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Recent trends in the application of essential oils: The next generation of food preservation and food packaging

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ABSTRACT

Background: Essential oils (EOs) are plant-derived volatile and aromatic extracts with diverse biological effects like antibacterial, anti-inflammatory, and antioxidant properties. Recently, consumers' perceptions of synthetic preservatives have grown unfavorable, spurring research in EOs and their application in food preservation and packaging of vegetables, dairy products, fruits, meat products, and other food items. However, the main impediments to using EOs as food preservatives include their safety limitations, distinctive organoleptic effects, and possible contamination by chemical substances like pesticides.
Scope and approach: This review discusses the recent developments in the application of EOs from plants and spices as antimicrobial agents for food preservation and shelf-life augmentation. We have also highlighted new developments in encapsulating strategies to get beyond some significant intrinsic constraints, such as low water solubility, volatility, bioavailability, and stability in food systems. Lastly, we have also shed light on the recent pioneering in smart packaging systems to prolong the shelf-life of the food product.
Key findings and conclusion: EOs have the potential to preserve food matrices from various microbes and maintain the quality of meat, fish, dairy, fruits, and vegetable products. They have also proven to greatly influence cooking and increase the shelf life of food products. The core material of encapsulated and nano-encapsulated EOs promise to ensure their continuous release in response to various triggers and promote better food preservation. Overall, this article provides current knowledge about the EOs in food preservation and identifies research avenues that can facilitate the implementation of EOs as natural preservatives in foods.

1. Introduction

Access to food, food stability, food use, and, most significantly, the food's preservation in order to prevent future contamination are the four pillars on which the attainment of food security is now founded. Due to their lasting effects all the way down the food chain and food web, microorganisms and the toxins they produce are key contributors to food spoilage and biodeterioration and therefore to food insecurity (Maurya et al., 2021). Around the world, one-third of the food produced is lost or squandered, amounting to 1.3 billion tonnes annually and costing over $1.0 trillion (Liegeard & Manning, 2020). Many conventional food preservation techniques presently in use can preserve food to some extent but can also degrade food quality by lowering its nutritional content. Consumer health has reportedly been put at risk by several synthetic antimicrobials that have been licensed by regulatory bodies and used as food preservatives. Sulfites, a class of sulfur-based chemicals used in food preservation, have been linked, for instance, to various anti-nutritional effects such as the deterioration of thiamine or vitamin

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B1 in food (Falleh et al., 2020; Gutiérrez-del-Río et al., 2018). Nowadays, consumers are expressing a growing desire for food products that are devoid of chemical additives and have a greater natural appeal. Therefore, plant-based essential oils (EOs) garnered much interest in recent years as natural food preservatives.

EOs are complex combinations of volatile chemicals released as secondary metabolites by aromatic plants and are found in the glandular trichomes or canals, cavities, secretory cells, and epidermic cells of aromatic plants. Chemically, EOs are a complex blend of phenolics, terpenoids, and terpenes, among other bioactive chemical components (Voon et al., 2012). EOs and their phytoconstituents have achieved tremendous attention in food preservation due to their antifungal, antibacterial, insecticidal, antiviral, and antibacterial properties (Burt, 2004). Although there are more than 3000 different types of EOs, only 300 are used widely in the food industry (Burt, 2004). In the year 2021, the global EO market was USD 8.74 billion. During the projected period of 2021–2028, the market for EOs is anticipated to increase from $9.62 billion in 2021 to $18.25 billion in 2028, at a CAGR (compound annual growth rate) of 9.57 percent (Future Business Insights, 2021).

However, it's worth stating that the high reactivity, intense scent, hydrophobicity, poor solubility, and possibly unfavorable interaction with fat, carbohydrate, and fatty acids in food may restrict their practical applicability despite their great preservation effectiveness in the food system (Hyldgaard et al., 2012). Encapsulation of EOs is one potential solution to these issues since it improves stability and protection, controls the release of chemicals, reduces strong tastes and aromas, extends shelf life, and enhances bioavailability and palatability (Liu et al., 2019; Reis et al., 2022). In the realm of food science and technology, nanotechnology is a rapidly evolving field of research. Many studies focus on this phenomenon because nanomaterials, due to their particle size, have unique properties that make them potentially helpful in food systems. Moreover, recent innovations in materials science and packaging engineering have led to a new packaging technique called "active packaging." The volatile nature of EOs makes them appropriate for antibacterial packaging systems to improve the shelf-life of packaged food products. It offers several advantages regarding physicochemical stability, biological activity, and product quality. EOs have also been employed in developing biodegradable and edible films to mitigate the negative environmental impact of petrochemical-based plastics used for food packaging (Zhang et al., 2021).

This review aims to bring together and discuss the current status of the application of EOs as additives in food preservation and packaging, as well as the recent advancements. First, a concise description of the chemical components of the EOs is presented, followed by a discussion on its anti-bacterial mechanism of action. We have also highlighted the research progress of spice EOs in food preservation. The review then provides an update on studies investigating the efficacy of EOs as antimicrobial agents in food preservation. Furthermore, this review discusses various encapsulation techniques to improve food preservation as a roadmap for future research to serve as a foundation for potential industrial applications, which may pave the way for their use as natural food preservatives, opening up new avenues in this field. Nonetheless, insights into the effective contribution of EOs and research trends in the packaging of perishable food products to extend their shelf-life are also outlined in this review. The overarching objective is to fill up the gaps in knowledge and make information about the use of EOs in food preservation more accessible to the food industry and scientists worldwide.

2. Chemistry of the essential oils

EOs comprise nearly 300 distinct components that make them complex mixtures. They mainly constitute low-molecular-weight volatile organic molecules. The components of EOs may be broken down into two categories: terpenoids and non-terpenoid hydrocarbons. Terpenoids, which are generated by combining two (monoterpene), three (sesquiterpene), or four (diterpene) isoprene units, and phenylpropanoids (non-terpenoid hydrocarbons) are the two structural classes of phenolic chemicals that make up the primary constituents (Maurya et al., 2021). However, phenolic compounds are present in both groups and are occasionally recognized as the main ingredients in several EOs. Although terpenes and their oxygenated derivatives (terpenoids) are more frequent and abundant in EOs, some species have large concentrations of shikimates, particularly phenylpropanoids, which, when present, give the plant a distinctive fragrance and flavor. Short-chain alcohols and aldehydes are examples of non-terpenoid hydrocarbons that may be found in EOs. These hydrocarbons are generated either through the metabolic conversion of phospholipids and fatty acids or by breaking down these two types of molecules. Common aromatic phenols, alcohols, aldehyde, and methoxy derivatives of EOs are cinnamic alcohol, cinnamaldehyde, elemicin, anethole, eugenol, and estragol (Hüsnü et al., 2007). Compounds containing sulfur or nitrogen, such as isothiocyanates and glucosinolates, are frequently found in members of the Brassicaceae family with diverse secondary metabolic sources (Maurya et al., 2021). Recently, one study reported on a number of significant functional groups of EOs, including hydrocarbons (α-pinene, sabinene, α-phellandrene, and farnesene), oxides (linalool oxide, ascaridole, and cineol), lactones (citroptene and bergaptene), esters (eugenol acetate, and linalyl acetate), alcohols. These chemicals make up a significant portion of all EOs and are crucial antioxidant and antibacterial agents (Bora et al., 2020). The chemical structures of some of the main components of EOs are shown in Fig. 1. Table S1 sumamrizes various EOs, their sources and variation in their major composition content based on the geographical location as is provided as supplementary material.

3. Antimicrobial activity of essential oils for food preservation

Since antiquity, EOs and their components have been known to have antibacterial properties (Burt, 2004; Calo et al., 2015). Various commercial products, including food (feed additives for nursing sows and weaned piglets), medicine (dental root canal sealers, antiseptics), and agricultural application (crop protection), use the antibacterial properties of EOs and the key elements of EOs. Since the chemical components of EOs are so diverse, it is difficult to define the exact mechanisms of action for their antibacterial activity. EOs effectiveness is either bacteriostatic (EOs limit bacterial growth, allowing microbial cells to regain

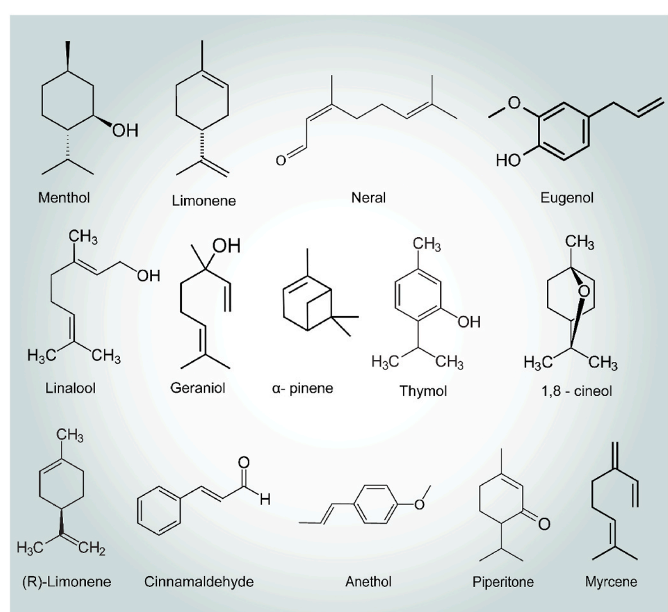

Fig. 1. The chemical structures of some important EOs components.

their reproductive capabilities) or bactericide (EOs destroy bacterial cells) (Chandorkar et al., 2021; Mali et al., 2022, pp. 417–442). Despite this, it is highly likely that the antibacterial activity of EOs is not owing to a single or particular mechanism but is connected to many targets within the bacterial cell (Calo et al., 2015). In this regard, there is widespread consensus regarding the idea that the hydrophobicity and lipophilicity of EOs enable these compounds to pass through the cytoplasmic membrane of cells as well as the mitochondria, thereby permeabilizing the various layers of fatty acids, polysaccharides, and phospholipids found in these organelles (Burt, 2004). The phenolic components of EOs have also been demonstrated to cause the cell membrane to rupture, limiting the cell's capacity to function and eventually causing the cell's internal contents to flow out. This may be due to the phenolic component's ability to damage cytoplasmic membranes, alter microbial cell permeability, disrupt the proton motive force, and interfere with the cellular energy (ATP) generation system. As a result, the cytoplasmic membrane's permeability is compromised, ultimately leading to cell death (Burt, 2004). The antimicrobial mechanism of action of EOs is shown in Fig. 2. The antimicrobial activity of various EOs on various food product pathogens is represented in Table 1. Methods such as agar dilution, agar/disc diffusion, broth micro/macro dilution, direct bioautography, antimicrobial gradient method (Etest), time-kill test, adenosine triphosphate (ATP) bioluminescence assay, flow cytofluorometric method can be utilized in order to ascertain the presence of these antibacterial properties (Balouiri et al., 2016).

