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REVIEW ARTICLE

Essential Oil Nanoemulsion Edible Coating in Food Industry: a Review

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Abstract

The food industry is dealing with the challenge of preserving fruits and vegetables and extending their shelf life, so the methods of food preservation have been investigated. Pathogens causing intestinal infections have been identified as a major cause of human disease; therefore, efforts should be made to reduce these pathogens in fruits and vegetables. Essential oils extracted from herbs and edible plants have natural antimicrobial additives. Due to their low water solubility, high volatility, and strong organoleptic qualities, essential oils are not commonly used to reduce microbial growth in fruits and vegetables. To overcome these challenges, encapsulation of essential oils in nanoemulsions plays an important role as a potential solution. Nanoemulsions prepared from essential oils have both antioxidant and antimicrobial properties that make them stand out among food additives. Nanoemulsions are often used to provide physical stability. The use of nanoemulsions improves bioactivity while also reducing the impact on food organoleptic characteristics. This review paper discusses the recent advances in the preparation and stability of EO-based nanoemulsions, their antibacterial efficacy, and their application in fruit and vegetable products. In addition, this paper discusses the antibacterial mechanism of action of EO-based nanoemulsions and the applications of nanoemulsions in various sectors.

Keywords Antimicrobial · Essential oils · Fruits and vegetables · Nanoemulsions

Introduction

Fruits and vegetables are important parts of a daily diet and have become increasingly common in recent years among the public. They are a storehouse of vitamins, minerals, antioxidants, bioflavonoids, dietary fibers, and flavor compounds that are susceptible to living and non-living stresses (Ma et al., 2022). Fruits and vegetables are perishable, and there are significant losses due to bacteria, insects, respiration, and transpiration during the postharvest period (Li et al., 2016; Tiwari, 2014). The magnitude of postharvest losses of fresh produce is estimated to be 5 to 25% and 25 to 50% in developed and developing countries, respectively (Buzby et al., 2014; FAO, 2011). This enormous food waste represents a significant economic, social, and environmental burden on humanity, so there is an urgent need to improve current practices and develop new means to reduce waste. Between 40 and 50% of global losses are in fruits and vegetables, including 54% in the production, postharvest, handling, and storage stages and 46% in processing, distribution, and consumption, with a total annual loss of $750 billion (Dos Santos et al., 2020; FAO, 2013). According to previous reports, in the USA, the total amount of fruit and vegetable losses at retail and consumer stages was estimated at 8.3 and 11.4 million tons, respectively (Porat et al., 2018). The external and internal factors are responsible for this, including O_2 and Co_2 levels, temperature, stress factors, and the growth stage of fruits and vegetables (Gallagher & Mahajan, 2011).

During the process of production, the climatic conditions and management are responsible for the quality of fruits/vegetables; therefore, it is crucial to undertake specific procedures to prevent microbiological degradation and minimize the biochemical as well as physiological changes responsible for spoilage of postharvest fruits. In order to increase the consistency and shelf life of fruits, the analysis of packaging methods, which include the composition of atmospheric

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gas, is important (El-Sayed et al., 2020; Jarma-Arroyo et al., 2019; Li et al., 2017).

Chemical methods have also been used to control the microbiological spoilage of postharvest, such as sulfur dioxide (SO_2), which is used to extend the storage time of fruits like grapes because of its antimicrobial and anti-browning properties. But these chemical methods have limitations, as excessive residues in fruit lead to quality degradation, rancidity, and health problems for consumers such as nausea, allergies, and skin redness (Simone et al., 2020).

Nowadays, the food industry has demonstrated an increasing demand for natural product-based formulations for the development of novel food preservatives that can prevent the growth of microorganisms and extend the shelf life of food, as well as maintain innovation in food packaging (Asbahani et al., 2015).

Essential oils (EOs) obtained by plants contain compounds, which produce fragrance with a broad scope of biomedical activities (Asbahani et al., 2015; Ban et al., 2020). These EOs were also used as flavoring additives in food industries, as medicines and cosmetics, and also insecticidal, antioxidant, anti-inflammatory, anti-allergic, and anticancer agents (da Silva et al., 2021; Dima & Dima, 2015). Additionally, EO function as natural antimicrobial agents, inhibiting food-borne microorganisms, results in a more consistent supply of food quality and protection (Donsi et al., 2012).

The antimicrobial activity of EOs results in the degradation of the bacterial cell membrane (Moghimi et al., 2017). Additionally, EOs provide a shield for food against foreign agents such as ultraviolet light, insects, and pathogens. These essential oils were stored in the glandules or vacuoles of plants. Due to the high reactivity, volatility, susceptibility to environmental conditions, low stability, and hydrophilic nature of essential oils, their direct introduction into foods and beverages raised a major challenge (Prakash et al., 2018). This challenge can be overcome by encapsulating the essential oils in a suitable delivery system such as nanoemulsions (Li et al., 2015; Prakash et al., 2018). Essential oils consist of more than 250 bioactive compounds, which show excellent natural antimicrobial and antioxidant properties resulting in preservation and improvement properties in the food industry (Prakash et al., 2018). Other natural products such as wax and honey have higher amounts of calories which may change nutritional properties, or also these substances have lower polyphenolic activity than essential oil (Ismail et al., 2021).

Nanoemulsions consist of two immiscible phases, oil and water, with nanoemulsion droplet sizes ranging from 10 to 100 nm. They are optically transparent and thermodynamically unstable (Pathania et al., 2018).

Nanoemulsions composed of various plant-based oils stabilized with a nonionic surfactant are pure biocompatible and stable. To reduce the surface energy per unit area to a low level, the selected surfactant must be capable as it supports the dispersion phase during the nanoemulsion preparations (Pathania et al., 2018). Nanoemulsions have been shown to enhance the transport of active ingredients through cell membranes, thus increasing their biological activity, i.e., improving the bactericidal activity of EOs (Shokri et al., 2020). Nanoemulsions play an important role in extending the shelf life or improving the quality of different foods. They also prevent the growth of microorganisms, loss in weight, color, and appearance of different food and also result in less oxidation compared to conventional packaging (Ahari & Naeimabadi, 2021). They also add value to different food products by modifying a number of macroproperties of foods such as taste, color intensity, texture, bioavailability, and solubility. Nanoemulsion preparation required an organic phase and aqueous phase, and breakdown of their droplets in small size can be done by low-energy method instead of using high-tech instruments required for high-energy approach, which also results in low-cost production (Dasgupta & Shivendu, 2018).

Many studies have been carried out on the antimicrobial activity of EOs and their application in food systems. As a result, there was an immediate need for encapsulating EOs with delivery systems that are compatible with food applications (Donsi & Ferrari, 2016). Recently, the work on essential oil nanoemulsion gained interest, and there are no sufficient studies on it. Therefore, this review provides interesting information for the food industry about nanoemulsions prepared from natural essential oil and its antimicrobial activity, which could be considered sustainable.

