

Review Article

Essential Oils-Loaded Electrospun Biopolymers: A Future Perspective for Active Food Packaging

Shahla Ataei ¹, Pedram Azari ^{2,3}, Aziz Hassan,¹ Belinda Pinguan-Murphy ²,
Rosiyah Yahya,¹ and Farina Muhamad ²

¹Department of Chemistry, University of Malaya, 50603 Kuala Lumpur, Malaysia

²Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

³Centre for Applied Biomechanics, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

Correspondence should be addressed to Shahla Ataei; sh.ataei.k@gmail.com and Farina Muhamad; farinamuhamad@um.edu.my

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The growth of global food demand combined with the increased appeal to access different foods from every corner of the globe is forcing the food industry to look for alternative technologies to increase the shelf life. Essential oils (EOs) as naturally occurring functional ingredients have shown great prospects in active food packaging. EOs can inhibit the growth of superficial food pathogens, modify nutritious values without affecting the sensory qualities of food, and prolong the shelf life when used in food packaging as an active ingredient. Since 2016, various reports have demonstrated that combinations of electrospun fibers and encapsulated EOs could offer promising results when used as food packaging. Such electrospun platforms have encapsulated either pure EOs or their complexation with other antibacterial agents to prolong the shelf life of food products through sustained release of active ingredients. This paper presents a comprehensive review of the essential oil-loaded electrospun fibers that have been applied as active food packaging material.

1. Introduction

For many decades, synthetic polymers have dominated food packaging industry due to their favourable properties such as softness, lightness, and transparency. So far, petrochemical-based plastics such as polyethylene terephthalate (PET), polyvinylchloride (PVC), polyethylene (PE) [1], polypropylene (PP) [2], polystyrene (PS) [3], and polyamide (PA) [4] have been extensively used as packaging materials as a result of their low cost of synthesis, decent mechanical performance, lack of permeability to oxygen, carbon dioxide, anhydride, and aromatic compounds as well as heat sealability, all of which contribute to food preservation and waste reduction. Despite several desirable properties, the usage of conventional plastics needs to be restricted since their long degradation cycles pose serious ecological threats to the environment. Therefore, it is increasingly important to employ novel

biodegradable raw materials. Although complete replacement of conventional plastics with eco-friendly plastics is impossible to achieve, at least for specific applications such as food packaging, the use of biobased active food packaging seems to be a realistic solution. Active food packaging is a new method to prolong the shelf life of food products and to maintain of their safety, quality, and integrity. According to the European regulation (EC) No. 450/2009, active packaging consists of systems that interact with the food as they would absorb substances such as moisture, carbon dioxide, or odour from packaged food or release desired materials such as antimicrobial, antioxidant compounds or flavours into the packaged food (European Commission 2009) [5]. Despite the importance of active food packaging, there are limitations associated with the existing polymeric materials to serve as optimal active packaging and modifications are necessary. Such modifications involve addition

of other additives such as antimicrobial and antioxidant agents which are required.

EOs derived from different parts of aromatic plants have been extensively researched for being a natural product and their nutritional health benefits. The main interest in EOs lies in their various therapeutic properties, namely, antioxidant, antimicrobial, antitumour, analgesic, insecticidal, antidiabetic, and anti-inflammatory [6–9]. As of 2019, the number of published papers regarding essential oils in food industry is almost 800 papers, indicating the use of EOs as biopreservatives in all types of foods [10].

EOs hold great potential for active food packaging applications as they can be directly added to the food products or incorporated into food packaging for gradual release during transportation and storage to improve shelf life and preservation [11]. Although EOs have been demonstrated as an alternative to chemical preservatives in active food packaging systems, they are associated with certain limitations that need to be resolved for successful incorporation in active food packaging systems. High volatility, low aqueous solubility, and intense smell are the major shortcomings that have limited the usage of EOs in food industry. Therefore, the encapsulation of oils has been considered as a key solution in food packaging. Recent advances in encapsulation technology have improved the stability of sensitive components during production, through a reduction in evaporation and degradation of volatile compounds as well as firmer control over the capsules' dimensions, shape, and morphology during the encapsulation process [12, 13]. These methods carry out chemical encapsulation through ionic gelation, simple and complex coacervation, cocrystallization, interfacial polymerization, molecular inclusion, entrapment in liposomes, and ionic gelation plus electrostatic interactions [14].

Among the various approaches for nanoencapsulation, electrospinning is a versatile, easy to operate method for continuous fabrication of nanostructures [15]. Electrospun membranes exhibit a fibrous morphology with large surface area to volume ratio, high porosity, and fiber diameters in the range of nano to micron, all of which are favourable properties for the sustained release of active ingredients from the packaging membrane to the surface of the food [16]. While electrospinning is widely applied in the fields of tissue engineering [17], wound dressing [18], enzyme immobilization [19], and electrode materials [20], its application as food packaging is only recently explored [21]. These recent advances in applications of loaded electrospun membranes in active food packaging call for a review on this topic. Although there are several reviews on relevant topics, the subject has the potential to be reviewed on its own merits.

Fernández-López and Viuda-Martos studied application of EOs in food systems [10]. Ribeiro-Santos et al. reviewed application of EOs incorporated into films and coatings in food packaging. Films containing EOs are usually produced via casting method [22]. In another study, São Pedro et al. reviewed nanoencapsulation of EOs into lipid carriers such as solid lipid nanoparticles, liposomes, and nanoemulsions for drug delivery systems. They concluded significant

improvement in antimicrobial activity of EOs [23]. In the above-mentioned reviews, the authors have emphasized the potential of EOs to be used as a part of packaging materials or their direct incorporation into the food matrix. However, this review focuses on EOs, as effective protective antimicrobials, and their incorporation in active food packaging through electrospinning. The properties of the polymeric matrices, main active components of EOs, and encapsulation through electrospinning are reviewed. The main objective of this review is to provide a broad insight into the potential applications of electrospun nanofibers encapsulating EOs as active food packaging materials. To the best knowledge of the authors, there is no review available on application of encapsulated EOs in food packaging using electrospinning technique.

2. Essentials Oils (EOs) for Active Food Packaging

EOs are produced by angiospermic plants and have found various usages in different industries [24]. Among all the plant species, only aromatic plants are sources of EOs. Aromatic plants form about 10% of plant species (over 17,000) and are well distributed around world [25]. EOs are secondary metabolites which could be derived from different plant organs including flowers (jasmine, rose, chamomile, violet, and lavender), buds (clove), leaves (thyme, eucalyptus, salvia, and rosemary), fruits (star anise), twigs (*Luma chequen*), bark (cinnamon), seeds (cardamom), wood (sandal), rhizome, and roots (ginger), all of which have the potential to be applied in food packaging as antimicrobial and antioxidant agents [26–30].

The chemical composition and quality of EOs depend on characteristics of the source plant such as growth conditions, variety, geographical origin, age, season, and condition of the plant when harvested. Extraction method, analysis conditions, and processing chemicals can also affect their properties [31–34]. Their extraction yield is usually very low (about 1%) which makes them valuable rare substances. EOs consist of concentrated lipophilic volatile aroma compounds including terpenes, terpenoids, and phenol-derived aromatic and aliphatic components. The phenolic compounds in EOs can diminish or almost eliminate the presence of microorganisms and minimize lipid oxidation [35].

The natural extracts of EOs are classified as Generally Recognized as Safe (GRAS) by the US Food and Drug Administration (FDA) and received approval for safety and effectiveness [36]. Therefore, in food related application, they are more suitable alternatives to synthetic antioxidants such as butylated hydroxytoluene (BHT) or butylated hydroxyanisole (BHA) which might have a carcinogenic effect [36].

These oils are substances accountable for the active function of packaging with the flexibility to be settled in a different container or be directly added to the packaging material. In either of the cases, the release of the oils during transportation and storage leads to increased shelf life.

Electrospun-loaded EOs could be the answer to market demands as they allow foods to reach the consumers with

their original or enhanced organoleptic properties, increased shelf life, and improved safety [37–40]. The packaging materials produced in these systems can contain active ingredients designed for sustained release during storage or transportation to delay food deterioration.

