated through a life-cycle assessment to ensure overall sustainability.

4. Sustainable scaling and regulatory integration: Translating these advanced formulations to the industry requires addressing scale-up challenges, conducting rigorous cost-benefit and lifecycle analyses, and

proactively engaging with regulatory bodies to establish clear safety and labeling guidelines for EO-based combination treatments and novel delivery systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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