Essential Oil

Essential oils are natural multicomponent systems made primarily of volatile terpenes and hydrocarbons (Huang et al., 2019) and are defined as secondary metabolites (Baptista-Silva et al., 2020) from plants with a characteristic odor. The chemical profile of EOs products varies not only in terms of the amount of molecules present but also in terms of the stereochemical categories extracted (Paul et al., 2020). Since ancient times, EOs derived from aromatic and medicinal plants have been known to have beneficial effects on health. Several EOs and metabolites found in plant extracts are “Generally Recognized as Safe” (GRAS) (Pandey et al., 2017). Antioxidant and antimicrobial activities are the most prevalent biological activities of EOs, and these activities have been investigated in numerous studies. The addition of EOs to binary or ternary combinations can boost biological activities (Mutlu-Ingok et al., 2019). Food products are frequently contaminated with molds and the toxins produced by these molds, in addition to disease bacteria (Lorenzo et al., 2018). Contamination can occur at various points, e.g., during food supply chain, including postharvest processing, shipping, and storage. Fungal growth and mycotoxins, including bacterial contamination, can deteriorate the product quality and pose health hazard. They also a pose health hazards (Leyva Salas et al., 2017).

As per the Food and Agricultural Organization (FAO), mycotoxins affect crops growing worldwide. Different agricultural products like melon seeds and linseeds get contaminated due to poisonous metabolites of fungus. Different surveys suggested that about 50% of the damage to grains is due to mycotoxins (Kumar et al., 2017). To determine the efficacy of EOs in food systems, in vitro experiments were followed *by* in vivo antimicrobial tests. Due to recognizing EOs as natural antioxidants and a non-toxic nature of them, different researchers use them as a substitute for synthetic antioxidants (Mutlu-Ingok et al., 2020).

Essential oils have antimicrobial properties that can inhibit microbial growth (Tariq et al., 2019). Antibacterial activity can be assessed using agar/disc diffusion, broth micro/macrodilution, or agar dilution techniques. The antibacterial action of EOs is mostly determined by their chemical composition and plant components. On the other hand, Gram-positive and Gram-negative bacteria differ in their susceptibility to EOs (Amor et al., 2019). Several investigations have been carried out to check the bactericidal activity of various plant EOs against Gram-positive (*Bacillus subtilis*, *Staphylococcus aureus*, *Listeria monocytogenes*) and Gram-negative (*Escherichia coli*, *Salmonella typhimurium*, *Pseudomonas aeruginosa*, *Campylobacter* spp.) pathogens (Ksouda et al., 2019). Some examples of different EOs and their antibacterial activities are shown in Table 1.

At room temperature, EOs are very volatile (Bhavaniramya et al., 2019) and easily destroyed by oxygen and temperature changes (Beyki et al., 2014). As a result, approaches to improve the stability and activity of EOs are needed, and novel techniques such as encapsulation, edible coatings, nanoemulsions, and active packaging may be able to help overcome these issues (Prakash & Kiran, 2016). Various studies were done focusing on the utilization of EOs, particularly employing new technologies like edible coatings on meat and cheese (Behbahani et al., 2020; Ksouda et al., 2019), as well as on bread by nanoencapsulation method.

Edible Coatings

Edible coatings can be defined as a thin layering of material which is good to eat and applied to the outside of foods for their protection. The storage life of the products is increased by this coating, as they protect food from oxygen, light, microorganisms, and moisture (Hasan et al., 2020). Edible coatings also have barrier properties. Properties like tensile properties and elongation at break are also considered as edible coating properties which show their preventive nature (Valencia-Chamorro et al., 2011). The stability of the food product depends on the edible coating requirement and its type, which may include the need to prevent oxidation degradation, control oxygen levels, and occasionally reduce oxygen consumption and ethylene output in different food (Zambrano-Zaragoza et al., 2018). Edible coatings may contain hydrophobic groups, such as lipids or waxes, as well as hydrocolloids or hydrophilic groups, such as polysaccharides or proteins, or a combination of both groups to enhance their function. Edible coatings are not synthesized chemically and are entirely natural. It is typically used to preserve the freshness of fruits and vegetables (Chen et al., 2021). Edible coatings are classified into three classes, i.e.:

- Hydrocolloids, e.g., polysaccharides and alginate
- Lipids, e.g., fatty acids, acryl glycerides, and waxes
- Composites, e.g., protein and protein, polysaccharides and protein, and lipid and polysaccharides (Fig. 1)

Edible coatings are extremely useful, and the primary advantage of using them on food products is that they offer a glossy finish and often serve as a safe and environment friendly alternative to plastic packaging, resulting in fewer waste disposal issues and a healthier atmosphere (Suhag et al., 2020). Commercially available edible coatings include those made of essential oils, waxes, and adhesives (natural or synthetic), chocolate coatings for confections, corn zein coatings for sweets, and gelatin coatings for pharmaceuticals, among others (Hassan et al., 2017). Essential oils are considered as a liquid that do not mix with water because of their hydrophobic nature with strong aromatic flavor and also have an ability to act as an antimicrobial agent against different pathogenic microorganisms as well as insects. But they also have a limitation of affecting the sensory feature of the final food product due to their low stability and strong flavor. Thus, nanoemulsions play an important role in overcoming this problem by increasing their stability (Prakash et al., 2018).

Nanoemulsions

Nanoemulsions or emulsions are two incompatible liquids that have colloidal dispersion and are mainly considered as oil and water in food applications (Huang et al., 2021). The dispersion of liquids takes the form of fine droplets (McClements, 2011). The size of the droplet is a primary parameter in the distribution of emulsions from nanoemulsions. As mentioned previously, the size of emulsion ($d > 200$ nm) is larger than that of nanoemulsion ($d < 200$ nm). Nanoemulsions differ significantly from microemulsions and macroemulsions in terms of shape, size, stability, and creation. All three emulsion kinds

Table 1 Overview of studies about antibacterial and antifungal characteristics of essential oils

Essential oil source	Bacterial culture/antibacterial method	Fungal culture/antifungal method	MIC values	Key findings	References
Brassica (mustard), *Cinnamomum verum* (cinnamon)	*E. coli*, *Bacillus cereus*, *Salmonella enteric*, *Pseudomonas putida*, *Pseudomonas aeruginosa*/broth dilution method	NR	12.5–200 µg/ml	Mustard EO and cinnamon EO were compared against different food-borne pathogen, and results concluded that mustard EO exhibited stronger antimicrobial properties	Clemente et al. (2016)
Brassica s (mustard), *Cinnamomum verum* (cinnamon)	NR	*Penicillium expansum*, *Aspergillus niger*, *Aspergillus flavus*, *R. stolonifer*, *Fusarium* sp./broth dilution method	0.8–50 µg/ml	Mustard EO was found more efficient to reduce mold growth on bread as compared to cinnamon EO	Clemente et al. (2019)
Cinnamon (*Cinnamomum verum*), clove, pepper, citronella, peppermint EO	*E. coli*, *S. aureus*, *Bacillus subtilis*/microdilution broth	NR	0.125–4 mg/ml	Study concluded that out of all cinnamon EO and clove EO exhibited higher antibacterial activity against food-borne pathogens	Tu et al. (2018)
Cinnamon, anise, clove, pepper, citronella, peppermint, camphor EO	NR	*Aspergillus niger*, *Aspergillus oryzae*/gradient plate method	0.125–800 mg/ml	Out of all seven EO, cinnamon and clove EO showed the strongest antifungal activity, and both EO can use to control the mold growth on bread and can also extend its shelf life	Hu et al. (2019)
Artemisia herba alba, *Lavandula angustifolia*, and *Rosmarinus officinalis* EO	*Staphylococcus aureus*, *Pseudomonas aeruginosa*/broth dilution, disc diffusion	NR	1.33–42.67 µl/ml	All three EOs showed the highest antibacterial activity and combination of these EOs resulting in enhanced antibacterial activity	Messaoudi Moussii et al. (2020)
Anethum graveolens (dill weed), *Elettaria cardamomum* (cardamom), *Cuminum cyminum* (cumin)	*Campylobacter coli*/broth microdilution	NR	0.012–0.025 µl/ml	Study concluded that using these EOs can control the diseases caused by *Campylobacter* spp.	Mutlu-Ingok et al. (2017)
Cumin, cardamom, and dill weed EO	*Escherichia coli*, *Staphylococcus aureus*, *Campylobacter coli*, *Campylobacter jejuni*/broth micro dilution	NR	0.012–15.00 µl/ml	Combinations of these EOs were effective for lower concentrations of EOs to control *C. coli*, *C. jejuni*, *E. coli*, and *S. aureus*	Mutlu-Ingok et al. (2019)
Clove, mandarin, cinnamon, and lemongrass EO	NR	*Aspergillus carbonarius*/poisoned food technique	100% inhibition at 50–100 µl/l	Study concluded that these EOs can result in the prevention of mycotoxins as they showed high efficacy in inhibition of fungal growth	Lappa et al. (2017)