3.1. Antimicrobial activity of essential oils in meat and meat products

Meat and products made from meat are especially vulnerable to the intensification of microbes and pathogens present in food, both of which can result in significant financial losses and health risks. They have a variety of nutritional compositions, including high-quality protein content, essential minerals, B – complex vitamins, and amino acids, which are suitable for the growth and proliferation of meat spoilage micro-organisms and common foodborne pathogens (Ji et al., 2021). Bacteria such as *Campylobacter jejuni, Listeria monocytogenes, Salmonella* spp., *Escherichia coli* O157:H7, *Pseudomonas, Acinetobacter, Clostridium* spp, *Lactobacillus* spp., *Enterobacter, Brochothrix thermosphacta,* and others, as well as molds and yeasts, are affiliated to the deterioration of meat and related meat products.

(Radünz et al., 2020) studied the antibacterial potential of spray-dried *Thymus vulgaris* EO to conserve hamburger-like meat products. The authors reported inhibition against *E. coli, L. monocytogenes, S. aureus, S. typhimurium,* thermotolerants, and coliforms up to 14 days, indicating tremendous potential as a natural preservative for meat-based products. (Khanjari et al., 2019), demonstrated the tremendous potential of *Pimpinella anisum* EO (0.3% and 0.5%) for the preservation of refrigerated beef as well as shelf-life enhancement. The study demonstrated successful inhibition of *Listeria monocytogenes*, *Vibrio parahaemolyticus*, *Salmonella typhimurium* with MIC (Minimum Inhibitory Concentration) of 0.015% (v/v) for *Listeria* and 0.12% (v/v) for *Vibrio* and *Salmonella* by *Pimpinella anisum* EO during the storage period (8 days) without altering sensory properties. Ramli and co-workers demonstrated a similar study to improve the shelf-life of stored meat using *Artocarpus heterophyllus* EO. The authors reported strong antibacterial activity against *E. coli, S. marcescens, P. aeruginosa, and S. aureus* (Ramli et al., 2021). The antimicrobial effects of several EOs on meat product pathogens are summarized in Table 2.

3.2. Antibacterial activity of essential oils in fish products

Fish and other seafood are among the most easily spoiled food products. This is primarily because of the development of microorganisms and the oxidation of lipids, which are well-established to be the main causes of the deterioration in the quality of such products. Researchers are investigating the antibacterial characteristics of natural resources, such as the EOs of plants in an effort to identify products that are an effective replacement for synthetic chemicals, improve the oxidative and microbial stability of foods, extend the shelf life of those foods, and are less hazardous to the environment (Hassoun & Emir Çoban, 2017). Since some EOs efficiently lessen or prevent the consequences of bacterial infections in fish, investigations have shown that using EOs in the prevention and/or management of infectious disorders in fish may be a feasible strategy to decrease aquaculture's reliance on conventional antibiotics.

(Chagas et al., 2020) studied the antimicrobial activity of *Mentha*

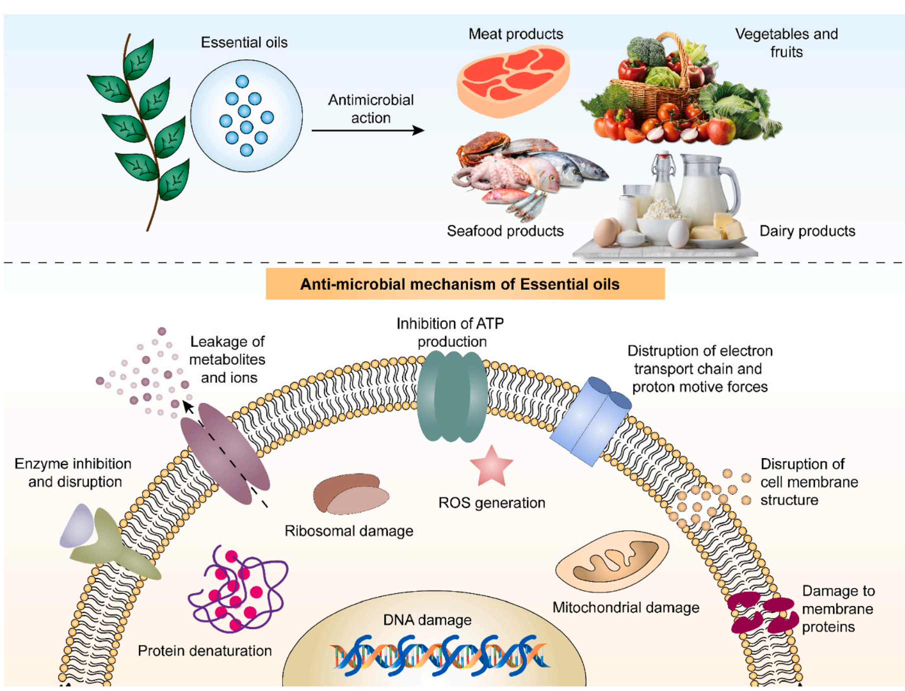

Fig. 2. The antimicrobial mechanism of action of essential oils.

Table 1
Antimicrobial activity of various essential oils on various food product pathogens.

Name of EOs	Major components	Microorganisms inhibited	MIC	Ref
Cymbopogan citratus	Neral (31.50%), citral (26.10%), and geranyl acetate (2.27%)	*B. cereus, E. coli O157:H7, K. pneumoniae, S. aureus C. albicans*	0.08 mg/ml, 0.63 mg/ml, 0.04 mg/ml, 0.31 mg/ml, and 0.16 mg/ml, respectively	Zulfa et al. (2016)
Satureja Montana	Carvacrol (53.35%), γ-terpinene (13.54%) and the monoterpenic hydrocarbons p-cymene (13.03%), β-caryophyllene (2.23%), α-terpinene (1.70%), linalool (1.84%), β-bisabolene (1.30%), myrcene (1.30%), borneol (1.14%).	*Campylobacter jejuni*	250 mg/L	Šimunović et al. (2020)
Origanum vulgarae	Thyme (23.49%), Carvacrol (21.31%) and p-Cymene (24.01%).	*S. Enteritidis, S. Thyphimurium, S. aureus, E. coli and B. cereus*	160–640 mg/L	Boskovic et al. (2015)
Piper betle	Safrole (48.7%) and chavibetol acetate (12.5%)	*V. cholerae, E. coli ATCC 25922, E. coli O157:H7 NCTC 12049, S. dysenteriae-1 MJ-84 and S. aureus ATCC 25923*	0.625% (w/v) –0.75% (w/v)	Hoque et al. (2011)
Ocimum basilicum	Methyl eugenol (39.3%) and methyl chavicol (38.3%)	*B. cereus*	100–200 μgnmL^{-1}	Baldim et al. (2018)
Rosmarinus officinalis	1,8-cineol (38.5%), α-pinene (12.3%), camphor (17.1%), limonene (6.23%), linalool (5.70%) and camphene (6.00%)	*E. coli O157:H7 and L. monocytogenes*	200 and 270 μg/mL	Santomauro et al. (2018)
Mentha piperita	Menthol (45.34%), menthone (16.04%), menthofuran (8.91%), and *cis*-carane (8.70%)	*P. putida, E. aerogenes, S. typhi, E. coli, L. mesenteroides* subsp. *mesenteroides, L. monocytogenes, B. cereus and S. aureus*	0.625–1.25 μg/mL	Moosavi-Nasab et al. (2016)
Salvia sclarea	linalyl acetate (14.30%), linalool (17.20%), geranyl acetate (7.50%), geraniol (6.50%), nerol (5.50%), terpineol (15.10%), neryl acetate (5.20%) and sclareol (5.2%)	*Listeria monocytogenes NCTC 11994 (serotype 4b), L. monocytogenes CP6 (PFGE type 11), L. monocytogenes M12 (PFGE type 3), P. aeruginosa P2, P. aeruginosa P6, Yarrowia lipolytica CBS 6659, Y. lipolytica ISA 1668 and Y. lipolytica ISA 1708.*	11.25–900 μg mL^{-1}	(Santos et al., 2017)
Allium sativum	diallyl-disulfide (28.05%), and diallyl-trisulfide (33.55%)	*E. coli and S. aureus*	25–133 mg/ml	Liaqat et al. (2019)
Cuminum cyminum	α–Pinene (29.2%), limonene (21.7%), 1,8-cineole (18.1%), linalool (10.5%), linalyl acetate (4.8%), and α-terpineole (3.17%)	*B. cereus, S.s aureus, E. coli, and S. Typhi*	128 mg/ml	Wongkattiya et al. (2019)

Table 2
Antimicrobial activity of various essential oils on meat and aquatic product pathogens.