Table 1 summarizes the essential oils that have been successfully used in food packaging for improved efficiency.

3. Electrospinning and Nanoencapsulation in Active Food Packaging

Electrospinning which was first patented by Cooley and Morton in 1902 is a straightforward method for producing continuous micro- and nanofibers [62]. Unlike the conventional methods of fiber production which are based on application of mechanical force, electrospinning uses high-voltage electrostatic repulsive force for drawing and fiber stretching. Therefore, via electrospinning, it is possible to obtain fibers with diameters in the range of nanometres [63]. A typical electrospinning device is made up of a high voltage power source, a pump with tuneable feeding rate, a capillary as spinneret, and a collector. High voltage power source oppositely charges the capillary (commonly more than 10 kV) and the collector creating the pulling force for whipping instability [63]. When the charges building up within the polymer solution accumulate to a critical amount, a jet starts initiation from the capillary tip. The jet undergoes uniaxial stretching and thinning, while moving toward the oppositely charged collector and solvent evaporation is happening in the meantime. Once the jet reaches the collector, all the solvent should be evaporated, and formation of micro- or nanofibrous morphologies should have taken place. There are two sets of parameters that affect the morphology of the electrospinning products: intrinsic parameters such as solution viscosity, solvent evaporation rate, and conductivity of the polymer solution and processing parameters which include applied voltage, feeding rate, collector shape and texture, and collection distance [64]. Figure 1 shows the various aspects involved in production of encapsulated electrospun fibers including EO extraction (Figure 1(a)), complexation and solution preparation (Figure 1(b)), and a typical electrospinning system (Figure 1(c)). Several other techniques such as phase separation, bicomponent extrusion, template synthesis, drawing, centrifugal spinning, and melt blowing have been reported to produce polymeric micro/nanofibers [65–69]. However, for food applications, most of these methods suffer from various shortcomings such as difficulty of control, lack of applicability to a wide range of materials, and exposure to chemicals affecting the stability of sensitive nutrients and prohibiting their usage due to toxicity concerns [70–72]. Due to their size and high specific surface area, electrospun nanofibers have an edge in encapsulation efficiencies and demonstrate major potential for applications requiring controlled release of active ingredients, while exhibiting appropriate levels of biodegradability and biocompatibility [73]. The electrospun antimicrobial membranes are fabricated by adding antimicrobial agents into the polymer solution followed by electrospinning. Although the incorporation of EOs into nanofibers was demonstrated earlier, there was no report on

the application of electrospun-loaded EOs for antimicrobial packaging materials until 2016 [74]. Biopolymers such as polyvinyl alcohol (PVA) [75], chitosan (CS) [74], polycarbonate (PC) [76], and polyethylene oxide (PEO) [77] have been popular options for encapsulation of EOs through electrospinning because of their excellent properties in generating nanofibers and membranes [21].

Within the last few years, nanoencapsulation of biological compounds in carrier materials has found its way to food technology as a simple yet effective technique for modification of the quality of food and preservation [78]. Encapsulation is effective in enhancing the stability and solubility of EOs as well as masking their strong flavour. Due to the hydrophobicity, instability, and volatility of EOs, they usually cannot be directly added to electrospinning solution and a carrier substance such as cyclodextrins (CDs), liposomes (LO), and CS is usually required [79, 80].

3.1. Encapsulation of Cinnamon Essential Oil (CEO). CEO is a plant-derived antimicrobial substance of which FDA has categorized it as GRAS. Its protective qualities do not disturb the physicochemical or nutritious properties of the food. CEO exhibits a broad spectrum of antimicrobial activity against a variety of microorganisms through prevention of cell wall biosynthesis, functions of membrane, and specific enzyme activities [81]. Encapsulation of CEO protects it from harsh environmental conditions, extends the shelf life, and allows controlled release of the active compound [82].

Conn et al. reported successful use of CEO as an antimicrobial agent against common microorganisms [83, 84]. CEO was encapsulated into β -cyclodextrin (β -CD) before incorporation in electrospun PVA fibers. CDs are cyclic oligosaccharides produced through enzymatic conversion of starch and exhibit nontoxic and biodegradable characteristics. Several studies have reported the use of CDs for food-related applications [85–87]. CDs are composed of α -1,4-linked glucopyranose units and form a shortened cone-like structure cavity. As a result of their unique chemical structure, they form noncovalent host-guest inclusion complexes with EOs, CEO/ β -CD inclusion complex (CEO/ β -CD-IC), enhancing their solubility, chemical stability, and bioavailability and protecting them from oxidation [88]. The mechanism behind the complexation is the displacement of the high-enthalpy water molecules occupying the cavity, with a guest molecule of proper polarity and dimensions [89, 90]. Therefore, they are often used to encapsulate various types of food additives and essential oils [89].

β -CD is the most commonly used member of CDs which is a hydrophobic molecule capable of entrapping EOs within its inner cavity [91]. A novel antimicrobial membrane electrospun based on PVA, CEO, indicated molecular interactions amongst PVA, CEO, and β -CD, resulting in enhancement in thermal stability of CEO and masking its special flavour. Thermogravimetric analysis of PVA/CEO/ β -CD nanofibers indicated a shift of the second weight loss peak to higher temperature (110–160°C) due to possible formation of chemical or hydrogen bonds between PVA and CEO. The inhibition zone of nanofibers based on PVA/CEO/

TABLE 1: Essential oils incorporated in food packaging applications.

Essential oil combinations	Properties	Food product	Applied film material
Rosemary [41]	Antimicrobial	Chicken	Cellulose acetate
Cinnamon clove [42]	Antimicrobial	Bakery	Cassava starch
Lemon, thyme, and cinnamon [43]	Antibacterial	NA	Chitosan
Cinnamon, winter savory, and oregano [44]	Antimicrobial	Bologna and ham	Alginate
Bergamot [45]	Antifungal and antibacterial	NA	Chitosan
Garlic, rosemary, and oregano [46]	Antimicrobial	NA	Whey protein isolate (WPI)
Oregano [47]	Antimicrobial (against <i>S. aureus</i> , <i>Shewanella putrefaciens</i> , and <i>Yersinia enterocolitica</i>) and antioxidant	NA	Quince seed mucilage
Oregano [48]	Antimicrobial	Pizza	Cellulosic resin
Oregano [49]	Antimicrobial	Ripened sheep cheese model	Polypropylene (PP) and polyethylene terephthalate (PET)
Oregano and thyme [50]	Antimicrobial (against <i>Pseudomonas</i> spp. and <i>coliform bacteria</i>)	Fresh ground beef	Soy protein
Oregano [51]	Antimicrobial	Fresh beef	Whey protein isolate (WPI)
Mixture of oregano, pimento berry, and lemongrass (mix A) and mixture of nutmeg, lemongrass, and citral (mix B) [52]	Antimicrobial (against <i>L. monocytogenes</i>)	Fresh broccoli	Methylcellulose (MC) and blend of polycaprolactone/alginate (PCL/ALG)
Ginger, turmeric, and plai [53]	Antioxidant	NA	Fish skin gelatin
<i>Satureja hortensis</i> [54]	Antibacterial and antioxidant	NA	k-Carrageenan
Oregano and pimento [55]	Antioxidant	Whole beef muscle	Milk protein
Clove [56]	Antibacterial	Fish	Gelatin chitosan
Clove [57]	Antibacterial and antioxidant	Sardine patties	Sunflower protein concentrate
Linalool or methyl chavicol [39]	Antimicrobial	Cheddar cheese	Low-density polyethylene (LDPE)
Oregano and bergamot [58]	Antimicrobial	Formosa plum	Hydroxypropyl methylcellulose and limonene constituent EO
Cinnamon and mustard [59]	Antibacterial	Tomatoes	Zein
Limonene constituent EO, lemongrass, and oregano [60]	Antimicrobial	Strawberries	Chitosan
Peppermint, red thyme, chitosan, and lemon [61]	Flavouring	Strawberry	Chitosan

β -CD was reported to be wider than that of PVA/CEO. The entrapment of CEO into the cavities of β -CD improved the solubility of CEO and led to a more effective release into the agar medium [92]. Moreover, water contact angle results indicated that addition of CEO/ β -CD reduced the hydrophobicity of the nanofibrous membrane. Perhaps that explains the excellent antimicrobial properties of the PVA/CEO/ β -CD nanofibrous film against both Gram-positive and Gram-negative bacteria. According to the report, it effectively extended the shelf life of strawberries and showed potential for active food packaging applications. Furthermore, the electrospun membranes are managed to incorporate greater amount of CEO compared to casted film which resulted in enhanced antimicrobial activity.