Table 1 (continued)

Essential oil source	Bacterial culture/antibacterial method	Fungal culture/antifungal method	MIC values	Key findings	References
Eugenia caryophyllus (clove), *Cinnamomum zeylanicum* (cinnamon)	*Pseudomonas aeruginosa*, *Pseudomonas putida*, *Bacillus subtilis*/broth macrodilution	NR	1.25–10 µl/ml	Cinnamon EO showed higher antibacterial activity as compared to clove EO, and these EOs showed high antioxidant activities as compared to commercial antioxidants	Lalami et al. (2019)
Oregano, thyme, clove, lavender, clary sage, and arborvitae	NR	*Chaetomium globosum*, *Penicillium chrysogenum*, *Cladosporium cladosporioides*, *Alternaria alternata*, and *Aspergillus fumigates*/disc diffusion assay	0.025–0.075%	The genotoxic effects of the oils on HEL 12,469 human embryo lung cells were evaluated using an alkaline comet assay, and the results revealed that none of the oils induced significant DNA damage in vitro after 24 h	Puskarova et al. (2017)
Oregano, thyme, clove, lavender, clary sage, and arborvitae	*Escherichia coli*, *Salmonella typhimurium*, *Yersinia enterocolitica*, *Staphylococcus aureus*, *Listeria monocytogenes*, and *Enterococcus faecalis*/disc diffusion method	NR	*0.0–-0.05%*	The genotoxic effects of the oils on HEL 12,469 human embryo lung cells were evaluated using an alkaline comet assay, and the results revealed that none of the oils induced significant DNA damage in vitro after 24 h	Puskarova et al. (2017)
Origanum vulgare, *Rosmarinus officinalis*, and *Thymus vulgaris*	*Campylobacter jejuni*, *Listeria monocytogenes*, *Staphylococcus aureus*/broth dilution	NR	0.016–85 µL/mL	Meatballs containing 0.5% of EO were acceptable in terms of taste, and the oils were able to suppress concentrations of < 1 0^2 CFU/g of the pathogens	Pesavento et al. (2015)
Syzygium aromaticum/*Cinnamomum zeylanicum*/*Piper nigrum* (black pepper)	*Staphylococcus aureus*, *Listeria monocytogenes*, *Salmonella typhimurium*, and *Pseudomonas aeruginosa*/microdilution	NR	58.54–114.63 (µg/ml)	The results revealed the efficacy of cinnamon oil/clove oil combination in the food and pharmaceutical industries at sufficiently low concentrations	Purkait et al. (2020)

Table 1 (continued)

Essential oil source	Bacterial culture/antibacterial method	Fungal culture/antifungal method	MIC values	Key findings	References
Syzygium aromaticum/*Cinnamomum zeylanicum*/*Piper nigrum* (black pepper)	NR	Aspergillus niger/microbroth dilution	15.18–94.65 µg/ml	The results revealed the efficacy of cinnamon oil/clove oil combination in the food and pharmaceutical industries at sufficiently low concentrations	Purkait et al. (2020)
Satureja hortensis L	*Escherichia coli*, *Salmonella typhimurium*, *Pseudomonas aeruginosa*/agar dilution	NR	2–4 mg/mL	The EO showed antibacterial effect against Gram-positive and Gram-negative bacteria and powerful antioxidants in different in vitro method. Further, EO showed toxicity in normal lung, liver, and epithelial cells	Abou Barker et al. (2020)
Thymus vulgaris, *Origanum vulgare*	*Bacillus cereus*, *Staphylococcus aureus*, *Salmonella enteritidis*, *Salmonella typhimurium*, *Salmonella typhimurium*/broth dilution	NR	160–640 µg/mL	The EO from *Origanum vulgare* (oregano) was one of the most effective EOs against microorganisms	Boskovic et al. (2015)
Mentha haplocalyx (peppermint), *Cinnamomum camphora* (camphor), *Cinnamomum zeylanicum* (cinnamon), Cymbopogon nardus (citronella), *Pimpinella anisum* (anise)	*Staphylococcus aureus*, *Bacillus subtilis*, *Salmonella typhimurium*/microdilution broth	NR	0.12–4 mg/mL	The results revealed the utilization of EOs derived from plants as natural food preservatives to counteract food spoilage and pest's management	Tu et al. (2018)
Mentha pulegium, *Rosmarinus officinalis*	*Bacillus subtilis*, *Escherichia coli*, *Listeria monocytogenes*, *Pseudomonas aeruginosa*, *Proteus mirabilis*, *Staphylococcus aureus*/broth micro dilution	NR	0.25 to > 2 mg/mL	The findings showed that the EOs of *M. pulegium* and *R. officinalis* are good sources of bioactive molecules and can be used in the food and pharmaceutical industries	Bouyahya et al. (2017)
Pimpinella saxifraga	*Bacillus cereus*, *Escherichia coli*, *Listeria monocytogenes*, *Micrococcus luteus*, *Pseudomonas aeruginosa*, *Salmonella typhimurium*/microdilution	NR	0.78–3.12 mg/mL	The EO at 3% concentration improved cheese preservation and enhanced the oxidative and bacterial stability	Ksouda et al., (2019)

Table 1 (continued)