Essential oil	Bacterial species	Concentration of EO	Food product	Ref
Satureja montana and *Juniperus communis* EOs	*Listeria monocytogenes*	0.5–1%	Wine marinated beef	Vasilijević et al. (2019)
Myristica fragrans EO	*Escherichia coli, Staphylococcus aureus, psychrotrophic bacteria,* and fungi	512 mg ml^{-1}	Beef	Kiarsi et al. (2020)
Rosmarinus officinalis L., *Thymus vulgaris* L., *Syzygium aromaticum* L. EOs	*B. subtilis, S. aureus, L. monocytogenes and E. coli,*	1.5%	Chicken meat	Sarıcaoglu and Turhan (2020)
Black cumin EO	*Staphylococcus aureus and Escherichia coli*	1.0%	Chicken breast meat	Konuk Takma and Korel (2019)
Thymus vulgaris and *Origanum vulgare* L. EO	*Salmonella enterica and lactic acid bacterial strains*	1.0%	Poultry meat	Bartkiene et al. (2020)
Syzygium aromaticum, L. EO	*S. aureus, E. coli, L. monocytogenes* and *S. Typhimurium*	1.0%	Ground meat products	Radünz et al. (2019)
Sage herbal dust EO	*Escherichia coli*	0.6 μl/ml	Minced pork	Danilović et al. (2021)
Thymus capitatus and *Thymus algeriensis* EOs	*Escherichia coli, Staphylococcus aureus,* and *Salmonella typhimurium,*	1 and 3%, respectively	Minced beef meat	Jayari et al. (2018)
Origanum majorana, Mentha suaveolens, Rosmarinus officinalis, Salvia officinalis and *Mentha pulegium*	*Salmonella and* L. *monocytogenes*	0.25–1.0%	Meat	(Ed-Dra et al., 2020)
Oregano EO	*Vibrio vulnificus*	0.06–0.15 μL/mL	Oysters	Luo et al. (2022)
Laurus nobilis, Anethum graveolens, and *Zingiber officinale* EOs	*Aeromonas hydrophila* spp., *Staphylococcus* spp., *Enterobacter cloacae, Vibrio alginolyticus, Klebsiella oxytoca, Klebsiella ornithinolytica,* and *Serratia odorifera*	0.05–0.2 mg/mL	Fish and Shellfish	Snuossi et al. (2016)
Eucalyptus EO	*Escherichia coli, Shewanella putrefaciens, Pseudomonas aeruginosa, Vibrio parahaemolyticus,* and *Staphylococcus aureus*	0.63–2.00 μl/ml	Aquatic products	He et al. (2022)

arvensis and *Mentha piperita* against twelve *Aeromonas* spp. isolates in a native fish species *Colossoma macropomum* from Brazil. Both the *Mentha* species were able to inhibit the twelve *Aeromonas* spp. isolates with minimum inhibition concentration (MIC) carrying between 1250 and 16666 μg mL^{-1}. The authors reported that *Mentha arvensis* has superior antimicrobial properties than *Mentha piperita.* (H. Liu et al., 2020) the antimicrobial activity of citral against *Vibrio alginolyticus*, a critical fish pathogen. It was observed that citral inhibited *Vibrio alginolyticus* MIC of 0.125 mg/mL. The authors reported that citral caused invaginations of the cell membrane, inhibition of biofilm formation and motility, and blockade of serum protease production. (da Silva et al., 2021) demonstrated antimicrobial and antibiofilm potential of S- (−)-Limonene and R- (+)-Limonene against *Aeromonas hydrophila.* The authors reported weak antibacterial activity (MIC 3.2 mg/mL^{-1} for S-(−)-Limonene and

MIC 6.4 mg/mL^{-1} for R-(+)-Limonene) and strong antibiofilm against *A. hydrophila*. The antimicrobial effects of several EOs on seafood product pathogens are summarized in Table 2.

3.3. Antibacterial activity of essential oils in dairy products

The safety of dairy products is a worldwide concern for public health that calls for innovative strategies and cutting-edge technologies to combat the spread of foodborne pathogens. Pathogens of concern in dairy products include gram-positive bacteria such as *Listeria monocytogenes* (Gandhi & Chikindas, 2007) and *Staphylococcus aureus* (Castro et al., 2018) and gram-negative bacteria such as *Salmonella* spp. (Humphrey & Jørgensen, 2006) and *Cronobacter sakazakii* (Healy et al., 2010). EOs from several different types of herbs and spices, such as thyme, cinnamon, oregano, and lemongrass, have the ability to prevent the growth of pathogenic bacteria in dairy products resulting in a product that has a longer shelf life and is safer to consume. Hashemi & Khodaei, 2020 studied the antimicrobial activity of *Satureja Khuzestanica* Jamzad and *Satureja bachtiarica* Bunge EOs against *Shigella flexneri* and *Escherichia coli* in table cream containing *Lactobacillus plantarum LU5*. The combination of both the EOs showed the highest inhibition. CFUs (colony forming units), a common measurement for estimating the number of microorganisms in a test sample, were employed to quantify the anti-bacterial activity. There was a significant decline in the number of *E. coli* (2.3 log CFU/g), *S. flexneri* (1.9 log CFU/g), and *L. plantarum* (1.4 log CFU/g) after 10 days of storage compared to the control samples (9.3 log CFU/g). The authors reported that the additions of the EOs did not alter the sensorial properties of the cream. Badola et al., 2018 demonstrated the antibacterial efficacy of clove bud and curry leaf EOs on a milk-based confection called *burfi*. The authors demonstrated that curry leaf EO in the concentration between 0.05 and 0.15 ppm and clove bud EO in the concentration range of 0.15–0.25 ppm are optimum for prolonging the shelf life of *burfi* without affecting the sensorial properties. The antimicrobial effects of several EOs on dairy product pathogens are summarized in Table 3.

Table 3
The antimicrobial effects of EOs on the dairy product pathogens.

Essential oil	Concentration	Bacterial species	Food product	Ref
Oregano and rosemary EOs	*Oregano* (0.07 μL/g) *Rosemarinus* (2.65 μL/g)	*E. coli O157:H7, L. acidophilus LA-5,*	Minas cheese	Diniz-Silva et al. (2020)
Zataria multiflora EO	0–150 ppm	*Escherichia coli O157*	White-brined cheese	Mehdizadeh et al. (2018)
Origanum vulgare L. and *Rosmarinus officinalis* L. EOs	*Oregano* (0.03 μL/g) *Rosemary* (1.32 μL/g)	*Escherichia coli O157:H7*	Fresh cheese	Diniz-Silva et al. (2019)
Pimpinella saxifraga EO	1–3% (w/v)	*Escherichia coli, Pseudomonas aeruginosa, Salmonella Typhimurium, Listeria monocytogenes, Micrococcus luteus and Bacillus cereus*	Cheese	Ksouda et al. (2019)
Heracleum persicum EO	2500 μg/mL	*Listeria monocytogenes*	Cheese	Ehsani et al. (2019)
Cinnamon EO	10 μL/mL	*Listeria monocytogenes*	Milk	Mortazavi and Aliakbarlu (2019)
Bunium persicum EO	0.5% v/v	*Listeria, lactic acid bacteria, Enterobacter, Escherichia, and Pseudomonas species*	Gouda cheese	Saravani et al. (2019)
Thymus vulgaris L., *Mentha piperita* L. and *Ziziphora tenuior* L. EOs	0.2% v/v	*Staphylococcus aureus*	Yoghurt-based drink (Doogh)	Abdolshahi et al. (2018)
Origanum vulgare (L.) EO	0.02% (v/v)	*Multidrug-resistant S. aureus, E. coli, and the fungi Fusarium oxysporum, Aspergillus flavus,* and *Penicillium citrinum*	Minas cheese	Leonelli Pires de Campos et al. (2022)

3.4. Antibacterial activity of essential oils in fruits and vegetables

Fruits and vegetables are perishable foods that can undergo unfavorable changes in color, flavor, texture, and aroma, lowering their quality (Perumal et al., 2022). The EOs components have demonstrated an inhibitory effect on the oxidative deterioration of fruits and vegetables, thereby hindering the growth of molds, yeasts, bacteria, microbial toxins, viruses, and insects (Jin et al., 2012; Sellamuthu et al., 2013). Moreover, by reducing respiration rates and raising internal CO_2 and O_2 concentrations around fruits, EOs can delay ripening. Furthermore, antioxidant capabilities of EOs that decreased oxygen transport and increased CO_2 build-up at fruit surfaces have been connected to their ability to control fruit ripening (Shehata et al., 2020). EOs have been shown to interfere with ethylene production. (György et al., 2020) investigated the antimicrobial efficacy of a combination of EOs, namely lemongrass, thyme, oregano, juniper, sage, rosemary, fennel, mint, dill, and rosehips, on some pathogenic and spoilage bacteria isolated from the surface of various fresh vegetables. It was shown that oregano EO had the highest antibacterial activity against spoilage microorganisms and that five different EO combinations had a synergistic impact. Synergy occurs when the combined antibacterial activity of two antimicrobial substances is higher than the sum of their separate antimicrobial activities. In theory, there are four ways by which antimicrobial interactions might work together to have a synergistic effect: Suppression of enzymatic reactions that degrade or eject antimicrobials, sequential inhibition of multiple steps in a biochemical pathway, multiple antimicrobials interacting with the cell wall, or interplay with the cell membrane or wall to boost the absorption of other antimicrobials. Synergistic effects may also occur if the antimicrobials target are distinct but have interdependent locations inside the cell but work through different mechanisms (Davidson & Parish, 1989; Hyldgaard et al., 2012). (Rashid et al., 2020) evaluated the antibacterial potential of cinnamon EO edible coatings to improve the safety and stability of fresh apples. The authors reported that 5% cinnamon EO could exhibit maximum antimicrobial effect against *P.expansum* and *E.coli* while maintaining the physiochemical properties of the coated apples for 2 months at 5 °C. The various EOs used in the preservation of fruits and vegetable due to their antimicrobial potential is summarized in Table 4.

4. Essential oils in food preservation and shelf-life prolongation

Because of the emergence of a food safety issue in recent years, customers typically reject benzoic acid and its related salts as synthetic additions (Ju et al., 2017). Applying a natural antimicrobial agent to preserve food or extend its shelf life is now one of the leading research areas of interest for the concerned researchers. Natural plant EOs dominate food industries, especially in food preservation, as they are

Table 4
Various EOs used in the preservation of fruits and vegetables.