Rieger and Schiffmann investigated the antimicrobial property of electrospun CS/cinnamaldehyde/PEO nanofibers against *E. coli* [74]. It was demonstrated that the inherent antibacterial properties of chitosan combined with the quick release of cinnamaldehyde (CA) achieved elevated inactivation rates against *Escherichia coli* and *Pseudomonas aeruginosa* [74].

Wen et al. for the first time reported the use of polylactic acid (PLA) and CEO as antimicrobial food packaging

material. CEO/ β -CD-IC was successfully produced through coprecipitation method and modified the thermal stability of CEO. PLA was the selected polymer matrix since it is an FDA approved bioplastic as food-contact material [83, 93]. The CEO/ β -CD-IC was encapsulated into PLA nanofibers by electrospinning [94]. The electrospun biodegradable PLA/CEO/ β -CD nanofilm demonstrated better antimicrobial activity, against *Escherichia coli* and *Staphylococcus aureus*, compared to PLA/CEO nanofilm. The results indicated that PLA/CEO/ β -CD fiber efficiently increased the shelf life of pork, suggesting a potential application in active food packaging [94].

Liu et al. studied the effect CEO contents (1%, 1.5%, 2%, and 2.5% v/v) on the efficiency of encapsulation, nanoparticle dimensions, and antibacterial activity of CS nanoparticles loaded in PLA. CS nanoparticles as the carriers of CEO were added to the PLA solution followed by electrospinning. The obtained electrospun fibers were capable of sustained release of CEO [95]. The study suggested that addition of CEO could enhance the antibacterial activity of the PLA/CS-CEO fibers. The optimal composition was reported to be PLA/CS-CEO-1.5, which showed the greatest antibacterial activity against *E. coli* and *S. aureus* (99.3% and

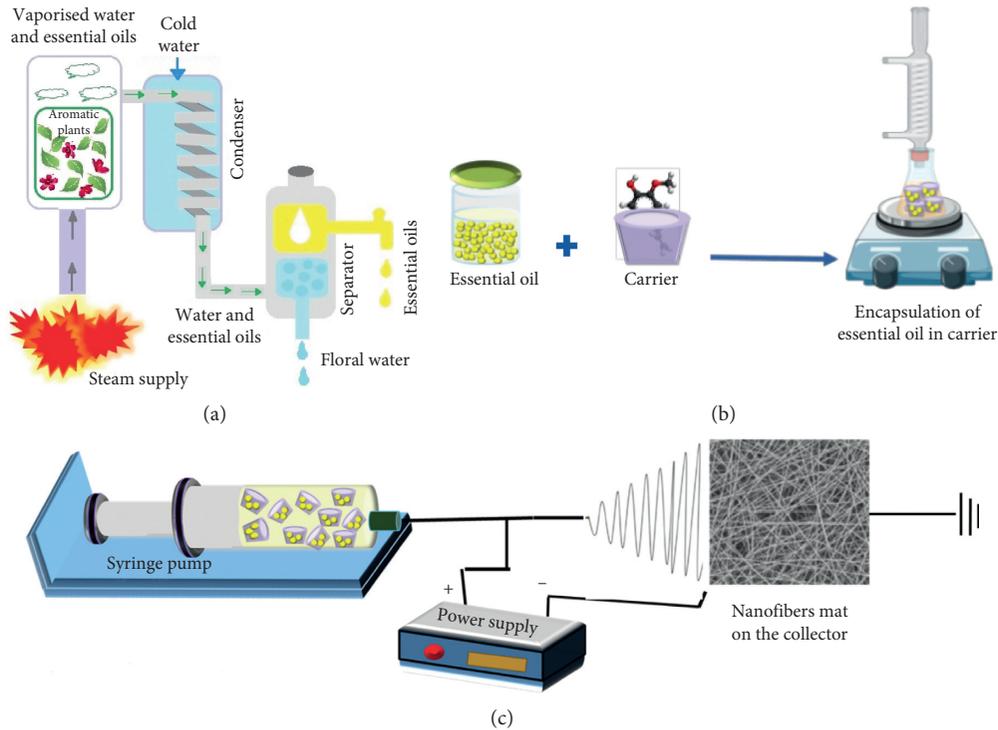


FIGURE 1: An overview of fabrication of essential oils-loaded electrospun nanofibers for active food packaging. (a) Extraction of essential oils. (b) Complexation with carrier and incorporation in electrospinning solution. (c) Electrospinning of composite solution.

98.4%, resp.) during the incubation period. The observation was a result of high crystallinity of CEO and its strong interactions with CS which lowered the solubility of PLA and allowed the CEO to exhibit a similar antimicrobial activity even at slower release rate [96].

Lin et al. reported encapsulation of CEO/ β -CD/proteoliposomes into polyethylene oxide (PEO) nanofibers to study their antimicrobial behavior against *Bacillus cereus* (*B. cereus*) [97]. *B. cereus* is one of the major sources of contamination and spoilage in meat products [98]. *B. cereus* shows high adaptability to extreme environments (acidic, alkaline, and high temperature) [99]. Nanoantibacterial liposomes, artificial lipid vesicles, are microscopic morphologies made up of a central section enclosed by concentric phospholipid bilayers embedding aqueous cores. They are capable of encapsulating both hydrophilic substances in the inner aqueous section and hydrophobic matters within lipid bilayers and amphiphilic molecules at the lipid/water interface [88]. Proteoliposomes tend to agglomerate and shed when they come into a direct contact with food surface, as a result reducing the bioactivity of encapsulated substances. In addition, the hydrophobic nature of nanoliposomes has a negative effect on their encapsulation efficiency (EE) of EOs. Therefore, for further enhancement of the EE and stability of CEO in proteoliposomes, β -cyclodextrin (β -CD) is added to the system.

The physicochemical stability of CEO proteoliposomes was significantly enhanced by introduction of β -CD. Taking advantage of bacterial protease secreted from *B. cereus*, the controlled release of CEO from proteoliposomes was achieved

via proteolysis of protein in proteoliposomes. Additionally, the antibacterial efficiency of CEO/ β -CD proteoliposomes against *B. cereus* was improved as a result of their stability by encapsulation in nanofibers. The nanofibrous combination showed satisfactory antibacterial efficiency as active food packaging for beef against *B. cereus* without any impact on sensory quality while extending the shelf life.

Figure 2(a) shows the steps involved in preparation of CEO/ β -CD (Figure 2) proteoliposomes and their incorporation in PEO spinning solution, while Figure 2(b) displays *B. cereus* proteinase-triggered CEO release from proteoliposomes. The CEO/ β -CD proteoliposomes can precisely prevent bacterial multiplication by the stimulus-response of casein to bacterial protease in presence of *B. cereus*.