Essential oil source	Bacterial culture/antibacterial method	Fungal culture/antifungal method	MIC values	Key findings	References
Mentha piperita, *Cymbopogon citrus*, *Lavandula angustifolia*	*Staphylococcus aureus*, *Escherichia coli*/dilution	NR	62.5–125 µL/mL	The results suggest that the essential oils and ethanolic extracts can be used as antibacterial and antifungal supplements in the development of herbal formulations and detergents	Gishen et al. (2020)
Mentha piperita, *Cymbopogon citrus*, *Lavandula angustifolia*	NR	*Candida albicans*/disc diffusion method	125–250 µL/mL	The results suggest that the essential oils and ethanolic extracts can be used as antibacterial and antifungal supplements in the development of herbal formulations and detergents	Gishen et al. (2020)
Lavandula mairei Humbert	*Listeria monocytogenes, Listeria innocua, Bacillus subtilis*/broth macrodilution	NR	0.6–1.2 mg/mL	The study revealed that the EOs is rich in component carvacrol having high potential industrial importance	El Hamdaoui et al. (2018)
Lavandula angustifolia, *Artemisia herba alba*	*Pseudomonas aeruginosa*, *E. coli*, *Staphylococcus aureus*/disc diffusion method	NR	1.33–42.67 µL/mL	The evaluation of the combination of EOs demonstrated synergistic effects at very low concentrations ranging from 0.015 to 1 µl/ml	Messaoudi Moussii et al. (2020)

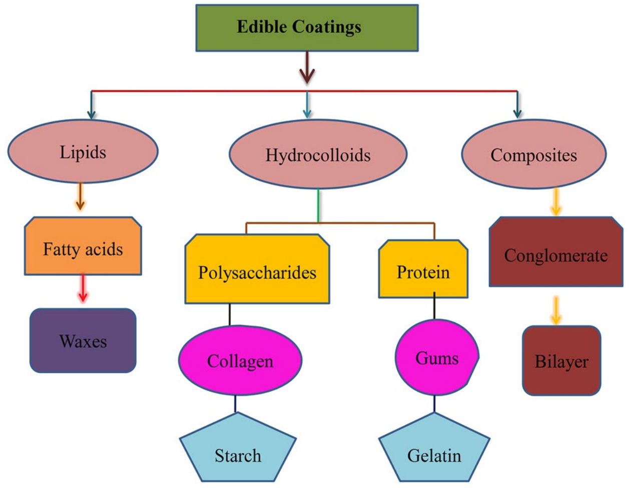

Fig. 1 Schematic illustration of main materials used in the manufacture of edible coating

are spherical in shape. Emulsions, nanoemulsions, and macroemulsions are synthesized using both low- and high-energy processes. Microemulsions, on the other hand, can only be synthesized using low-energy processes. Nanoemulsions are both thermodynamically and kinetically unstable. Microemulsions have a thermodynamic stability, while macroemulsions are thermodynamically unstable (Gupta et al., 2016).

Two separated liquids, i.e., oil and water, have lower free energy than emulsions or nanoemulsions, and this results in thermodynamically unstable emulsions (Vladisavljevic, 2019). The high kinetic energy difference between the separated and emulsified system results in long life span of nanoemulsions (Sarheed et al., 2020). Numerous researches have been conducted on the beneficial effects of nanoemulsions resulting in enhancing the storage life of different foods such as fruits and vegetables (Table 2). Nanoemulsions have the capacity to improve the distribution of effective ingredients

Table 2 Nanoemulsion-based edible coatings for different food products

Type of food product	Conditions	Nanoemulsion	Properties affected	Researchers
Tomatoes	Enhance the shelf life of tomatoes	Essential of sweet orange was used	Quality of tomatoes, characterization of nanoemulsions and its antimicrobial properties	Das et al. (2020)
Fresh-cut cucumber	Impact of antimicrobial coatings with pulsed light	Carvacrol	Microbiological analysis against *E. coli* and *Listeria innocua*	Chime et al. (2014)
Plum	Microbiological stability and storage qualities in terms of physicochemical	Lemongrass essential oil	Microbiological analysis, weight loss, firmness, antimicrobial activity, and emulsion stability	Kim et al. (2013)
Okra	Extension of shelf life	Basil oil nanoemulsions was prepared	To check the moisture, firmness, antifungal activities etc	Gundewadi et al. (2018)
Apple fruit	Enhance postharvest storage of apple fruit	Starch-based nanoemulsion edible coating	Decrease in loss of weight, change in skin color	Thakur et al. (2019)
Fresh-cut pineapple	Microbiological stability	Citral nanoemulsion	Reduces the microbial growth and lower the rate of respiration	Prakash et al. (2020)
Mango	Enhances storage stability	Thai essential oil was used	Coated mangoes resulting in decreased loss in weight, firmness, and soluble solid content was increased	Klangmuang and Sothornvit (2018)
Strawberries	Reduction of fungal spoilage	Cinnamon essential oil	Had great impact on fungal spoilage and their reduction on strawberries	Yousuf et al. (2018)
Grapes	Nanoemulsion coating to enhance postharvest shelf life	Lemongrass essential oil	Resulting in the glossy appearance of berries and have no negative effect on the flavor. Also resulting in decreased weight loss and firmness	Kim et al. (2014)
Green beans	Preservation of green beans	Mandarin essential oil	Results showed constant decrease in *Listeria innocua* during the storage period of green beans	Donsì et al. (2015)

when utilized in the form of edible coatings for various types of postharvest fruits, including papaya, mango, and strawberry. The encapsulation method is broadly used in the food industries as it enhances the properties of the products (Oberoi et al., 2019). Nanoemulsion edible coatings applied on the strawberry which was made from chitosan or nutmeg seed oil resulted in retaining the freshness and inhibited microbial development for more than 5 days (Horisonet al., 2019).

Characteristics of Nanoemulsions

Nanoemulsions employed in food packaging have a number of advantages, including the potential to reduce the transfer of important elements, minimize contact with different food ingredients, and improve the antibacterial, antioxidant, and uniformity of food packaging (Al-Tayyar et al., 2020; Neethirajan & Jayas, 2011). Due to the small size of the droplets, they may be easily deposited on substrates, which also facilitate their spread due to the droplets having low surface tension and low interfacial tension (Chime et al., 2014). Moreover, nanoemulsions have additional advantages for application in personal care, cosmetics, and healthcare. Creaming or deposition during storage is prevented by the small particle size and the presence of motion where particles are suspended in a medium to resist gravity (Tadros et al., 2004). Nanoemulsions are more resistant to environmental conditions and have a longer life span, ranging from months to many years. Due to their huge surface area, nanoemulsions can aid in increasing medication absorption when used in drug delivery techniques. These are adaptable and can be prepared in a variety of ways using low or high energy, and some are prepared using mechanical equipment to break the particles into the desired size. Additionally, these are harmless due to the fact that they are composed of water, oil, and surfactants, all of which are deemed safe to consume. Additionally, these have the benefit of being applicable to a wide variety of applications, including food, cosmetics, medicine delivery, and pharmaceuticals (Azmi et al., 2019).

Nanoemulsion Preparation

A traditional nanoemulsion is composed of oil, water, and an emulsifier; other polar compounds such as carbohydrates, minerals, and acids may also be used (Fig. 2). The oil process can be prepared using a number of non-ingredients, including triacylglycerols, fatty acids, essential oils, mineral oils, and waxes (Choi & McClements, 2020).