Essential oil	Concentration	Bacterial species	Food product	Ref
Eucalyptus globulus EO	0.8–4 μL/mL	*Escherichia coli, Pseudomonas aeruginosa, Enterobacter sakazakii, Bacillus cereus, Klebsiella ornithinolytica, Staphylococcus aureus, Aspergillus flavus, Aspergillus niger, Aspergillus fumigatus and Saccharomyces cerevisiae, Aspergillus brasiliensis, Candida albicans and Trichosporon sp Candida parapsilosis.*	Orangina Fruit Juice	Boukhatem et al. (2020)
Pomegranate peel extract and *Pomegranate EO*	0–150 ppm	*P. italicum* and *P. digitatum*	"Satsuma" mandarin	Givi et al. (2019)
Clove EO	0.05–0.8% (v/v)	*Penicillium italicum*	Citrus Fruit	(Chen et al., 2019)
African apple star EOs	0.195–6.250 mg/mL	*Staphylococcus aureus, Staphylococcus pneumoniae, 5 Bacillus subtilis, Salmonella typhi, Pseudomonas aeruginosa, Klebsiella pneumoniae, and Escherichia Coli, Candida albicans*	African Star Apple	Nartey et al. (2021)
Thymus zygis EO	0.003–0.4% (v/v)	*Listeria monocytogenes*	Fresh vegetables	Coimbra et al. (2022)
Litseacubeba EO	1.5 mg/mL	*Escherichia coli O157:H7*	Vegetable juices	Lin, Wang, and Cui (2019)

safe, eco-friendly, and easily biodegradable. The primary barriers to using EOs as food preservatives are their safety restrictions, distinct organoleptic effects, and potential contamination by chemicals like pesticides (Falleh et al., 2020). Various plant EOs have different levels of safety limits. The acute oral test, which allows for the measurement of LD_{50} or Median Lethal Dose value, is one of the most popular techniques for evaluating the safety of EOs. The greater the LD_{50} value of EOs, the safer they are as food preservatives. According to (Ju et al., 2018), the cinnamon and clove EOs are known to increase the shelf life of baked goods. The MIC of cinnamon and clove EOs against molds were 0.21–0.83 and 0.21–1.67 μL/mL, respectively, and the Minimum Lethal Concentration (MLC) were 0.42–0.83 and 0.83–1.67 μL/mL, respectively. In a normal packaging system at 30 °C, cinnamon and clove EOs was shown to prolong the shelf life of green bean cake to 9–10 and 3–4 days, respectively as well as prolonged the shelf life of finger citron crisp cake for 5–6 and 2–3 days, respectively. Additionally, adding cinnamon EO to green bean cake and finger citron crisp cake in vacuum packaging at 30 °C demonstrated an increase in their shelf lives to more than 15–16

Table 5
Application of EOs in the augmentation of shelf-life of food products.

Source	Food product	Storage condition	Research outcomes	References
Syzygium aromaticum	Red Grapes	5 °C for 15 days	Firmness: Reduced from 12.65 to 6.01 N (PMS films), 12.54 to 9.03 N (PMS + Kudzu CNCs), and 12.67 to 9.34 N (PMS + Kudzu CNCs + EO) on the 9th day of storage. Titratable acidity: Grapes packaged in PMS + Kudzu CNCs + EO films had a slower rate of decreasing acidity, followed by PMS + Kudzu CNCs films, PMS films, and unpackaged red grapes. Total soluble solid: TSS was either stable or slightly increased during the storage for grapes packaged with PMS + Kudzu CNCs and PMS + Kudzu CNCs + EO films.	Punia Bangar et al. (2022)
Perilla frutescense	Strawberry	7 days at room temperature	EOx – NNSC had good antibacterial and antioxidant activity against *Staphylococcus aureus, Salmonella enteritidis, Escherichia coli and Pseudomonas tolaasii*, decreasing the decay of strawberries.	Wang et al. (2021)
Gracilaria lemaneiformis	Beef	4 °C for 16 days	Edible coatings from AS + GEO increased shelf life by 9 days compared to the uncoated sample. TVC, PTC, *E. coli*, *S. aureus*, yeasts, and molds were found to be 7.50, 6.86, 6.20, 4.70, and 3.90 log CFU/g at the end of storage for AS + GEO coated samples which were lower compared to uncoated samples	(Zhang et al., 2021)
Thymus vulgaris	Mango	10 days at 25 ± 1 °C and 60–70% RH	TEO-M starch films showed an inhibitory effect against *Colletotrichum gloeosporioides and Botryodiplodia theobromae* Increase in thickness, opacity, water solubility and tensile strength TEO–M films had lower moisture content, water solubility and water vapor permeability Had better preservation effect compared with that of the starch film alone	(Cai et al., 2020)
Syzygium aromaticum	Pomegranate arils	60 days at 5 ± 0.5 °C and 90 ± 5% RH	CEO -ChNPs extended aril's shelf life to 54-day Microbial quality, weight, total soluble solid, titratable acidity, pH, total phenol and total anthocyanin content, as well as antioxidant activity and sensory quality, were all maintained	Hasheminejad and Khodaiyan (2020)
Origanum vulgare	Purple yam	4 °C for 5 days	Coatings made from citric acid + sodium alginate + β-cyclodextrin-oregano EO microcapsules (CA-SA- β-CD OEO-MC) prevented browning and maintained firmness, anthocyanin content, and ascorbic content of the yam	Huang et al. (2020)
Thymus vulgaris	Pork	4 °C for 14 days	TEO loaded with alginate beads 1% and 3% containing cellulose nanocrystals (CNCs) (0–40%) showed 2 and 4 log reductions of *L. innocua* during 10 and 14 days of storage, respectively	Criado et al. (2019)
Syringa	Peach	35 days at 1 ± 0.5 °C and 90% RH	SEO – 1- MCP helped in ethylene release and delayed decaying of fruit	Yang et al. (2019)
Cinnamomum verum	Mango	14 days at 25 °C and 50% RH	CEO containing chitosan and alginate solutions increased the shelf life of mango to 14 days	Yin et al. (2019)
Thymus vulgaris	Lettuce	5 °C for 12 days	TO:β-CD (31.6, and 47.5 g L^{-1}) maintained the sensory attributes and increased the antioxidant properties of minimally processed lettuce	Viacava et al. (2018)

Where PMS = Pearl millet starch film; PMS + Kudzu CNC = Pearl millet starch film reinforced with 5% Kudzu cellulose nanocrystals, and PMS + Kudzu CNC + EO = Pearl millet starch film reinforced with 5% Kudzu cellulose nanocrystals and loaded with 1.5% essential clove bud oil; EOx – NNSC = Essential oil – Nisin N-succinyl chitosan; AS + GEO = Agar/Sodium alginate containing ginger EO; PVC = Plate viable count; PTC = Psychrotrophic counts; TEO – M = Thyme essential oil microcapsules; CEO – ChNPs = Clove EO loaded chitosan nanoparticles; CA-SA- β-CD OEO MC = citric acid + sodium alginate + β-cyclodextrin-oregano EO microcapsules; C-M EEO = Casein-maltodextrin encapsulated EO; TEO = Thyme EO; SEO – 1- MCP = *Syringa* EO- 1-methylcyclopropene; CEO = Cinnamon EO; TO:β-CD= Thyme EO in β-cyclodextrin.

and 8–9 days, respectively, whereas adding clove EO to those same desserts showed an increase in their shelf lives for 10–12 and 7–9 days, respectively. Sensory analysis revealed that the taste and fragrance of the baked food products were unaffected by the 1%-point addition of EOs. In another study (Yousuf & Srivastava, 2017), evaluated the effects of flaxseed gum and lemon grass EOs on the storage of ready-to-eat pomegranates arils. The outcomes demonstrated that the yeast and mold development reduced considerably to 4.5 CFU/g and 4.3 CFU/g, respectively, from a total plate count (TPC) of 8.3 log CFU/g during the 12-day storage period. The ratio of total soluble solids (TSS) and TA, also called as the ripening index (RI) was determined, and it was observed that RI was greater in the coated samples as compared to the control. The sensorial analysis showed no effect on the quality parameters (appearance, texture, flavor, fragrance, juiciness, and general acceptability) of the pomegranate arils. (Artiga-Artigas et al., 2017) investigated the impact of oregano EOs on the cheese's shelf life. The shelf life of cheese increased from 6 days to 17 days by using oregano EOs (2.0% w/w). It significantly reduced the *Staphylococcus aureus*, mold, and yeast growth and their reproduction during the storage period. The sensorial analysis showed that the cheese pieces were able to maintain their bright color as well as their texture. The effects of *Myrcia ovata Cambessedes* EO-edible coatings (1.25%) on the storage quality of mangaba fruits were also investigated by (Frazão & de Aquino Santana, 2017). The outcome revealed that this technique might successfully inhibit yeast and mold growth by ~2–3 log reduction during 12 days storage period. Table 5 lists the many EOs that demonstrate the extended shelf life of food products by thwarting harmful and deadly bacteria.

5. Essential oils from spices as natural food preservatives

The nutritional value and sensory quality of food are significantly impacted by food oxidation due to the formation of ketones, quinones, phenols, carboxylic acids, aldehydes and anhydrides which is another cause of non-palatability (Chen et al., 2019). In addition, the oxidation of frying oil can produce harmful compounds like di- and mono-acylglycerols, glycerol, and free fatty acids. Spices are seasonings used in food that are obtained from dried plant tissues such as seeds, roots, or bark (Diniz Do Nascimento et al., 2022). Due to their antioxidant qualities, spice essential oils (SEOs) of natural origin have a great potential to replace synthetic antioxidants used as food preservatives, such as nitrates, which have been alleged to have adverse effects on human health. Studies have demonstrated that the antioxidant action of SEOs, which include rosemary, cumin, anise, cinnamon, basil, and cloves, has been proven (Ibrahim & Kiki, 2020). The phenolic components of SEOs, which give them their redox characteristics and enable them to function as hydrogen donors, reducing agents, singlet oxygen quenchers, or metal chelators, are principally responsible for the antioxidant actions of SEOs (Mahomoodally et al., 2019). The direct or indirect scavenging of free radicals is another antioxidant mechanism in SEOs (Maqsood et al., 2013).