The combination of EO and lysozyme (LYS) when used as antimicrobial packaging can decrease the dose of EO besides extending the application of LYS-derived packaging material. Feng et al. reported a novel antimicrobial electrospun nanofilm based on PVA/ β -cyclodextrin/CEO/LYS, where the combination of CEO and LYS was acting as antimicrobial agent [75]. LYS is a natural antimicrobial enzyme classified as GRAS which is usually derived from chicken egg white [100, 101]. LYS exhibits antimicrobial action toward Gram-positive bacteria through splitting the bonds between N-acetylmuramic acid and N-acetylglucosamine of the peptidoglycan in the cell wall [102]. In this study, CEO was selected for its antimicrobial activity against bacteria (*L. monocytogenes* and *S. enteritidis*) and molds (*A. niger* (ATCC1015) and *Penicillium* (CICC41489)). The choice of PVA as the electrospinning matrix was because of its

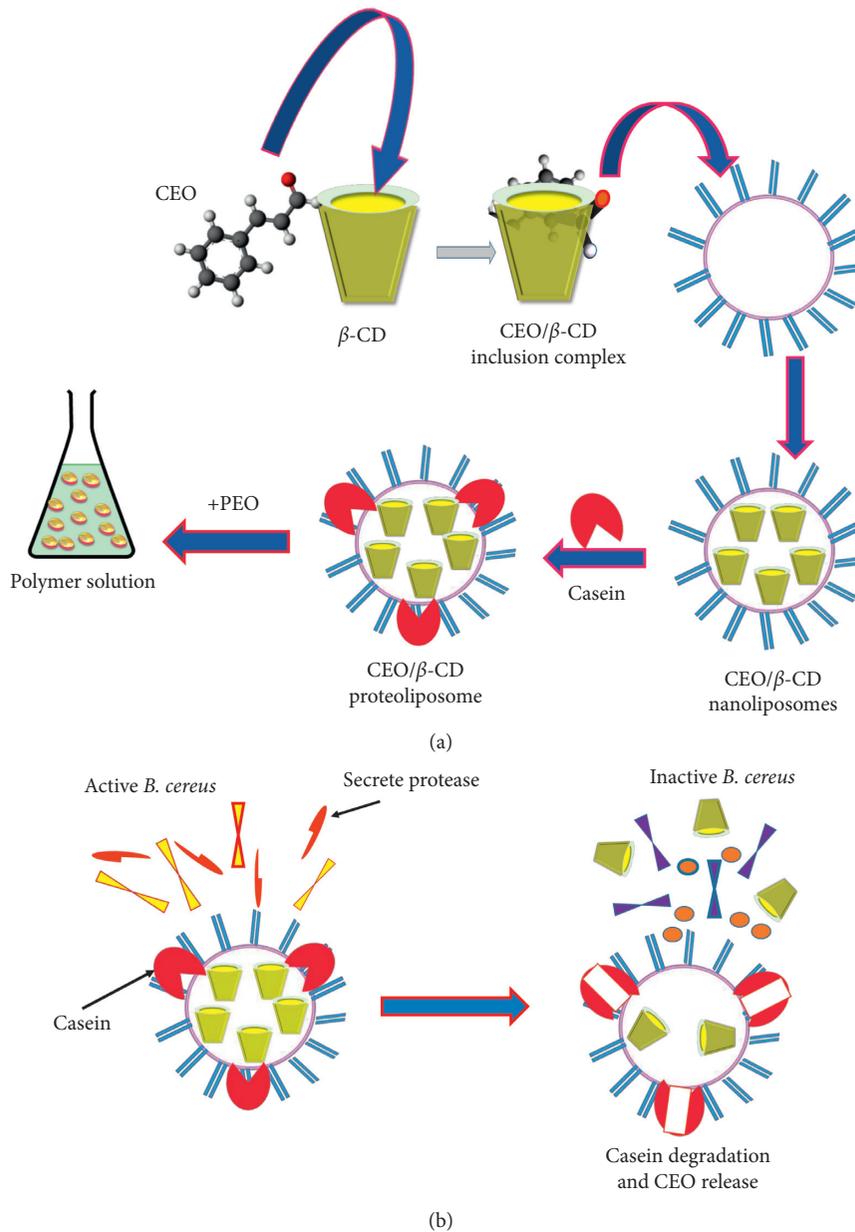


FIGURE 2: Encapsulation of CEO in β -CD and PEO and their antibacterial activity against *B. cereus*. (a) Preparation of CEO/ β -CD proteoliposomes and incorporation in PEO spinning solution. (b) Schematic of *B. cereus* proteinase-triggered CEO release from CEO/ β -CD proteoliposomes.

solubility in water soluble and biocompatibility as it has been extensively used in food preservation [103]. Furthermore, PVA could be applied without usage of organic solvents, thereby preventing the denaturation of LYS [104]. The aim of their study was to reduce the dosage of CEO in the packaging material without affecting antimicrobial action. The study suggested that the concentration of antimicrobial agent consisting 2% CEO and 0.25% LYS (w/w) in PVA matrix has a decent performance as food packaging material.

Shao et al. fabricated ultrafine PVA/permutite/CEO membranes via electrospinning [105]. PVA doped with permutite powder was applied as polymer matrix and CEO was encapsulated as the antibacterial component. Permutite

is a nontoxic highly stable aluminosilicate which can be engaged in reversible interactions with various types substances including gas molecules [106]. The fabricated membranes were characterized for physicochemical properties such as morphology, porosity, surface area, tensile, and chemical interaction. Furthermore, the antibacterial action of the as-prepared films was explored for fruit packaging by using fresh cut strawberries. Fresh cut fruits hold a large share of the market since they only require partial processing without any additional preparation [107]. However, being susceptible to microorganisms such as mold, yeast, and fungi remains to be the major problem for the fresh cut fruit [108]. The release behavior in electrospun

membranes is diffusion controlled as it is physically adsorbed by polymeric matrix and very low activation energy is required for the release process [109]. Such property finds importance at lower temperatures (4–6°C), where the release of EOs at low temperatures will hardly achieve the minimum concentration required for preservation [110]. In the study, differential scanning calorimetry and pore distribution results suggested weak physical interactions between the CEO and the fibers as a result of mesoporous adsorption (15.77 J/g and 37.7 J/g) which can benefit the release of CEO at low temperature. The authors concluded that PVA/permutite/CEO fibrous films have the potential to delay the rapid corruption of strawberries during storage.

3.2. Encapsulation of Eugenol Essential Oil. Eugenol (4-allyl-2-methoxyphenol), most abundantly found component in clove oil, nutmeg oil, and cinnamon oil, has been successfully applied in food preservation, cosmetics manufacturing, and traditional medicine. Several researches have confirmed antibacterial, antioxidant, anti-inflammatory, and local anesthetic properties of eugenol [111]. Presence of high contents of phenolic compounds such as eugenol in volatile oils exhibits strong antioxidant properties [112]. Eugenol is a yellow oily liquid which exhibits lipid peroxidation induced by reactive oxidase system (ROS) because of its radical scavenging activity [35, 36, 113]. Like other EOs, eugenol also suffers from high volatility and poor water solubility. Therefore, encapsulation of eugenol is necessary to increase its effectiveness and longer shelf life [114]. Kayaci et al. in a joint research demonstrated that the EE of the volatile active agents such as menthol, vanillin, eugenol, geraniol, and allyl isothiocyanate was only effective when used with CD inclusion complexes (CD-IC) [15, 115–118]. One of the challenges in encapsulation is to incorporate higher amounts of the active ingredient in the polymeric matrix [115, 119]. When electrospun polymers appear as carrier matrix, the amount of the active ingredients in CD system is often limited to 5% of the fabricated membrane's weight. This is due to difficulty of electrospinning uniform nanofibers from polymeric solution containing higher amounts of CD. This research group recently focused on nanofibrous webs encapsulating much higher amounts of active agents (loading of ~10% (w/w) or more with respect to fibrous CD matrix). They reported that production of polymer-free electrospinning from only CD systems was spun [120–123].

Celebioglu et al. prepared excessively concentrated aqueous CD solutions (160% (w/v)) [124]. They prepared inclusion complexes between eugenol (guest molecule) and cyclodextrins (host molecules) at a molar ratio of 1:1 CD:eugenol followed by electrospinning to obtain nanofibrous webs (eugenol/CD). Since dimensions and form of the CD cavity are a significant parameter for formation of effective inclusion complexation, three different CD derivatives were applied in this work. The three modified CDs, namely, hydroxypropyl-beta-cyclodextrin (HP- β -CD), hydroxypropyl-gamma-cyclodextrin (HP- γ -CD), and methyl-beta-cyclodextrin (M- β -CD), were used to create inclusion complexes with eugenol. The resulting electrospun eugenol/

CD samples showed self-standing and flexible characteristics as a mat web and displayed rapid solubility in water. Figure 3 demonstrates the chemical structure of modified CDs, eugenol, and schematic illustration of the inclusion complexation formation between CD and eugenol. Moreover, thermal stability of eugenol was enhanced for eugenol/CD/IC (up to ~310°C) in comparison with pure eugenol (up to ~200°C). Furthermore, eugenol/CD exhibited effective antioxidant activities. The strongest interactions within the complex were observed between M- β -CD and eugenol compared to the other two host CD molecules (HP- β -CD and HP- γ -CD) for eugenol/CD samples. The authors suggested potentials for their membranes in food related and oral-care applications.