The second most important phase in the preparation of nanoemulsions is the aqueous phase, which consists of the different components such as proteins, minerals, alcohols, acids, and bases. These components play a major role in the stability of nanoemulsions and physiochemical properties by indicating the polarity, refractive index, pH, and density (McClements & Rao, 2011). Two distinct processes can be adopted for the preparation of nanoemulsion edible coatings. One approach is preparing the nanoemulsion in a single step by dissolving all the components in

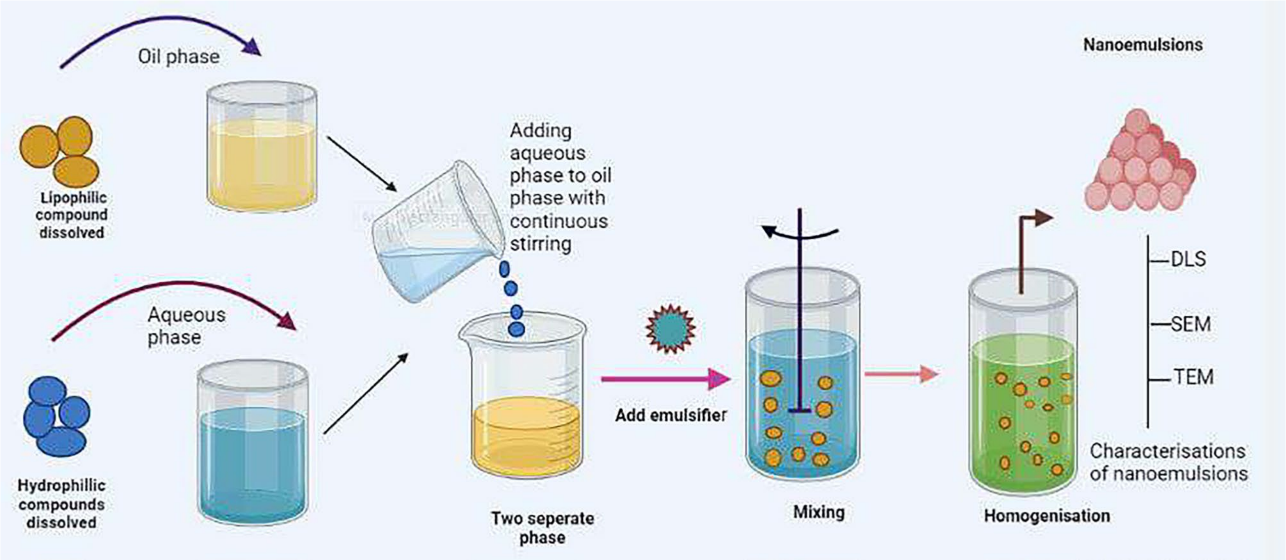

Fig. 2 Preparation method of water in oil (W/O) and oil in water (O/W) emulsions with lipophilic and hydrophilic compounds

a fine solution, and then homogenization will be done for the production of nano-sized droplets. The other approach involves the preparation of nanoemulsions in two steps where aqueous solution is prepared first and then mixed with a biopolymer solution (Dasgupta et al., 2019). The intermixing of two phases, namely, the oil and water phase, results in the formation of emulsion, which will be stable for a temporary phase and can break down easily. Thus, stabilizers such as emulsifying agents are utilized to prevent nanoemulsions from collapsing and to maintain their stability. The majority of emulsifying agents are classified as surfactants such as tweens and hydrophilic colloids such as acacia and veegum. These substances are non-toxic, lower surface tension, and hinder coalescence, which contributes to the development of a nanoemulsion stable for longer time (Jaiswal et al., 2015). Nanoemulsions are obtained by different methods, which can be classified into two categories, namely, high- and low-energy methods (Fig. 3). Some examples of emulsion techniques are shown in Table 3.

Low-Energy Methods

Low-energy methods are more effective than high-energy methods for the production of nanoemulsions; however, low-energy methods are not used for all kinds of emulsifiers. In low-energy approaches, when the oils and the emulsifiers mix are prevented in terms of their composition or environment, nanometric droplets are spontaneously generated (McClements & Rao, 2011). This approach requires relatively a little energy to generate nanoemulsion, but the magnetic stirrer utilized must move rapidly so that the droplets are not interrupted (Maali & Mosavian, 2013).

Spontaneous Emulsification

Despite the differences in the two phases or the experimental settings, the spontaneous emulsification method is a very simple procedure that requires no expensive equipment. Two liquids are combined in this process (Jin et al., 2016). The aqueous phase of one liquid is preserved, while the other is a mixture of oil,

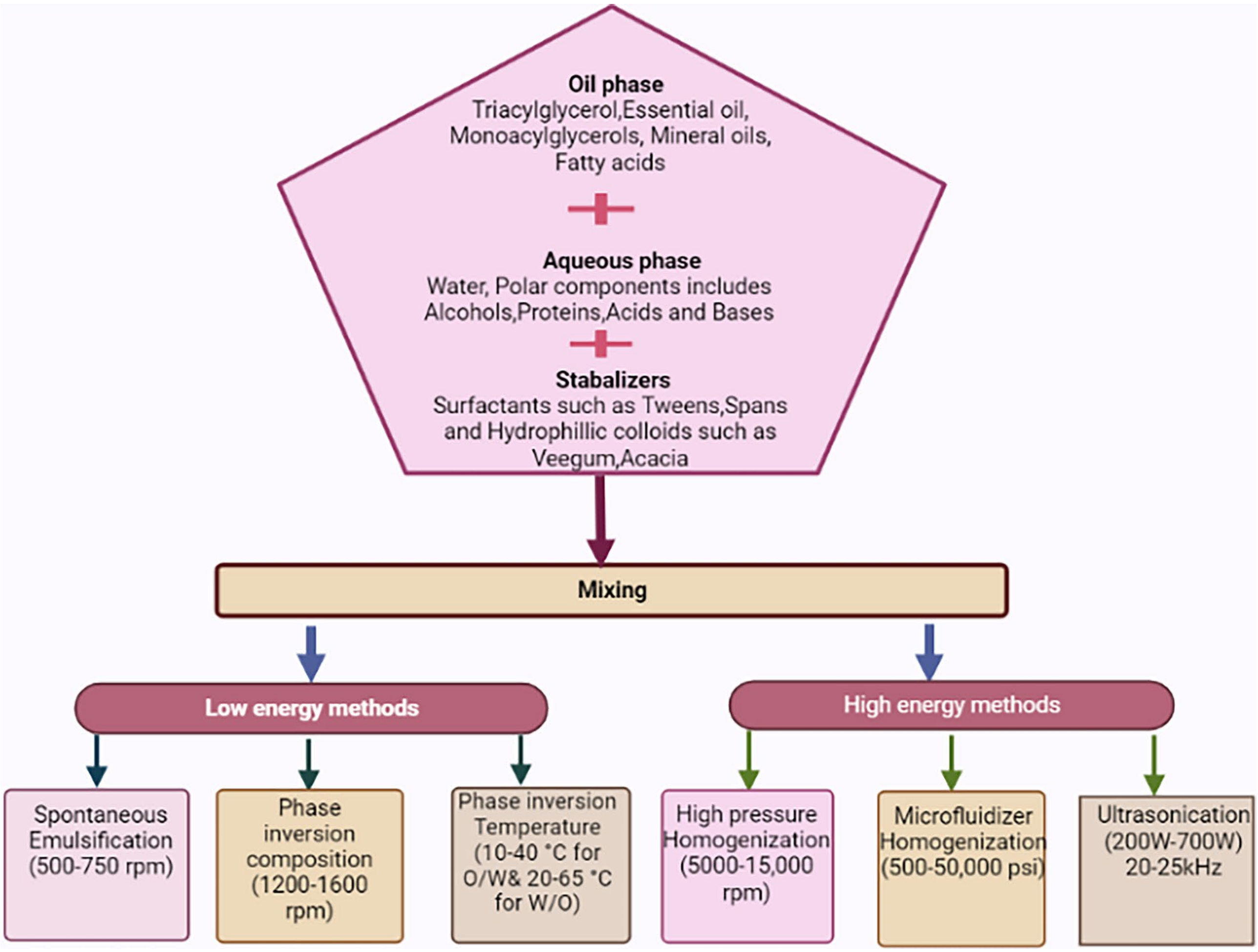

Fig. 3 Illustration of nanoemulsion preparation using low- and high-energy methods