The peroxide value measures the amount of unsaturation in fats and oils, which can be an indicator of rancidity. During the refrigerated storage (4 °C) of 30 days, the pepper EO decreased the peroxide value of the cheese produced due to the significant decomposition of hydroperoxides and preserved its edible quality (da Silva Dannenberg et al., 2016). Clove EOs have demonstrated shelf-life prolongation upto 20 days of goat meat balls by controlling lipid oxidation and microbial growth (Singh et al., 2022). In another study, black cumin (*Nigella sativa*) EO (0.3%) exhibited excellent antioxidant activity compared to synthetic antioxidant butylated hydroxyanisole, in cooked beef patties without affecting acceptability and sensorial properties. The shelf-life was prolonged at refrigeration storage for 15 days (Rahman et al., 2021). Furthermore, oregano EOs (100 mg/kg) also demonstrated superior anti-oxidant activity compared to synthetic anti-oxidant (butylated hydroxytoluene). As a result, the shelf-life of ground beef was extended for over seven days of storage at 4 °C without significantly impacting the sensorial attributes (Cantú-Valdéz et al., 2020). Research and technological advancements will lead to improved methods of cultivating spices that contain higher levels of antioxidants in response to rising consumer interest in natural preservatives.

6. Encapsulation of essential oil for application in food chemistry

Natural and healthier food products are in demand from consumers (Noguerol et al., 2021). These days preservatives or artificial additives are being replaced with natural ingredients like EOs because of the emerging trends in the food industry (Asbahani et al., 2015; Donsì & Ferrari, 2016). However, due to their hydrophobicity, potent scent, and flavor, they are difficult to incorporate into food products successfully. Such issues may be resolved by encapsulating EOs which can improve stability, protection and modulate the release of components, reduce strong smells and aromas, extend shelf life, and improve the bioavailability of the encapsulated materials (Hosseini et al., 2019). Along with the added value, encapsulation also offers the opportunity to enhance the product's visual appeal and marketing strategy. Additionally, foods containing encapsulated EOs demonstrated higher acceptance than those with direct oil application (Jeyakumari A et al., 2016). While potentially enhancing their bioactivity and enabling controlled release, encapsulation techniques such as spray drying, extrusion, solvent removal, coacervation, liposomes, and ionic gelation can be employed to overcome the constraints of EOs (Amaral et al., 2019). The schematic representation of the various encapsulating methods used for EOs is shown in Fig. 3.

6.1. Spray drying

One of the earliest techniques for encapsulating EOs is spray drying as it helps in continuous manufacturing on a large scale, is economical, and permits the use of various coating/wall materials (Mohammed et al., 2020). Polysaccharides such as maltodextrin, sodium caseinate, proteins from soy and whey, gums, starch, chitosan, and gelatin are frequently utilized as wall materials in spray drying processes. The production of the coating-core material, homogeneity of the dispersion of the wall-core, atomization, and subsequent drying are the three steps that

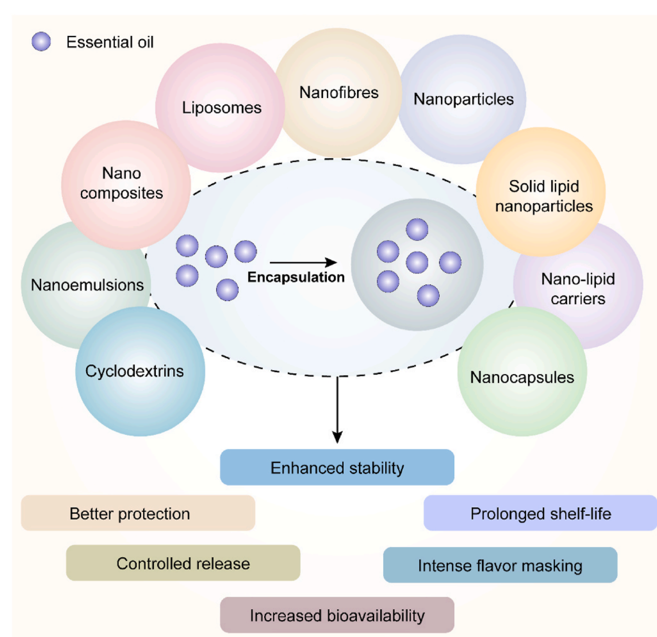

Fig. 3. The various encapsulation techniques used for EOs for food preservation.

typically makeup spray drying (Poozesh & Bilgili, 2019; Vergis et al., 2015). EOs have been discovered to have less viscosity when dissolved before being added to the wall material dispersion, encouraging the development of minute droplets and coating materials. When spray drying EOs, retaining the volatile components is essential since they influence their bioactivity. The retention of the volatile compounds is influenced by various aspects such as the input and outlet temperature of the processing chamber, solids present in the solution of feed, and the type of wall material and its concentration (Botrel et al., 2015). Extremely high temperatures, however, may cause particle surface rupturing, leading to the loss of volatile compounds found in EOs. The percentage loss of volatile compounds varies for different EOs and depends upon the wall material used and the oil concentration (Mohammed et al., 2020). Maltodextrin and modified starch were used for coating for spray-drying rosemary EOs at 190 °C. However, no notable changes were observed in the main components, such as α-pinene (23%), borneol (16%), and bornyl-acetate (10.4%) (Ferreira et al., 2021). It is recommended to conduct optimization studies since different EOs will require different environments, given the numerous factors that influence the spray drying of EOs.

6.2. Extrusion

EOs and other volatile, unstable organic materials are frequently encapsulated via extrusion. Almost exclusively, glassy carbohydrate matrices are utilized using this approach (Tackenberg & Kleinebudde, 2015). The extrusion also finds its applications frequently outside the food sector, like in the pharmaceutical and cosmetic industries (Figueroa-Robles et al., 2021; P. M. C. L. Reis et al., 2019; Tambe et al., 2021). It entails distributing the core substance across a melt. Different type of extrusion techniques used in encapsulating EOs are hot melt extrusion (HME), electrostatic/electrospinning, co-extrusion/centrifugal, melt injection and particle from gas saturated solution (PGSS) (Bamidele & Emmambux, 2020). Maltodextrin is a starch hydrolysate that has key matrix-forming capabilities and can resist high temperatures. The microencapsulation of oil-soluble materials such flavours (cinnamaldehyde, eugenol, and orange turpentine), vitamins (ascorbic acid and tocopherol), and oils (lemon oil and orange oil) is typically done using starch hydrolysates (e.g., maltodextrin). Melt injection extrusion is a flexible process that uses less energy and allows for greater matrix state control, making it ideal for encapsulating taste components. By employing electrostatic extrusion, *Thymus serpyllum* L. was enclosed in calcium alginate beads by Stojanovic et al. (2012). It was observed that calcium alginate bead size was around 730 μm, and *Thymus serpyllum* L. encapsulation effectiveness ranged from 50% to 80% in calcium alginate.

6.3. Solvent evaporation

The basis of the solvent evaporation method is the dissipation of a chemical and coating material in an appropriate solvent. The mixture is heated to a temperature above the melting point of the encasing substance while being emulsified. Natural waxes and other lipids with low melting points are typically employed as coating materials. This method, commonly employed in encapsulating amino acids, proteins, or oils, enables the encapsulation of water-soluble or water-insoluble particles. The emulsifier's type and volume, the solvent's volume, the rate of solvent removal/evaporation, the ratio of the volume of the phase, and temperature affect the microsphere formation process (Reis et al., 2022).

6.4. Coacervation

This method is useful for encapsulating fragrance compounds and EOs. It can also encapsulate minerals, preservatives, vitamins, and enzymes (Khatibi et al., 2021; Santos, Geraldo de Carvalho, & Garcia-Rojas, 2021). Many different materials can be utilized as coatings, including gelatin, modified starch, gums, alginate, and proteins (Rutz et al., 2016).

Several parameters, including the EO concentration, coating material, and nature of chemicals, affect the encapsulating efficiency of EOs. In a study, it was observed that when the agglomeration of the substance present in the wall-like collagen hydrolysate was increased, the effectiveness of encapsulating thyme and coriander EOs decreased (Sousa et al., 2022). In another study, as the wall material, gelatin's concentration was increased (Hernández-Nava et al., 2020), observed a sharp surge in the encapsulation efficiency. However, the encapsulation efficiency started to decrease over a certain concentration. Another study revealed that the concentration of oil directly or indirectly affected the Tea Tree Oil (TTO) encapsulation efficiency when it was cross-linked with gelatin and glutaraldehyde. It was observed that the higher the oil content, the more successful the encapsulation. Furthermore, the release rate was affected by the oil content, crosslinking density, and polymer wall concentration. The spherical nature of the microcapsules was confirmed by analyses using optical and scanning electron microscopy (Ocak et al., 2011).

6.5. Liposomes

Encapsulating EOs in liposomes has been employed in commercial and functional food applications (Jahangir et al., 2022; Ju et al., 2019). The efficacy of encapsulating EOs in liposomes depends on the type of phospholipid selected. Liposomes have been employed to encapsulate plant EOs with high eucalyptol and camphor content yielding a good percentage of encapsulation efficiency (EE) and achieve excellent liposome characteristics (Risaliti et al., 2019). In order to maintain the beneficial properties of EOs, liposomes are also used to prevent them from oxidative degradation (Atarés & Chiralt, 2016). For the liposomal formulation to preserve its stability with higher antioxidant activity, laurel EO (LEO) was added (Wu et al., 2019). An antimicrobial curry leaves EO encapsulated liposome was prepared to inhibit the growth of *Bacillus cereus*, which is known as a foodborne pathogen. Its application in rice flour showed an extended shelf-life up to 5 days (Cui et al., 2017). Due to their extensive bioactivities, plant oils and EOs are receiving a lot of attention in the food and pharmaceutical industries. Therefore, using liposome technology could be a successful way to resolve the problems with stability and sustainable release.