Liposomal encapsulation of eugenol is an alternative way to decrease the damage to eugenol at processing and storage phase. Liposome containing eugenol is a natural and effective antioxidant that can encapsulate hydrophobic and lipophilic drugs [125]. However, liposomal instability as a major drawback can affect their efficiency as an antioxidant. Furthermore, conventional liposomes often have low EE and instability of vesicle aggregation, fusion, or rupture, all of which pose serious challenges to the commercial exploitation of eugenol liposomes as an industrial antioxidant. Therefore, the stability of eugenol liposome can affect the performance of the final product as active food packaging material. The stability of liposomes is being improved through various strategies such as polymer-coated liposomes, hydrogel-liposome composites, and nanoparticle-stabilized liposomes [126–128].

Cui et al. reported an undemanding method to form an antioxidant based on novel complexes of liposome encapsulated SiO₂-eugenol. SiO₂-eugenol forms a supramolecular assembly with a core of colloidal particles covered by a lipid shell [127]. SiO₂ nanoparticles in food industry serve as an additive which can provide stiff support for the lipid bilayer thin film to enhance physical stability of liposome [129]. Besides being porous, the hydrophilic property of SiO₂ nanoparticles facilitates absorption when volatilization occurs [130, 131]. There are few reports of immobilization of liposome on electrospun nanofibers for food preservation [132, 133]. While SiO₂-eugenol liposomes could not be electrospun on their own, their combination with PEO could be electrospun and showed great potential as food packaging material [103, 134]. Cui et al. reported production of a novel electrospun membrane based on PEO and SiO₂-eugenol liposomes [135]. Figure 4 shows schematic illustration of liposomes-encapsulated SiO₂-eugenol.

The study explored application of SiO₂ as an architectural template for liposomes which could bring promising prospects to application of eugenol-based antioxidant. As a proof of concept, their electrospun membranes were exposed in contact with beef over a period of 60 days and exhibited excellent antioxidant activity.

Munteanu et al. investigated the biodegradation and tensile properties of PLA membranes coated with antimicrobial and antioxidant CS-EO complexes [136]. Chitosan has exhibited significant antibacterial action against various pathogens such as *Klebsiella pneumoniae*, *Escherichia coli*,

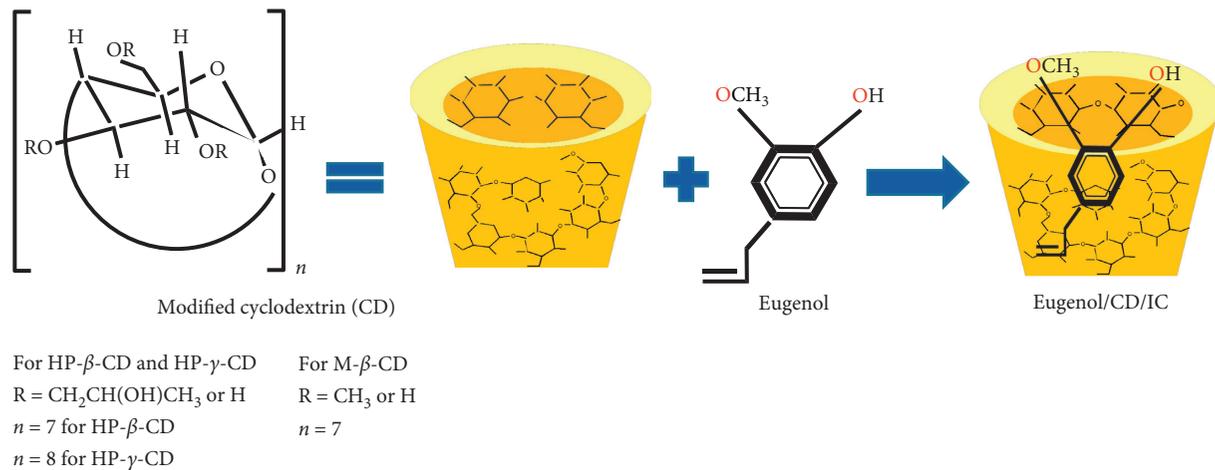


FIGURE 3: Chemical structure of modified CD [125], eugenol, and schematic illustration of IC formation between CD and eugenol.

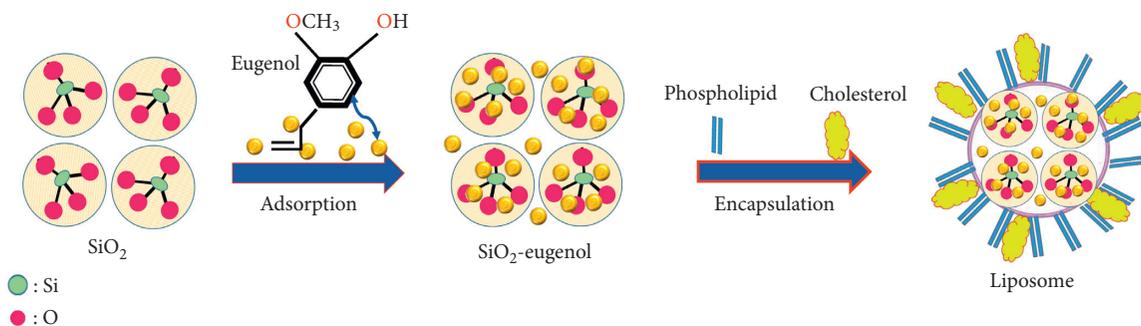


FIGURE 4: Schematic illustration of liposomes-encapsulated SiO₂-eugenol.

Staphylococcus aureus, and *Pseudomonas aeruginosa* [137]; therefore, it has been a popular subject of studies in antibacterial coatings [138]. It also can encapsulate other antibacterial agents such as nisin [139], which could further enhance the antimicrobial action of the packaging coatings [140]. PLA electrospun membranes were coated with bioformulations containing the essential and vegetable oils, that is, clove and argan oils loaded into CS. 99% of the argan oil is composed of acylglycerols, while the antioxidant constituents are tocopherols, squalene, sterols, and phenols [141, 142]. Eugenol as the major volatile constituent of clove oil (about 80%) is accountable for its antioxidant and antimicrobial properties [143]. The study involved coaxial electrospinning of encapsulated CS over the electrospun PLA membrane which was placed on the metallic collector. Based on the report when high molecular weight CS was used, the coaxial electrospinning produced beaded CS nanofibers with the oil encapsulated and distributed along the beaded fibers. On the other hand, use of lower molecular weight CS led to electrospinning loaded chitosan nanoparticles and providing smoother surface. The PLA films coated with CS-EO formulations exhibited higher antibacterial activity compared to the films coated only with CS. The clove oil's antibacterial activity was higher than argan oil due to its higher phenolic content. The beaded fibers showed better antibacterial activity compared to nanoparticles perhaps due to the higher specific surface area of the rougher nanofibrous morphology of the coating layer.

Melendez-Rodriguez et al. encapsulated eugenol within the pores of mesoporous silica nanoparticles (MCM-41) by vapor adsorption [144]. Subsequently, for the first time, electrospinning technique was applied to include MCM-41 particles containing eugenol into poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV). To fabricate continuous films, the produced electrospun fibers were thermally treated at 155°C. The resultant PHBV films filled with eugenol-loaded mesoporous silica nanoparticles revealed increased mechanical strength, adequate thermal resistance, and good barrier properties to water vapor and limonene. According to their results, they suggested that the films can be used in the form of coatings or interlayers for active food packaging applications.