Table 3 Emulsion techniques applied to vegetables

Emulsion technique	Important functional compound	Benefits	Food	References
Ultrasonication	Essential of oregano was used	It has high antimicrobial activity	Work was done on lettuce	Bhargava et al. (2015)
High-pressure homogenization (HPH)	Carvacrol was used as functional compound	Antimicrobial activity	Work was done on zucchini or also known as baby marrow	Donsì et al. (2014)
HPH	Lemongrass essential oil, citrus extract, and cranberry juice were used	They all show good antibacterial activity	Frozen green berries	Maherani et al. (2018)
HPH and ultrasonication	Carvacrol nanoemulsions	High in antimicrobial activity	To inactivate bacteria and yeast on shredded cabbages	Sow et al. (2017)

surfactant, and a water-miscible solvent. After mixing these two liquids at room temperature, emulsions are created. When two thermodynamically stable liquids are mixed, a non-equilibrium condition is formed, resulting in the transfer of hydrophilic elements from the oil phase to the water phase. Because of the increased interfacial area, the droplets are converted into nanometric form during this process (Anton & Vandamme, 2009).

Phase Inversion Composition

At room temperature, phase inversion composition (PIC) is a nanoemulsion production process that improves curvature by changing the conformation. The Gibbs energy of emulsions was utilized to shift the phases, resulting in the inversion of the surfactant's curvature between the positive and negative phases (Jin et al., 2016). The formation of nanoemulsions by using phase inversion composition has been studied in a number of ways. Goncalves et al. (2018) and Pagan et al. (2017) carried out a study to create citral nanoemulsions and test their antibacterial activity using the PIC method. When compared to the traditional form of citral, the results showed that citral nanoemulsion was more effective.

Phase Inversion Temperature

The phase inversion temperature (PIT) method can be used to evaluate temperature fluctuations generated by rapid cooling to disperse nanoemulsion networks. In general, the mixture is heated and then cooled, altering the surfactant's affinity and resulting in the spontaneous formation of small droplets (Komaiko & Mcclements, 2016).The dehydration of the surfactant's head group causes a change in solubility, which causes the surfactant's affinity to change (Solans & Sole, 2012). The system showed low surface tension in the reversal stage; therefore, the mixture must be cooled fast to maintain the stability of nanoemulsion (Hilbig et al., 2016). Phase inversion temperature produces more stable and homogenous nanometric droplets without the need for expensive equipment. Temperature differences impact temperature-sensitive surfactants by modifying the curve of their surfactant layer, according to this method. The droplet interface temperature-sensitive surfactants, leading to a positive curve of the surfactant, become water soluble at lower temperatures (Ren et al., 2019). Chuesiang et al. (2019) used the PIT method to mix cinnamon EO with Tween 80 surfactant for 30 min at 25 °C, resulting in an outstanding nanoemulsion. They then quickly cooled the resulting emulsion to 4 °C in two phases after heating it to 67–78 °C (depending on the inversion temperature). They also studied how Tween 80 affected droplet size. Low surface tension at the oil–water interactions promotes increase in surfactant concentration which results in smaller droplets when the system was cooled (Chuesiang et al., 2019).

High-Energy Methods

Intensive disruptive forces are used in high-energy processes by using intense energy mechanical devices such as high-pressure homogenization, microfluidizers, and ultrasonication. By employing any type of oil and emulsifier, these technologies can be used to create food-grade nanoemulsions (McClements & Jafari, 2018).

High-Pressure Homogenization

According to this method, various factors such as cavitation, hydraulic shear, and turbulence are employed to synthesize nanoemulsions. To make nanoemulsions, co-surfactants and surfactants are passed through an opening in a homogenizer at a pressure of 500–5000 psi. This technology is commonly used in laboratories and factories, despite some disadvantages like high energy consumption and the fact that the temperature of the homogenizer rises during the operation, which can sometimes injure the components (Izquierdo et al., 2002). Alexandre et al. (2016) developed nanoemulsions containing ginger EOs at various concentrations utilizing a high-pressure homogenization process.

Microfluidizer Homogenization

The microfluidizer homogenization method is also known as the microfluidization technique, and it is related to the high-pressure homogenization method in that it is used to generate nanoemulsions. This approach involves pumping emulsion via a small opening and spinning emulsion droplets inside the apparatus to reach the desired droplet size. After then, nanoemulsions are formed as a result of the strong shear effect on the emulsion droplets (de Cenobio-Galindo et al., 2019). In terms of mechanics, microfluidizer is comparable to a high-velocity static mixer with no moving joints; this approach can also be used at both a laboratory and an industrial scale (Azmi et al., 2019). When compared to other approaches, the advantage of using this method for nanoemulsion synthesis is that it produces very tiny nanoemulsion droplets (Maali & Mosavian, 2013).

Ultrasonication

The ultrasonication approach for nanoemulsion generation is effective at reducing nanoemulsion particle size. The tip of the sonicator probe causes mechanical vibration inside the liquid emulsion, leading to the creation and disintegration of vapor cavities within the liquid emulsion. As a result, nanoemulsions are formed (Azmi et al., 2019). Ultrasound method has been used to encapsulate various EOs, including *Zataria multiflora* (Jimenez-Saelices et al., 2020; Mellinas et al., 2020) and *marjoram* (Almasi et al., 2020) EOs. Different irradiation times were tested for this goal; however, the most popular techniques for ultrasonic nanoemulsion creation involve short times (0–30 min) (Ghani et al., 2018). The use of ultrasounds with various pulses has also been examined. Because it avoids overheating, this method has shown considerable promise in temperature-sensitive chemicals (Keykhosravy et al., 2020). Different methods of nanoemulsion preparations are shown in Table 4.