6.6. Ionic gelation

Ionic gelation can encapsulate bioactive substances, EOs, or control food texture (Kurozawa & Hubinger, 2017). Alginate and chitosan are the two most common coating substances (Otálora et al., 2016). A suspension of core particles in the coating liquid that is then passed through a two-fluid atomizing nozzle to create the microparticles created by the external ionic gelation results in a thinly coated film (D. R. Reis et al., 2022). This technique can be used for preparing meat products and facilitates heating without affecting the structure of the microcapsule. To preserve pork slices under refrigeration at 4 °C, tarragon essential oils (TEO) were incorporated in the edible film based on chitosan and gelatin using the ionic gelation technique. The shelf life of the pork slices was extended from 8 to 12 days due to the TEO's high content of methyl chavicols and phenolic chemicals, which have antibacterial properties. The tight structure generated between chitosan and gelatin may be the reason why the chitosan and gelatin combination improved the preservation effect of the chitosan coating. When compared to free TEO, the controlled release of the active ingredients onto the surface of the pork samples resulted in a longer duration of action (Zhang et al., 2020).

6.7. Nanoencapsulation approaches

Nanoencapsulation deals with the scientific art of reducing the material size to a range of 1–100 nm that could be utilized as a carrier agent or coating material for plant-based bioactive chemicals. In recent years, the pharmaceutical sector has made nanotechnology a significant focus of its research efforts. In contrast, the food industry has only recently begun to show an increased interest in this area as a means of delivering nutraceuticals and plant-based preservatives. Nanoencapsulation of EOs has various benefits, including improved distribution, stability, oxidation protection, solubility, controlled release, simplicity of handling, and reduced or no negative impact on the organoleptic qualities of applicable food items. It also increases bioavailability. To enhance the biological and antifungal characteristics of the EOs from *Artemisia annua* (sweet wormwood) (Risaliti et al., 2019), implemented nanoliposomal encapsulation. Eucalyptol, estragole, pulegone, isoeugenol, terpineol, and thymol were the specific EOs encapsulated in cholesterol and non-hydrogenated soybean PC lipoid S100. Compared to the initial concentration, it was reported that significant amounts of encapsulated EOs were still present in the liposomes even after 10 months (Hammoud et al., 2019). Therefore, using nanotechnology to create preservatives based on EOs may improve their efficiency in the food system.

6.7.1. Mechanism of nano-encapsulated essential oils

According to (Donsì et al., 2012), nanoencapsulated EOs and their bioactive components with potent antibacterial activity are considered an alternative to microencapsulated EOs. Based on the range between MIC and MBC (Minimum Bactericidal Concentration) as well as carefully taking into account the LD_{50} and consumer satisfaction (no significant effect on the sensorial characteristics), the optimal concentration of EOs to completely inhibit the microorganisms may be determined. When used at the optimum concentrations (Kapustová et al., 2021), nanoencapsulated EOs interact more effectively with cell membranes due to their nano-range 10^{-9} m, improving their surface-to-volume area. Before releasing the EOs, the delivery mechanism can transfer the EOs across the phospholipid bilayer so they can act on the interior of the plasma membranes. Additionally, encapsulating materials deliver EOs to targeted locations with increased stability and dispersibility by establishing a barrier between the EOs and the food matrix. Furthermore, the EOs and carrier agents may work together to augment the antibacterial activity of the EOs that have been nanoencapsulated (Kapustová et al., 2021).

6.7.2. Nanoemulsion

One of the most popular conventional techniques in the food industry is the use of emulsions to alter the consistency and taste of foods such as mayonnaise, cream, and drinks. Modern technology has allowed for the benefit of sophisticated high-pressure homogenizers and impulsive emulsification, allowing the droplet size of the particle (oil/water/emulsifier) to decrease from the micro-to the nano-size range. In comparison to microemulsions, nanoemulsions demonstrated superior efficiency in terms of the food material's stability, appearance, and texture (Ahari & Naeimabadi, 2021). Using various emulsifiers, including lecithin, pea proteins, Tween 20, sugar ester, and glycerol monooleate, nanoemulsions containing EOs such as carvacrol, limonene, and cinnamaldehyde were created and investigated against different microbes like *Lactobacillus delbrueckii, Escherichia coli, and Saccharomyces cerevisiae*. The findings showed that the emulsifier agent impacts the antimicrobial efficiency of nanoemulsion; as a result, careful consideration must be given to achieve the desired antimicrobial effect in the food system before using nanoemulsion as a carrier agent (Prakash et al., 2018). According to (Almadiy et al., 2016), food-borne bacteria like *Salmonella enteritidis* and *Staphylococcus aureus* were more resistant to the nanoemulsions of *Achillea fragrantissima*, *Achillea biebersteinii*, *Achillea millefolium* and *Achillea santolina* than they were to the free oils. As a result, the food industry is becoming increasingly interested in nanoemulsion-based encapsulation systems as a carrier agent for EOs-based preservatives.

6.7.3. Solid nanoparticles

Solid-lipid nanoparticles could considerably improve the bioavailability of hydrophobic antimicrobials like EOs and their bioactive components in contrast to liquid droplets/or standard emulsion systems (Paliwal et al., 2020). According to the data, these nanoparticles showed excellent physical stability with low EO evaporation rates. According to (Mouwakeh et al., 2019), solid lipid nanoparticles containing *Nigella sativa* EO demonstrated great physical consistency for up to 3 months, and they suggested using them as ideal EO carriers. Although this encapsulation technology has great potential as an antimicrobial carrier, some of its technical drawbacks include its low loading capacity and the possibility of coated material expulsion. Table 6 describes the wall materials used for different encapsulation techniques of the EOs and their possible outcomes.

7. Use of essential oils in smart packaging

Food packaging is crucial in preventing physical damage, external contamination, and deterioration of commodities. Packaging should store food products at a minimal cost that is affordable by each consumer group segment while meeting the commercialization demands, assuring food safety, and minimizing the disposal effects on the environment. The rapid expansion of the food packaging market that has been noticed is primarily due to changing lifestyles, rising consumer earnings, and improved international exports. Due to pervasive globalization and deeper integration among the global, the packaging industry had a legitimate need to step up efforts to protect consumers, their health, and the environment. Today's ongoing research and development in packaging improvement have led to the revolutionary concept of active and intelligent packaging. The self-managing function extends the product's shelf life inside the box.

The active and intelligent packaging used in food may be categorised as smart packaging since it not only lengthens the shelf life of the food and increases its protection, but it also offers information on the quality and safety of the food (Kuswandi & Jumina, 2020). Active packaging can be defined as functional agents' insertion into the packaging system to extend the shelf life of product quality with the activity of active participation to modify the atmosphere around the product inside the package, such as antioxidant, antimicrobial, ethylene scavenging, oxygen scavenging, and moisture absorber, etc. (Gaikwad et al., 2018, 2019, 2020). At the same time, intelligent packaging can be characterized as a packaging system which can have the potential to carry out the monitoring of the package, such as sensing, detection, tracking, recording, and communications to facilitate decision-making for the consumer as well as for the product to keep product safe and stable for longer time or to make a purchasing decision at the point of sale (Müller & Schmid, 2019). The physical, chemical, and microbiological properties of food products convey visual information about the food through color-changing parameters of the detector strip or indication (temperature or pH indicators) inside or outside the food container (Kuswandi & Jumina, 2020). Bromothymol blue tetrabutylammonium ion pair dye was put into a multilayered packaging material as a CO_2 sensor in kimchi packets in an intriguing research to prevent dye migration into meals with high water levels (Lyu et al., 2019).

Active packaging can be classified into several categories, such as chemo-active and bioactive, depending on the type of additive incorporated into the packaging materials. Chemo-active agents are synthetic chemical additives, and bioactive refers to biologically derived additives in packaging materials. It can potentially affect the chemical makeup and the gaseous atmosphere inside the package. For this, gas scavenging packaging has a broad spectrum of applications in food packaging to extend the shelf life of fresh and processed products. As the presence of oxygen, CO_2, and ethylene can impact the quality of fresh products, an excess of any gas inside the food package could create a hazardous or germ-proliferating environment (Janjarasskul & Suppakul, 2017).

Additionally, the antioxidant packaging could bring down or inhibit

Table 6
Various encapsulation techniques of essential oils and their outcomes.