Cui et al. evaluate the antibacterial activity of clove oil-loaded chitosan nanoparticles (CO@CNPs) and gelatin electrospun nanofibers against *E. coli* O157:H7 biofilms on cucumbers [145]. Once CO@CNPs were used at 30% (w/v), *E. coli* O157:H7 population reduced to approximately 99.98% and high antibacterial activity was achieved after 8 hours. Following this, electrospinning was applied to incorporate the prepared CO@CNPs into gelatin nanofibers. After applying 9 mg/mL gelatin/CO@CNPs treatment for 24 h, the population of *E. coli* O157:H7 biofilm decreased to almost 99.99% in vitro. The results confirmed that treatment of the gelatin/CO@CNPs nanofibers could maintain the flavour and color of cucumber for more than 4 days. Based

on their results, both CO@CNPs and gelatin/CO@CNPs nanofibers at specified amount showed significant destruction effect on *E. coli* O157:H7 biofilms in vitro.

3.3. Encapsulation of Thyme Essential Oil (TEO) and Thymol (THY). TEO, a plant secondary metabolite possessing safe and nontoxic properties, is derived from thymus vulgaris. TEO exhibits excellent antibacterial action against a wide spectrum of bacteria such as *Escherichia coli* O157:H7, *Salmonella enterica* subsp. *enterica* serovar *Enteritidis* CICC 21482 (*S. enteritidis*), and *Salmonella typhimurium* CICC 22956 (*S. typhimurium*) [146]. However, TEO suffers from several shortcomings such as volatility, hydrophobicity, and special flavour which highlight the need for encapsulation which is usually achieved through a coprecipitation of TEO into β -CD [91].

THY is also the major volatile component of essential oils derived from plants belonging to the Lamiaceae family. It is a monoterpene usually found in oregano and thyme; however, its preservation and delivery applications remain to be a challenge due to its hydrophobic and volatile nature. It is registered in European flavouring list and classified as GRAS by FDA [147]. THY exhibits antimicrobial action against a wide range of microorganisms such as bacteria, fungi, and yeasts [148–150] through its capacity to disturb the lipid bilayer of the cell membrane and could increase membrane permeability [151]. THY is typically used for food preservation and control of postharvest decay of fresh produce [152, 153].

Lin et al. reported production of gelatin nanofibers containing TEO/ β -cyclodextrin ϵ -polylysine nanoparticles (TCPNs) for controlling the propagation of *Campylobacter jejuni* (*C. jejuni*) [154]. *C. jejuni* is the major source of contamination on poultry surface which poses huge threats to human health. Moreover, *C. jejuni* is a zoonotic pathogen that lives as a symbiotic microorganism in the digestive tract of the poultry [113]. During poultry slaughter, *C. jejuni* can leak and rupture through external channel and cause meat contamination. The *C. jejuni* contaminated meat is known to be the main cause of human campylobacteriosis which accounts for 8.4% of the diarrheal diseases [155].

C. jejuni meat contaminations may not be completely inactivated as it shows high resistance against some frequently used antibiotics such as cephalosporins, quinolones, and gentamicin [156] and the demand for an efficient natural antibacterial agent to replace chemical antibiotics frequently used in meat industry. Since *C. jejuni* primarily contaminates meat surface, an antimicrobial packaging has a great potential to inhibit its reproduction.

A simple TEO/ β -CD-IC is not effective against *C. jejuni* as β -CD has an electroneutral nature and its absorption onto negatively charged bacterial cell wall is limited. To address this issue ionic gelation was applied to adsorb cationic biopolymers onto the surface of TEO/ β -CD-IC [157]. In the study, ϵ -polylysine (ϵ -PLY), a biodegradable cationic biological metabolite with outstanding antibacterial properties, was selected to prepare TEO/ β -CD ϵ -polylysine nanoparticles (TCPNs) [158]. The

presence of $-\text{NH}_2$ along the ϵ -PLY chains improves nanoparticle binding onto negatively charged bacterial cell wall leading to an acceleration in the apoptosis process [159]. Antibacterial nanofibers were obtained by adding TCPNs into the polymer matrix via electrospinning. The prepared membranes showed outstanding antimicrobial action against *C. jejuni*, through membranolysis. The results confirmed that damaged cell membrane and proteins leakage of *C. jejuni* were results of antimicrobial activity of nanoparticles. Chicken samples packed in the antimicrobial membranes possessed lower aerobic bacterial count and thiobarbituric acid (TBA). Total volatile basic nitrogen (TVBN) and pH values were lower as well without any adverse effect on color, texture, and sensory evaluation, signaling bright prospects for the membranes in poultry preservation.

Aytac et al. reported encapsulation of THY/ γ -CD-IC into in electrospun zein nanofibrous web for food packaging application [160]. Two different molar ratios THY/ γ -CD (1:1 and 2:1, resp.) were prepared and encapsulated into electrospun zein nanofibers. Figure 5 shows the chemical structure of THY, schematic representation of γ -CD, and THY/ γ -CD-IC formation. The choice of γ -CD was due to its lack of adverse effects on nutrient absorption in food products and nutraceutical applications [161]. Successful formation of complex between THY and γ -CD at both molar ratios was reported. Cyclodextrin inclusion complexes of thymol (THY/CD-IC) have been demonstrated to be applicable in pork meat systems to prevent oxidation and enhance meat stability at high relative humidity (up to 75%) for long storage periods [162–165].

However, it is worth mentioning that the release of THY was higher than that from zein-THY/ γ -CD-IC nanofibrous membranes (2:1). Similarly, zein-THY/ γ -CD-IC nanofibrous membranes (2:1) had stronger antibacterial activity against *E. coli* and *S. aureus*. In brief, zein-THY/ γ -CD-IC nanofibrous membranes were most efficient at decreasing the bacterial count in meat stored over a 5-day period at 4°C. Thus, these membranes exhibit great potential as antibacterial food packaging material.

Zhang et al. encapsulated THY in poly(lactide-co-glycolide), PLGA fiber through core-shell coaxial electrospinning [166]. PLGA which is known for its biodegradability and controlled delivery properties [167] has the capability of encapsulating hydrophobic substances and had shown great potential in enhancing the efficiency of delivery in food systems [168, 169]. The study indicated that nanofibers with good core-shell structure were formed and volatile THY was encapsulated successfully. The results demonstrated that PLGA can efficiently suppress the volatilization of THY, so the encapsulated thymol gradually evaporates into the fruits and vegetables storage environment. In their work, the antibacterial and fruit preservation ability of the nanofiber films were tested by strawberry. The results suggested that the produced membranes efficiently inhibit bacterial, fungal, and yeast growth to extend the shelf life of fruits. This novel biocompatible antibacterial packaging material would have a huge application prospect for food preservation.

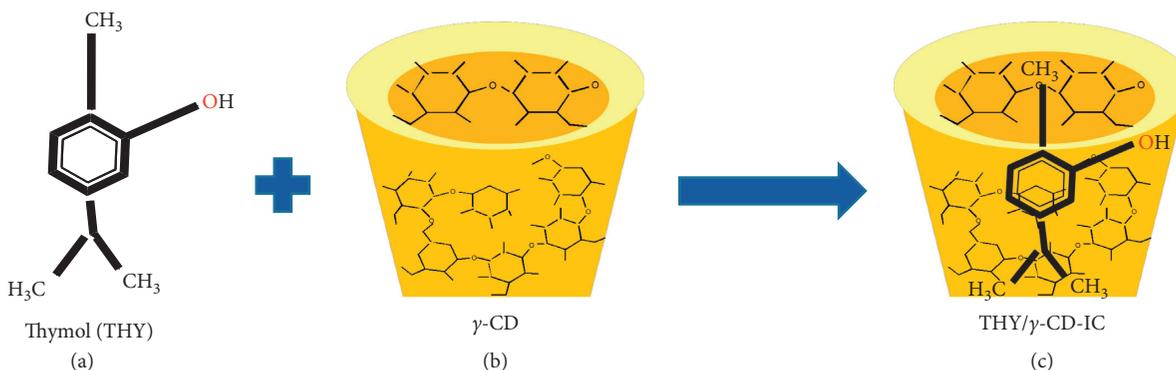


FIGURE 5: The chemical structure of (a) THY, (b) schematic representation of γ -CD, and (c) THY/ γ -CD-IC formation.