Essential Oil Nanoemulsions

Antimicrobial Activity of Essential Oil Nanoemulsions

The effect of essential oils on food decomposition and the pathogenic microorganisms responsible for spoilage have been intensively explored in recent decades. Due to the differences in the cell wall compositions, Gram-negative bacteria

Table 4 Nanoemulsion preparations by a variety of methodologies, as well as different experimental settings and matrixes

Method	Matrix	Environmental conditions	References
High-speed homogenization ultrasounds	Tween 80 Cinnamon EO 1–1-3% (v/v)	5000 rpm for 10 min, 750 W	Frank et al. (2018)
High-speed homogenization	Tween 80, pectin (1–3 wt% lemongrass EO (1% vol)	15.000 rpm for 6 min	Mendes et al. (2020)
High-speed homogenization	*Zataria multiflora* EO cinnamaldehyde (6 wt%) Tween 80	Addition of droplets at 400 rpm for 10 min and 10,000 rpm for 15–20 min	Amiri et al. (2019)
Ultrasounds	Tween 80 (20 wt% of EO) marjoram EO (1% wt)	200 W, 3000 rpm, 20 kHz for 15 min	Almasi et al. (2020)
Ultrasounds	Thymol, Tween 80, triglycerides of medium chain	40% amplitude, 700 W, 0–30 min off cycles	Robledo et al. (2018)
Ultrasounds	Tween 80, *Zataria multiflora* EO	Temperature, 15 °C, 150 W, 0–10 min, and 20 kHz	Hashemi Gahruie et al. (2017)
Ultrasounds	Soy protein isolate, cinnamon oil	60% amplitude, 25 kHz for 2 min	Ghani et al. (2018)
Spontaneous emulsification	Combination of corn oil and lime EO, Tween 80, and water (15–80%)	Mixing of oil phase at 750 rpm for 30 min, addition of aqueous phase in oil phase at 750 rpm for 30 min	Liew et al. (2020)
Spontaneous emulsification	Tween 80, water, combination of cinnamon oil and coconut oil (10 wt%)	Mixing of oil phase for 30 min at 750 rpm, addition of aqueous phase at 750 rpm for 30 min	Yildirim et al. (2017)
High-pressure homogenization	Soybean oil, Span 80, Tween 80, and rutin	100 MPa, 7000 rpm for 5 min	Dammak et al. (2017)
High-pressure homogenization	Canola oil, ginger EO, Span 60, Tween 20	3–6 cycles, 10,000 psi, 24,000 rpm for 5 min	Alexandre et al. (2016)

are less sensitive to essential oils than Gram-positive bacteria (Mumivand et al., 2019). There are no significant variations in the antibacterial activity of certain EO nanoemulsions against Gram-positive and Gram-negative microorganisms. For example, free thyme oil needed less time to inactivate *Listeria monocytogenes* (Gram-positive) than *Salmonella enteritidis* and *Escherichia coli* (both Gram-negative); no significant difference was detected when the same EO was encapsulated using a soybean polysaccharide (Wu et al., 2014). Similarly, no significant difference in the kinetics of eugenol inactivation against *L. monocytogenes* and *E. coli* was detected (Pernin et al., 2019). Overall, the antibacterial activity of EO nanoemulsions is highly dependent on the EO components, the tested bacterial strain, composition, and size of the emulsion (Donsi et al., 2015).

Mechanism of Antimicrobial Action of EO Nanoemulsions

Many EO nanoemulsions have a stronger antibacterial range than free EOs (Ju et al., 2019). The nanoemulsion-based delivery methods for EOs are likely to facilitate their interaction with microbial cell membranes via distinct pathways. Firstly, the outer cell membrane enhances the association with cytoplasmic membrane through increased surface area and passive transport. Hydrophilic surface with small-sized nanoemulsion droplets can pass the plasma membrane through the numerous porin proteins that act as hydrophilic channels from Gram-negative bacteria (Jimenez et al., 2018). In case of Gram-positive bacteria, by changing phospholipid bilayer integrity with active transport proteins embedded in phospholipid bilayer, small nanoemulsion droplets can carry EOs to the cell membrane surface, enhancing accessibility to microbial cells (Hakemi-Vala et al., 2017). Secondly, phospholipid bilayer cell membrane fusing with emulsifier droplets promotes EO release at specific locations. The use of different surfactants resulted in varied antibacterial action despite similar droplet size (Sedaghat Doost et al., 2020). Additionally, to enhance the antimicrobial activity of EO, specific emulsifier and cell membrane interactions play an important role (Ju et al., 2019). Thirdly, essential oil activity can be prolonged by the release of EOs from the nanoemulsions over time, promoted by dividing EO between the oil phase and the aqueous phase. For the dispersion between two different phases, i.e., oil and the aqueous phase, EO molecules in a state of dynamic equilibrium act as a nanotanks with nanoemulsion droplets (Lucia & Guzman, 2021).

Applications of EO Nanoemulsions in Different Products

It is a challenging task to include EO nanoemulsions into food items. The highly reactive compounds that comprise essential oils can be destroyed by contact with other food components (protein, lipids, and minerals), or they can adsorb to the various surfaces found in actual meals, resulting in uneven distribution and loss of antibacterial efficacy (Maurya et al., 2021). In general, a greater concentration of EOs is needed in meals than in synthetic media to achieve the same effect (Zhang et al., 2021). Moreover, due to their strong volatility, reactivity, odor, and taste, EOs can significantly affect the sensory properties of the product, resulting in undesirable characteristics (Das Purkayastha & Manhar, 2016). For instance, clove and oregano oils have been observed to react with iron, producing black pigmentations that detract from the look of the product (Majeed et al., 2016). However, the use of EOs in food preservation is restricted mainly by their strong flavor, with the maximum allowable dosage determined by the taste sensors in the particular product (Pathania et al., 2018). Previous study established that the effect of EOs on the sensory qualities of food products is highly dependent on their food compatibility and more specifically on the compatibility of the EOs components with the food products and their physicochemical features (Wan et al., 2019).

EO Nanoemulsions Mixing with Liquid Products

Due to their uniform distribution at concentrations beyond the solubility limit, EO nanoemulsions were shown to be more effective against microbial load than free EOs in milk with varying fat content (Fathi et al., 2021). The utilization of thymol results in antimicrobial activity against *L. monocytogenes* during a 7-day shelf life at 32 °C, keeping the bacterial population detection limits for skim milk and continuously declining for milk with a greater fat content (Ettayebi et al., 2000). Both tea tree oil and cinnamaldehyde nanoemulsions inhibited the inoculated microbial load in fruit juices in a concentration-dependent manner (Subhaswaraj et al., 2018). The antibacterial activity of tea tree oil nanoemulsions was detected in orange and pear juice after 16 days of storage at 32 °C, and no significant color change was observed over the same storage time (Donsì et al., 2011).

Effect of EO Nanoemulsion Washing on Food Surfaces

The use of EO-infused washing solutions is not new and has been widely studied. However, this approach is limited to the insolubility of EOs in water solutions. Nanoemulsions can be used to overcome this limitation as they can improve the water solubility of vegetable leaves and also increase the amount of EO in washing solutions. Recent research has revealed that EO nanoemulsions show antimicrobial activity on minimally processed food. For example, oregano oil nanoemulsion was applied to the surface of lettuce, resulting in the reduction of bacterial count in *L. monocytogenes*, *E.*

coli, and *Salmonella typhimurium*, i.e., 3.4, 3.09, and 2.29 log CFU/g, respectively, compared to the control (Rinaldi et al., 2021). Similarly, washing spinach leaves with carvacrol or eugenol nanoemulsion resulted in a substantial decrease of *E. coli* and *Salmonella enterica* inoculation on the leaves (Park et al., 2018). Landry et al. (2016) investigated the antibacterial effect of carvacrol nanoemulsion on processed sprouts such as broccoli, radish, and mung bean against *Salmonella enteritidis* and *Escherichia coli*. Radish and broccoli seeds were treated by soaking process with 4000 ppm carvacrol nanoemulsion for 60 min, resulting in inactivation of 2 levels of *S. enteritidis* and *E. coli* on radish seeds and found unsuccessful against infected broccoli seeds (Landry et al., 2016).