Encapsulation Technique	Source	Wall materials	Conditions	Research outcomes	References
Spray Drying	*Juniperus communis* L.	Gum arabica and maltodextrin (1:1)	Inlet and outlet air temp 120 °C and 80 °C Feed flowrate: 3.2 cm^3 min^{-1}	Microcapsule has achieved the desired release in the oily food system	Bajac et al. (2022)
	Cymbopogon citratus	Gelatine and maltodextrin (1:9)	Inlet air temp 148 °C Feed flowrate: 4 kg/h	Stability was increased, and the degradation of bioactive compounds decreased	Alencar et al. (2022)
	Origanum vulgare L.	Whey protein isolate and maltodextrin (1:1 and 1:3)	Inlet air temp 100 °C Outlet air temp 24–40 °C	The activity of encapsulated oils against *Escherichia coli* and *Staphylococcus aureus*is was found to be stronger than its pure form	Plati et al. (2021)
Coacervation	*Zingiber officinale*	Chitosan and sodium carboxymethyl cellulose	Temp: 25 °C Time: 360 h	The stability of microencapsulation was improved. Encapsulation efficiency was around 88.5%	Ban et al. (2020)
	Piper nigrum	Lactoferrin/Sodium alginate	Temp: 37° C Time: 6 h	β-Caryophyllene (main terpene) was preserved, whereas percentages of other terpenes were decreased due to high volatility and sensitivity to adverse factors. Encapsulation effectiveness improved from 31.66 to 84.48%	Heckert Bastos et al. (2020)
	Cinnamomum verum	Gelatin and low methyl pectin	Temp: 80 °C Time: 2 h	Encapsulation yield was above 90%. Encapsulation efficiency was around 85–89%. Stability and viscosity were increased	Muhoza et al. (2019)
Spray Drying + Coacervation	*Capsicum annuum* and *Glycine max*	Gelatin and Gum arabic	Wall material cross-linked with glutaraldehyde or transglutaminase using complex coacervation and dried using spray drying	Encapsulation efficiency was more than 96%	Veiga et al. (2019)
	Origanum vulgare	Gelatin	Temp: 120–190 °C	Moisture content: 3.1–5.1% Increase in solid yield from 31.2% to 51.8%	Asensio et al. (2018)
Extrusion	*Citrus limon*	Mannose/Maltodextrin	Barrel temp: 120–130 °C Die: 0.25 mm Screw speed: 60 rpm	Volatile flavor retained in the wall material	Ibáñez et al. (2020)
a) Hot melt	*Citrus × sinensis*	Maltodextrin/corn syrup/ methylaldehyde	Barrel temp: 100–150 °C Water feed rate: 10 ml/min Feed rate: 15 Ib/h	The stability of encapsulated oil increased the birefringence intensity of extruded particles increased	(J. Zhang & Normand, 2020)
	Origanum vulgare EO (OEO)	Poly(butylene adipate-co-terephthalate)	Barrel temperature – 80–130 °C Screw speed – 70 rpm	High antioxidant activity of the films. Thermal characteristics of the films were unaffected by OEO inclusion, while elastic modulus elongation at break and tensile strength were negatively impacted Water vapor permeability increased up to 170 °C The shelf-life of mozzarella cheese was prolonged up to 10 days under refrigeration	Cardoso et al. (2022)
b) Melt injection	*Citrus limon*	Native corn starch/b-cyclodextrin	Barrel temp: 130–167 °C Screw speed:158–240 rpm Die opening: 2 mm Feed rate: 16 g/min	Flavor retention in the encapsulated product via wall material Flavor retention and extrudate characteristics are mostly influenced by barrel temperature and capsule level. The performance of the extruder was also significantly impacted by screw speed	Dobrzyńska-Mizera et al. (2021)
c) Centrifugal (co-extrusion)	*Hibiscus sabdariffa* L.	Sodium alginate and high methoxyl pectin	Air pressure – 600 mbar Vibration frequency: 300 Hz Nozzle: 300 μm of inner nozzle and 400 μm of outer nozzle Voltage: 2.50 kV	Storage conditions - 65 °C for 24 days Microencapsulation efficiency was around 95.68% Encapsulated oil helped in retaining the unsaturated fatty acids and total phytosterol content Oxidation rate and loss of tocopherol were higher	Goh et al. (2021)
	Brassica napus	Alginate	Vibration frequency:1750 Hz Nozzle: 200.00 mm Voltage: 1.50 kv Flow: 30.00 ml/min	Encapsulation conditions influenced the holding efficiency of the Canola oil	Hussain et al. (2019)
d) Electrostatic	*Thymus serpyllum* L	Alginate/Soy protein Isolate	Voltage: 5.00 kV Flow rate: 39.3 ml/h	Stability improvement of the bioactive compounds Reduction of the particle size was seen Encapsulation efficiency of 72–80% was achieved	Stojanovic et al. (2012)

(continued on next page)

Table 6 (*continued*)

Encapsulation Technique	Source	Wall materials	Conditions	Research outcomes	References
	Baccharis articulata extract	Calcium alginate and Inulin	Voltage: 6.00 kV Flow rate: 39.30 ml/h	Insulin decreased the hydrogel's rigidity and prevented the microbead from collapsing	Chang et al. (2022)
	Mentha piperita L.	Gelatin/Alginate	Electrostatic potential – 8 kV Flow rate – 70 mL/h Distance between needle tip and collecting solution – 2.5 cm	Encapsulation Efficiency 98.4% Significant surface porosity was observed In comparison to free oil, encapsulating peppermint essential oil enabled controlled release of oil in a wider temperature range	Yilmaztekin et al. (2019)
	Lavandula angustifolia (Lavender)	Alginate	Electrostatic potential - 6 kV	Efficient in inhibiting the growth of *Salmonella typhimurium* and *Staphylococcus aureus* pathogenic bacteria (MIC values of 5 μg/mL)	Kokina et al. (2019)
	Citrus bergamia (Bergamot)		Flow rate - 40 mL/h	Lavender oil exhibited the highest antioxidant capacity	
			Length of needle – 1.1 mm	DPPH and ABTS radical scavenging activities of the essential oils reduced after 12 months of storage	
			Time – 60 min		
e) PGSS - Particle from gas-saturated solution	*Cinnamomum verum*	Poly Lactic Acid (PLA) film.	Pressure:12 MPa Temp: 40 °C	Cinnamaldehyde is more effectively encapsulated in PLA with improved thermal and structural properties at higher pressures and slower depressurization rates.	Villegas et al. (2017)
Solvent evaporation			Time: 3 h Depressurization rate: 10 MPa		
	Linum usitatissimum	Sunflower wax	Pressure – 10–30 MPa Temperature- 60 °C Time- 120 min CO2 flow rate- 2 L/h using ethanol as co-solvent (14% w/w)	Encapsulation efficiency at 10 MPa - 91.68% Encapsulation efficiency at 30 MPa - 86.23% Microcapsules at 30 MPa had a faster oxidation compared to 10 MPa Diameter of microparticles decreased with the increase in pressure	Klettenhammer et al. (2022)
	Psoralea corylifolia	Ethyl cellulose and polyvinyl alcohol Solvent- dichloromethane	Stirring and drying at room temperature at 4000 rpm for 3 h	Increased the stability of EO Antibacterial activity against *Staphylococcus aureus*, *Pseudomonas aeruginosa* and *Escherichia coli* was reported	Wadhwa et al. (2019)
	Lavandula hybrid	n-octenyl succinic (OSA)-modified starch, Solvent-water	Supercritical CO_2, Pressure 5–8 MPa, drying temperature 76–84 °C	Narrow particle size distribution was observed, which signified the controlled release of oil	Chiriac et al. (2021)
Ionic gelation	*Cinnamomum verum*	Sodium alginate, calcium chloride, and chitosan	Flow rate 1–1.6 mL/min, gelation time 30 min	Microcapsule showed good release behavior.	Farahmand et al. (2022)
	Thymus vulgaris	Sodium alginate and calcium chloride	Gelation time: 60 min	Encapsulated oil presented antifungal activity against *Saprolegnia* sp.	Benavides et al. (2021)
	Cananga odorata	Sodium-tripolyphosphate and chitosan	Gelation time: 40 min	Encapsulated oil suppressed fungal growth of stored food	Upadhyay et al. (2021)
Liposome	*Allium sativum*	Phosphatidylcholine and oleic acid	Average particle size:113 nm Zeta potential: −27.9 mV	Encapsulation efficiency 79.7%. Encapsulated garlic inhibited molds such as *P. herquei*, *A. Flavus and F. graminearum* for five days	Volpe et al. (2022)
	Cinnamomum verum	Lecithin	Average particle size:66.4 nm Zeta potential: 73 mV	Encapsulation efficiency 92% Showed antibacterial activity against *C. jejuni* on chicken. It did not affect the quality of chicken	Premanath et al. (2022)
	Chrysanthemum morifolium	Chitosan, Soy phosphatidylcholine and cholesterol	Zeta potential: −26 mV Average particle size: 200 nm Loading capacity of 1.28 mg/mL	Encapsulation efficiency 42.73 Good particle size and zeta potential values were achieved	(Lin, Gu, et al., 2019)
Solid lipid nanoparticles	*Zataria multiflora*	Lipid phase - Glyceryl monostearat Sufactant – Tween 80	-	Increase in antifungal activity as compared to non-encapsulated oil	Naseri et al. (2020)
Nanoemulsion	*Thymus capitatus*	Sodium dodecyl sulphate	-	Inhibited *Staphylococcus aureus* *T. capitatus* EO was safe at doses up to 2000 mg kg^{-1} b.w EO presented antioxidant and antibacterial proprieties probably due to high carvacrol content Recommended as a natural and effective foods preservative	Jemaa et al. (2018)
	Syzygium aromaticum	Poly (DL-lactide-*co*-glycolide)	-	Inhibited *Salmonella* spp. and *Listeria* spp.	Shahbazi (2019)
Nanogel	*Cuminum cyminum*	Chitosan	-	Increase in antimicrobial activity	Torres et al. (2020)

the free radical scavenging activity in the food and food packaging's environment. Antimicrobials from bioactive suc as EOs are prevalent, which can potentially diminish the growth of microorganisms. Although it is generally accepted that the significant EO components are primarily responsible for their biological activities, it is also known that lesser compounds may also have a role to play and may even have a synergistic effect. EOs and their components can be applied directly to food or incorporated in food packaging to be released during food storage and transportation, increasing the food's shelf life. EOs contain phenolic compounds, which have antibacterial and antioxidant effects and can reduce or even eradicate the presence of microbes as well as the process of lipid oxidation. As a result, they can decrease or even eliminate the requirement for synthetic additives (Carpena et al., 2021). To avoid the direct incorporation into food matrix, EOs are introduced into active and intelligent biopolymers to protect food wholesomeness during storage (Y. xin Li et al., 2022). For example, thin films are thin sheets manufactured beforehand and applied on food products as a wrapper, between layers, or coating after the product has been fully immersed in an active solution of various components in the preferred solvents. Furthermore, edible packaging is widely used to extend the shelf life of food products, which can be eaten alongside or without further removal.

EOs enhances the active properties of packaging material. Thus, several approaches have been made to introduce EOs into the packaging matrix to increase the bioactivity and modify the biopolymers' characteristics in food packaging applications. Among all the biopolymers proteins, polysaccharide-based edible or biodegradable polymers have gained special attention in the packaging sector. Still, these biopolymers' poor mechanical and barrier properties limit the application range for different products (Tongnuanchan & Benjakul, 2014). The performance of these polymers may be increased by chemical and enzyme processing; however, if the packaging material comes into close contact with food, safety concerns emerge. For this, hydrophobic substances like EOs can be added to change the biopolymer's physical and chemical composition, which ultimately enhances the performance of the package as a whole (Tongnuanchan et al., 2013). As shown in Table 7., a number of EOs have been extensively used in the process of incorporating them into the development of active packaging. The advantages of EOs in the application of smart packaging in shown in Fig. 4.