TABLE 2: Encapsulation of the EOs into different carriers and matrixes with their antimicrobial activities for food or food packaging.

Matrix	Essential oil (guest)	Carrier (host)	Food evaluated	Action	Findings
PVA [84]	CEO	β -CD	Strawberries	Antibacterial against Gram-positive and Gram-negative bacteria (<i>S. aureus</i> and <i>E. coli</i>)	(1) Addition of CEO/ β -CD caused to increase water contact angle and more hydrophilicity of the nanofibrous film (2) Enhanced antimicrobial action compared with that of casted films (3) The molecular interaction among PVA, CEO, and β -CD modified the thermal stability of CEO (4) Electrospinning achieved incorporation of greater amounts CEO in the membrane and enhanced antimicrobial action compared to film casting
PEO [74]	Cinnamaldehyde	CS	NA	Antimicrobial against <i>E. coli</i> and <i>Pseudomonas aeruginosa</i>	(1) The release of CA from CS/CA (0.5 and 5.0%)/PEO nanofibrous membranes directly affected cytotoxicity against <i>P. aeruginosa</i> (within three hours, $81 \pm 4\%$ of the <i>P. aeruginosa</i> was deactivated)
PLA [94]	CEO	β -CD-IC	Pork	Antibacterial against <i>E. coli</i> and <i>S. aureus</i>	(1) The CEO/ β -CD-IC was prepared by the coprecipitation (2) Formation of CEO/ β -CD-IC considerably improved the thermal stability and antimicrobial activity of CEO (3) The electrospun PLA/CEO/ β -CD nanofibers showed outstanding antimicrobial action against both Gram-positive and Gram-negative bacteria (4) Electrospinning achieved incorporation of greater amounts CEO in the membrane and enhanced antimicrobial action compared to film casting
PLA [95]	CEO	CS	NA	Antibacterial against <i>E. coli</i> and <i>S. aureus</i>	The optimal composition found to be PLA/CS-CEO-1.5, which exhibited the highest antibacterial activity for a long time
PEO nanofibers [97]	CEO	β -CD proteoliposomes	Beef and meat production preservation	Antibacterial against <i>B. cereus</i>	(1) The antibacterial effect of CEO/ β -CD proteoliposomes against <i>B. cereus</i> increased, and their stability enhanced due to encapsulation (2) The physicochemical stability and the EE of CEO proteoliposomes were significantly enhanced through introduction of β -CD

TABLE 2: Continued.

Matrix	Essential oil (guest)	Carrier (host)	Food evaluated	Action	Findings
PVA [75]	CEO/LYS	β -CD	NA	Antibacterial against <i>L. monocytogenes</i> and <i>Salmonella enteritidis</i> . Antifungal against <i>Aspergillus niger</i> and <i>Penicillium</i>	(1) The suitable CEO and LYS concentrations were as 2% (w/w) and 0.25% (w/w), respectively (2) The molecular interactions among PVA, β -CD, CEO, and LYS modified the thermal stability of CEO and LYS (3) The minimum inhibition concentration (MIC) against <i>L. monocytogenes</i> and <i>S. enteritidis</i> was approximately 0.8–1 mg/mL (4) Minimum bactericidal concentration (MBC) was approximately 6–7 mg·mL ⁻¹
PVA doped with permutite powder [105]	CEO	PVA/permutite	Fresh cut fruits (strawberry)	Antibacterial	(1) The nanofibrous mat exhibited high porosity with the pore size distribution ranging from 1.7 nm to 56.7 nm (2) DSC and pore distribution analysis indicated presence of weak physical interactions between the CEO and nanofibers due to mesoporous adsorption (15.77 J/g and 37.7 J/g) which helps release of CEO at low temperature
Eugenol/CD/IC-NW (self-standing (without matrix) [124]	Eugenol	CD/IC	NA	Antioxidant	(1) Volatility nature of eugenol was preserved (~70–95%) in eugenol/CD inclusion complex nanofibrous webs (eugenol/CD/IC-NW) (2) Thermal stability of eugenol for eugenol/CD/IC-NW increased up to ~310°C from ~200°C (3) The eugenol/CD/IC-NW showed rapid aqueous dissolution, contrary to poor water solubility of eugenol (4) The strongest complexation was between M- β -CD and eugenol compared to other two host CD molecules (HP- β -CD and HP- γ -CD) (5) The electrospun eugenol/CD/IC-NW samples exhibited improved antioxidant action compared to eugenol in its pure form (6) Radical scavenging property of eugenol/CD/IC-NW was enhanced compared to eugenol in its pure form
PEO [135]	SiO ₂ -eugenol	Liposome	Beef	Antioxidant	Liposomes containing SiO ₂ -eugenol was immobilized on electrospun nanofibers. This system exhibited outstanding antioxidant action on beef during 60-day storage

TABLE 2: Continued.

Matrix	Essential oil (guest)	Carrier (host)	Food evaluated	Action	Findings
PLA [136]	Clove containing 80% eugenol (essential oil) and argan oils (vegetable oils)	CS	NA	Antibacterial and antioxidant	<p>(1) The samples prepared with Chit-H showed higher roughness of the coating layer compared to samples prepared with Chit-L</p> <p>(2) Chit-H samples showed higher antibacterial action compared to Chit-L, for either of the oils, due to the higher specific surface area of the rougher morphology of the coating layer</p> <p>(3) The clove oil had better antibacterial activity than argan oil, in combination with both chitosan types</p> <p>(4) Chit-H samples showed higher antibacterial activity compared with Chit-L, in combination with both types of oil</p> <p>(5) PLA coated with chitosan-oil formulations had higher antibacterial action than the films coated with pure CS</p> <p>(6) The chitosan-clove oil combination showed higher antioxidant action compared to pure CS coating.</p>
PHBV films [144]	Eugenol	Mesoporous silica nanoparticles	NA	Antimicrobial against <i>S. aureus</i> and <i>E. coli</i>	<p>(1) The incorporation of eugenol EO on MCM-41 significantly increased plasticization on PHBV and a reduction in its crystallinity</p> <p>(2) The mechanical strength of the PHBV films and barrier properties were enhanced</p> <p>(3) The incorporation of MCM-41 with eugenol caused slight reduction in ductility</p>
Gelatin nanofibers [145]	Clove oil	CS	Cucumber	Antibacterial against <i>E. coli</i> O157:H7	Approximately 99.98% reduction in <i>E. coli</i> O157:H7 population was obtained after 8 hours of treatment, when CO@CNPs were used at 30% (w/v)
Gelatin [154]	TEO	β -CD ϵ -polylysine	Chicken	Antimicrobial against <i>C. jejuni</i>	<p>(1) The TCPNs loaded gelatin nanofibers (TEGNs) exhibited exceptional antimicrobial action against <i>C. jejuni</i> on chicken</p> <p>(2) The TEGNs packaged chicken samples had lower aerobic bacterial count, TBA, TVBN, and pH values without undesirable effect on color, texture, and sensory evaluation</p>
Zein [160]	THY/ γ -CD-IC	Zein	Meat	Antimicrobial against <i>E. coli</i> and <i>S. aureus</i>	<p>(1) THY/γ-CD-IC (2:1) exhibited higher preservation rate and stability than THY/γ-CD-IC (1:1)</p> <p>(2) Zein-THY/γ-CD-IC-NF (2:1) contained more THY as indicated by TGA</p> <p>(3) THY/γ-CD-IC (2:1) had higher stability. The released amount of THY from zein-THY/γ-CD-IC-NF (2:1) was more than zein-THY-NF and zein-THY/γ-CD-IC-NF (1:1)</p> <p>(4) Antibacterial action of zein-THY/γ-CD-IC-NF (2:1) was greater than zein-THY-NF and zein-THY/γ-CD-IC-NF (1:1)</p>

TABLE 2: Continued.