EO Nanoemulsion Coatings on Food Surface

For decades, edible coatings have been used to extend the shelf life of food by providing a physical barrier between the environment and the food and therefore preventing mass transport (Zambrano-Zaragoza et al., 2018). Lots of research has shown the incorporation of EOs into the coating solution. If EO is used directly into coatings or films, it significantly impairs their mechanical characteristics, reduces their capacity to load EOs, and increases the possibility of oiling of the essential oils (Dhall, 2013). It would give more beneficial characteristics if nanoemulsions were used in coating-forming solutions, which will improve film homogeneity, increase antimicrobial activity, reduce compound dosage, decrease interactions with other food matrix components, increase stability of the compounds under stress conditions, and decrease mass transport of the compounds through the coating (Avramescu et al., 2020). In another study different nanoemulsion edible films developed using sage, thyme, or lemongrass essential oils along with sodium alginate showed better antimicrobial activity, water vapour resistance and mechanical flexibility. Among the different essential oils used sage had the highest transparency, water vapour resisitance and mechanical flexibility, while thyme had the highest antibacterial activity against inoculated *E.coli*, (Nair et al., 2020; Acevedo-Fani et al., 2015). The use of EO nanoemulsions in edible coatings is a particularly promising technology for the preservation of a variety of products, both due to the small amount of EOs required for the protection layer's prolonged persistence and due to the possibility of synergy between the

Table 5 Applications of nanoemulsions in food industry

Types of nanoemulsions	Method of preparation	Key features	Applications	References
Ginger essential oil	Ultrasonication method	High antimicrobial activity against two pathogens, i.e., *Listeria monocytogenes* and *Salmonella typhimurium*	Edible coating for chicken	Noori et al. (2018)
linalool oil	Ultrasonication	*S. typhimurium*	Acts as antibiofilm agent	Prakash et al. (2020)
Starch-beeswax	Microfluidization	Showed antifungal and antibacterial activity, i.e., *R. stolonifer*, *B. cinerea* (fungus), and *S. saintpaul* (bacteria)	To increase shelf life of fresh food products, i.e., preparations of edible coatings	Arredondo-Ochoa et al. (2017)
Turmeric extract	Ultrasonication, high-speed homogenization	High antioxidant activity	Increasing shelf life of milk	Park et al. (2019)
Essential oil from cinnamon	Ultrasonication	Antifungal activity against different fungal species, i.e., *Rhizopus*, *Penicillium* sp., *Aspergillus niger*	Showed high potential for food applications	Pongsumpun et al. (2020)
Basil oil	Ultrasonication	Antifungal activity against *Aspergillus* and *Penicillium*	Act as natural preservative against food spoilage pathogens	Gundewadi et al. (2018)
Clove oil	High-speed homogenization	Antibacterial activity against *Listeria monocytogenes*, *E. coli*	High antimicrobial activity and acts as preservative	Majeed et al. (2016)
Orange peel essential oil	Ultrasonication	Antimicrobial activity and enhance shelf life of fresh-cut orange	Texture enhancer and antimicrobial agent	Radi et al. (2018)
Carvacrol essential oil with combination of chitosan	High-pressure homogenization	To decontaminate fresh-cut cucumber	High antioxidant and antimicrobial activity	Tastan et al. (2017)
Essential oil of lemongrass	High-pressure homogenization	Preservation of grapes	Antimicrobial activity	Oh et al. (2017)

EO biological activity and the physical barrier provided by the coating (Chaudhary et al., 2020).

Application of Nanoemulsion in Food Sectors

Nanoemulsions have made important contributions to a variety of industries in recent decades. According to the use of nanoemulsions in the last decade, the highest percentage of nanoemulsions can be found in pharmaceutics and cosmetics, followed by the food sector and other various industries (Azmi et al., 2019). Nanoemulsions can be used in the food industry to produce smart food products that contain substances, which are difficult to incorporate due to their poor solubility in water; one such ingredient is β-carotene, a pigment found in vegetables such as carrots that has numerous health benefits and also is responsible for color in vegetables (Aswathanarayan & Vittal, 2019). The use of nanoemulsions in the food industry brings about positive changes, especially in terms of covering the unpleasant tastes or odors of some bioactive constituents, extending the shelf life of food ingredients and improving food digestibility (Hosseini & Jafari, 2020). In addition, nanoemulsions also help in decreasing the food odor and degradation and also increase the bioavailability of certain components (Dima et al., 2020). Due to the high surface area and small droplet size of nanoemulsion formulations, they are regarded to be beneficial for foods. To ensure the stability of nanoemulsions during processing and storage, an emulsifier is required during their production; nanoemulsions can be manufactured utilizing a variety of emulsifiers that act as antimicrobial preservatives, enhancing food safety (Pavoni et al., 2020). Successful nanoemulsions of basil oil have been created by ultrasonically extracting a biosurfactant from an aqueous extract of *S. mukorossi*. The use of *Quillaja* saponins (QS) in nanoemulsions leads to an increase in thermal stability, which is also beneficial for the production of sterilized emulsion-based foods (Riquelme et al., 2019). Due to the natural and beneficial antioxidant and antibacterial properties of essential oils, they are in high demand and generate considerable attention in the food industry (Rather et al., 2021). Because of high volatility and reactivity of EOs with food components resulting in the loss of functionality, to overcome this drawback of essential oils, nanoencapsulation process is used, especially nanoemulsions to achieve the stability of EOs in food application (Chaudhari et al., 2021). These nanoemulsions are also responsible for enhancing the antimicrobial activity of EOs, and they have high compatibility with food (Ghasemi et al., 2018). Table 5 shows the uses of nanoemulsions in the food industry.

Concluding Remarks and Future Perspectives

The study discusses the potential for nanoemulsions containing essential oils that carry antimicrobial chemicals efficiently. Due to their high surface area and small droplet size, nanoemulsion formulations are believed to be a functional behavior for food stuff. Nanoemulsions can be prepared by combining several emulsifiers that act as antimicrobial agents, thus increasing food safety. Consequently, essential oils are used as natural antimicrobials which have the potential to improve product quality and safety, with a little impact on human health. In summary, essential oil-based nanoemulsions have enhanced antibacterial activities due to the presence of non-phospholipid-based, affordable, stable, and non-toxic antimicrobial agents with therapeutic applications.

Nanoemulsions have unique properties and higher stability than conventional emulsions and have great potential in a variety of industries, including food, pharmaceuticals, and cosmetics. However, apart from their large potential, they are not stable completely, so further research is needed to develop stable nanoemulsions for production. Encapsulation of essential oils in nanoemulsions has a number of advantages in terms of product behavior and biological and physicochemical stability. Since essential oils are sensitive to environmental conditions such as temperature and light, innovative methods may be beneficial in preserving and improving their properties and biological activities. On the other hand, future research should focus on the synergistic effects of several essential oils and their components, as well as their action of mechanisms. The stability of essential oil is a major problem, so new strategies are required for their stability. For food safety, the concentration of EO should be low with minimal sensory changes could be an attractive field of research for researchers.

Declarations

Conflict of Interest The authors declare no competing interests.

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