8. Conclusion and future perspectives

EOs have a significant amount of untapped potential for their application in food preservation as a natural antibacterial and antioxidant agent. Numerous inherent and extrinsic difficulties with EOs prevent their use as food preservatives. EOs-based preservatives face several difficulties, including a shortage of raw materials, chemotypic variation, variable efficiency, a lack of molecular mechanisms of action, negative effects on the food matrix, limited water solubility, high costs, and the risk of biodiversity losses. Additionally, the amount of EOs extracted from the raw materials is frequently inadequate for commercial use. Therefore, the price increase is also related to the quantity of plant material needed to produce EOs and the quality (high purity) of the EOs. To lower the price of the highest-quality EOs and encourage broad applicability, more inventive research is required to design the most efficient extraction process with the optimum time consumption, yield, and production costs (Elyemni et al., 2019). Recent developments in contemporary science and technology, like metabolomic engineering, combinatorial chemistry, newer extraction techniques, and nanotechnology, have extended the use of EOs and other natural products in the food industry. To this day, there is a lack of information on the therapeutic effects of EOs in "*in vivo*" circumstances as well as their interactions in food systems. Further research is warranted to understand the mechanism of action, standardization of study methodologies, supplementary experiments that confirm findings, deployment of new procedures, regardless of the microorganism being studied, and lastly, validation of the possibility of acute or chronic effects to get regulatory approval for their utilization as natural preservatives in the food industry.

Research into innovative methods to maintain the activity, stability, and bioavailability of EOs has been extensive in response to the rising interest in substituting natural molecules for synthetic ones. Some factors, such as compatibility with the food or beverage matrix, organoleptic properties, and volatility, need to be taken into account before they can be successfully applied in the food industry. To better understand the effects of different food matrices on the preservation effects of the EOs, additional research is needed to determine how to increase the stability and solubility of the EOs without compromising their functioning. Research and development in food science should also consider balancing aspects like ingredient constraints and industrial investment

Table 7
Recent investigations reported the incorporation of essential oils into the development of active packaging applications.

Essential oil	Biopolymer matrix	Concentration of EOs	Functional activity	Incorporation method	References
Clove EO	Polylactic acid	0.01–0.05 μL/mL	Antimicrobial	Immobilization	Lu et al. (2021)
Rosemary EO	Sodium casienate	0.5–2% (w/w) based on sodium caseinate	Antimicrobial	Solution casting	Alizadeh-Sani et al. (2021)
Lemon EO	Chitosan	0.1–0.4% (w/w) of chitosan	Antioxidant	Encapsulation	Jiang et al. (2020)
Tea EO	Carrageenan/agar	1:4 (w/w) of Cellulose nano fiber	Antimicrobial and antioxidant	Pickering emulsification	Roy and Rhim (2021)
Thyme EO	Sweet-potato starch	0–6% (w/w) on the basis of neat film solution	Antibacterial	Film forming solution	Issa et al. (2017)
Garlic EO	Banana flour	0.05–1.0 mg/mL of film solution	Antioxidant	Solution	Orsuwan and Sothornvit (2018)
Cinnamon EO	Gelatin	0.2% (v/v) cinnamon oil of film forming solution	Antioxidant	Emulsion	Ganeson et al. (2022)
Eugenol EO	Gelatin/chitosan	0.5 g/g of EO of biopolymer solution	Antioxidant	Solution	Bonilla et al. (2018)
Eucalyptus EO	Polylactic/corn starch	2:3 (w/w) of the total mass of matrix	Antibacterial	Microcapsule	(Chen et al., 2022)
Ginger EO	Sarcoplasmic protein/ chitosan	0.5% and 1.0% v/v to the solution	Antioxidant and antimicrobial	Emulsion	(Cai et al., 2020)
Turmeric EO	Porcin plasma protein/ chitosan	25% (w/v) EO to the film forming solution	Antioxidant	Encapsulation	Samsalee and Sothornvit (2020)
Lemon grass EO	Chitosan	1–9% (w/w) chitosan	Antimicrobial	Solution	Han Lyn and Nur Hanani (2020)
Basil EO	Chitosan	-	Antimicrobial	Solution	Amor et al. (2021)
Citronella EO	Alginate	EO added at 1:10 (v/v) to the ZnO nanoparticle suspended solution	Antimicrobial	Suspension	Motelica et al. (2021)
Oregano EO	Gelatin	4.5% (w/w) to the base matrix	Antimicrobial and antioxidant	solution	(Li et al., 2020)

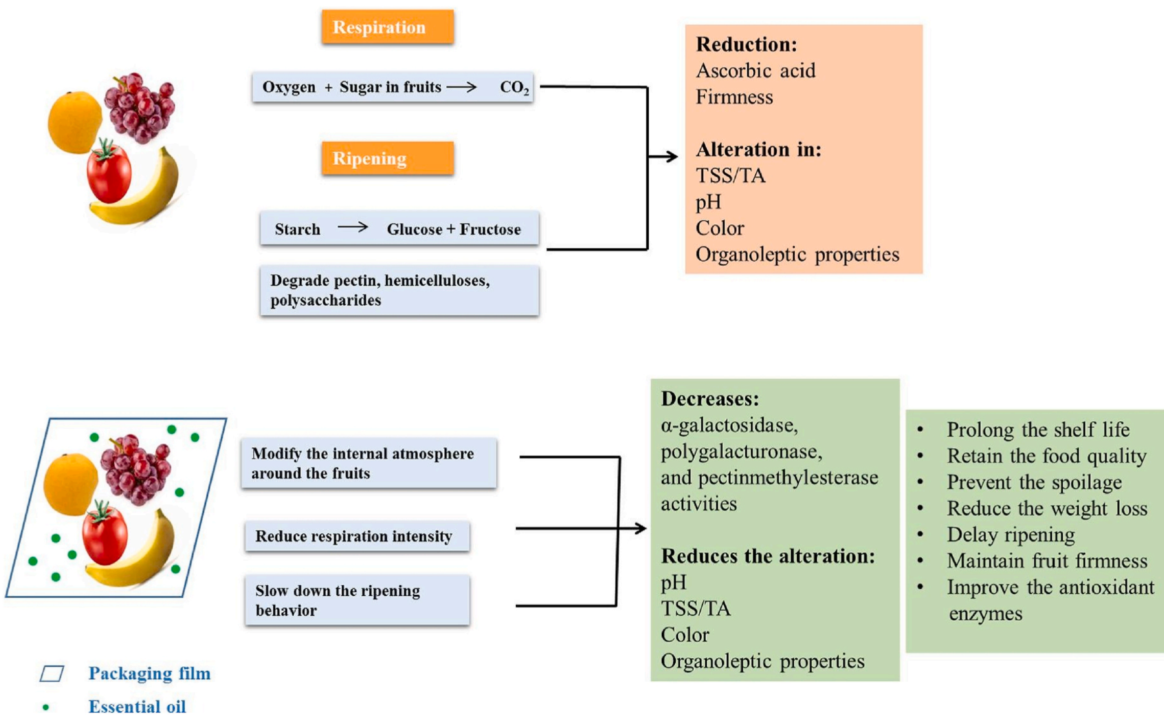

Fig. 4. The benefits of EOs in smart packaging of food products. Reproduced from (Perumal et al., 2022) with permission.

needs to make the encapsulation process industrially practicable (cost of implementing technology and the market value of the product). Each encapsulated component has unique properties, and the application's primary goal should be taken into account when deciding on an encapsulating technique. However, as is to be expected with any new form of technology, it is still necessary to carry out a number of studies in order to shed light on certain unanswered questions. These questions concern the standardization of particle size, the stability of micro- and nano-based systems, and possible toxicological consequences linked to ingesting micro- and nano-sized systems.

Additionally, the incorporation of EO-loaded smart food packaging, such as active and intelligent food packaging, holds great potential for their use as antimicrobial and antioxidant agents. These agents have the ability to inhibit both the oxidation process and the growth of microorganisms in a variety of food products. The utilization of low-temperature plasma, pulsed light, and radiation technologies are only a few examples of the cutting-edge methods that might be applied to the development of novel approaches for enhancing the sustained release and retention of EOs in active films and coatings in the future (W. Zhang et al., 2022). In addition, the on-demand release of EO, such as at a specified pH and temperature, would be highly useful and intriguing for food preservation applications. This is where future research should center. The creation of safer, more sophisticated, intelligent, green indicator packaging is an ongoing pattern in the freshness indicator technology. Safer and less harmful to the environment indicators can be achieved, for instance, by the invention of edible freshness indicators. The development of nanotechnology also opens up the prospect of greatly enhancing indication performance. Existing packaging materials may be coupled with flexible electronic printing technologies to create intelligent packaging that is lightweight, portable, and affordable. Additionally, the freshness indicator may be used in conjunction with other sophisticated technologies (such as bar codes, Radiofrequency Identification, and sensors) to achieve the total management of food quality through quality assurance, traceability, and other methods. Trends toward transferring data to the Internet or cellphones via sensors present an opportunity to increase the use of indicators on food packaging (Shao et al., 2021). Because of the technological restrictions and the greater cost of smart packaging, there are gaps or hurdles in the practical application of these technologies in the commercial sphere. Consequently, in order to commercialize these smart packaging technologies at a lower cost, with smaller devices, and reusable as well as long-lasting sensors or indications, a multidisciplinary approach is necessary. The rising use of natural preservatives and packaging in food systems has the potential to guarantee that nature will be conserved and restored for the benefit of future generations.

CRediT authorship contribution statement

Srutee Rout, Srushti Tambe, Ram Kumar Deshmukh - Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization, Validation. **Suraj Mali** - Conceptualization, Investigation, Writing – review & editing. **Prem Prakash Srivastav, Purnima D. Amin, Kirtiraj K Gaikwad** - Conceptualization, Supervision, Project administration. **Jorddy Cruz, Eloisa Helena de Aguiar Andrade, Mozaniel Santana de Oliveira** - Conceptualization, Resources, Project administration.

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Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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