Matrix	Essential oil (guest)	Carrier (host)	Food evaluated	Action	Findings
PLGA [166]	THY	PLGA nanofiber	Fruits	Inhibition of the growth of bacteria, fungi, and yeast	Due to core-shell morphology, THY encapsulated in the PLGA nanofiber is slowly released to inhibit the growth of bacteria on the surface of food
PEO [174]	TTO	β -CD-IC	Beef	Antibacterial against <i>E. coli</i> O157:H7	(1) The highest antibacterial action against <i>E. coli</i> O157:H7 was observed on the beef for 7 d, at 4°C or 12°C (2) The flavour values significantly enhanced in plasma-treated TTO/ β -CD-IC PEO nanofibers compared with the control groups (3) TTO/ β -CD-IC at concentrations of 30% and 40% exhibited great antibacterial action leading to a 99.94% and 99.96% decrease in population after 24 hours
Gelatin [176]	PO	Gelatin	NA	Antibacterial against <i>E. coli</i> and <i>S. aureus</i>	(1) The combination of PO and CO in gelatin nanofiber showed overall improved bioactivities compared to PO or CO alone (2) The surface hydrophobicity of nanofibers was enhanced with the addition of EOs
	CO	Gelatin	NA	Antioxidant	(3) The addition of EO was reported to improve mechanical flexibility of electrospun mats with the ability to tune tensile modulus and strength of nanofibers
CS [191]	CHEO	CS	Beef	Antibacterial against <i>L. monocytogenes</i>	(1) The cell membrane permeability of <i>L. monocytogenes</i> increased (2) Respiratory metabolism of <i>L. monocytogenes</i> was prevented (3) The slow release of CHEO from CHEO/CS/NF achieved an antibacterial inhibition efficiency of 99.91 to 99.97% between 4°C and 25°C (4) In presence of antioxidant agents in ECHO/CS/NF, the value of TBARS in treated beef was 0.135 MDA/kg
Gelatin [193]	MO	CS	Cheese	Antibacterial against <i>L. monocytogenes</i> and <i>S. aureus</i>	Nanofibers have high antibacterial effect at 4°C and 25°C with negligible effect on surface color

3.4. Encapsulation of Tea Tree Oil (TTO), Peppermint Oil (PO), Chamomile Oil (CO), Chrysanthemum Essential Oil (CHEO), and Moringa Oil (MO). TTO is a natural essential oil which is composed of several organic substances such as terpene hydrocarbons, terpene alcohols, and terpene phenols. There are several reports regarding antimicrobial and anticancer properties of TTO [170, 171]. However, like other EOs, the application of TTO remains limited due to its chemical instability in exposure to air and high temperatures [172]. Therefore, forming noncovalent inclusion complex with β -CD as an antibacterial agent paves the way toward stability [173].

Cui et al. studied the incorporation of TTO/ β -CD-IC, as antibacterial agent into electrospun PEO, to fabricate antibacterial packaging material [174]. As mentioned earlier, TTO is not completely soluble in aqueous PEO

solution and the volatilization of TTO would intensify during the electrospinning which might create further problems regarding quick release during storage [175]. Therefore, in the study, the β -CD and TTO were used as a host guest to create water-soluble inclusion complex. The membranes were subjected to plasma treatment, and after the treatment the efficiency of antibacterial agent release from PEO nanofibers was improved appropriately. The plasma treated electrospun membranes exhibited the highest antibacterial activity against *E. coli* O157:H7 on the beef for a period of 7 days, with inhibition efficiently of 99.99% at either 4°C or 12°C. According to their results, the plasma-treated PEO nanofibers containing TTO/ β -CD prolong the shelf life of beef and sustain its sensory quality which suggests a bright prospect in food preservation.

Tang et al. fabricated gelatin nanofibers incorporating two kinds of EOs, that is, peppermint essential oil (PO) and chamomile essential oil (CO), for potential edible packaging application [176]. PO has excellent antimicrobial property, which made it the subject of several studies in food preservation, pharmaceuticals, and wound dressing [177–179]. CO on the other hand is mostly used in medicinal tea, cosmetics, perfumery, and food industry due to its calming, antibacterial, and antioxidant properties [180–183]. Gelatin nanofibers loaded with PO and CO were successfully produced with morphological homogeneity and smoothness. All the gelatin nanofibers containing PO, CO, or their combination showed enhanced antibacterial action proportionate to EO content against *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*) as well as certain antioxidant property. Incorporation of CO resulted in improved antioxidant activity, while the antibacterial activity against *E. coli* and *S. aureus* was better for the nanofibers containing EO. The mixture of PO and CO in gelatin nanofiber showed overall better bioactivities compared to the samples that contained only one of them. Addition of EOs enhanced the surface hydrophobicity of nanofibers based on water contact angle results. This is important since the high hydrophilicity and sensitivity to moisture of gelatin are one of its major drawbacks as packaging material [184]. Therefore, it is not surprising that researches have been focused on blending gelatin with other hydrophobic materials to eliminate its drawbacks for food packaging applications [185, 186]. Along with hydrophobic polymers, EOs could be an alternative to be incorporated in gelatin-based packaging for improvement of bioactivities as well as the required physical properties [187]. The high surface area to volume ratio and the nanostructure of electrospun nanofibers were shown to improve the sustained release of bioactive ingredients to food surface and intensify the bioactive actions [16, 84]. Furthermore, the addition of EO is reported to enhance mechanical flexibility of electrospun membranes and to control tensile modulus and strength. The mentioned phenomena are achieved through affecting morphology and diameter of nanofibers by inducing rearrangement of protein network and cross-links between the polymer chains and some constituents of EOs [5]. Finally, the cytotoxicity test demonstrated the noncytotoxicity of gelatin nanofibers incorporated with PO and CO, thus indicating the potential of the gelatin/EOs nanofibers as prospective food packaging.

Chrysanthemum essential oil (CHEO) is an aromatic oil extracted from chrysanthemum which has antioxidant and anti-inflammatory properties [188]. Chrysanthemum has cardiovascular protective functions and can prevent a variety of diseases such as hypertension, atherosclerosis, and coronary heart disease [189, 190].

Lin et al. incorporated CHEO into CS nanofibers (CS/NF) using electrospinning [191].

Since CHEO had a negative effect on phosphofructokinase activity, hexokinase, and pyruvate kinase in *L. monocytogenes* cells, antibacterial properties of CHEO against *L. monocytogenes* increased. The slow release of CHEO from CHEO/CS/NF effectively prolonged the antibacterial action.

The antibacterial application of the CHEO nanofibers against *L. monocytogenes* was tested on beef. Beef parameters like thiobarbituric acid reactive substances (TBARS), pH values, and texture at different storage temperatures (4°C, 12°C, and 25°C) were evaluated. Due to the presence of antioxidant components in CHEO released from CHEO/CS/NF, the beef parameters like thiobarbituric acid reactive substances (TBARS) value in treated beef were lower (0.135 MDA/) comparing with the untreated sample. Moreover, pH value for beef sample packed with CHEO/CS/NF showed 6.43 (after 10 days of storage) that was lower than pH value of unpacked sample (7.05) at 4°C. They suggested a potential application in food packaging.

Moringa oil (MO), an essential oil derived from *Moringa oleifera*, is resistant to autooxidation. *Moringa oleifera* grows in South and Central America, Africa, Southeast Asia, and the Indian subcontinent [192]. Lin et al. fabricated MO-loaded chitosan nanoparticles (MO@CNPs) and loaded them into gelatin nanofibers for biocontrol of *L. monocytogenes* and *S. aureus* on cheese [193]. Beside the excellent physicochemical properties of nanofibers, they had outstanding antibacterial activity against *S. aureus* and *L. monocytogenes* on cheese at 4°C and 25°C and negligible impact on the surface color and sensory quality of cheese within 4 days of storage. Hence, the MO@CNPs loaded gelatin nanofiber demonstrated excellent antibacterial action as a candidate for further food application studies.

To summarize, Table 2 demonstrates successful encapsulation of the different EOs into various carriers and electrospun matrices with their food related properties. The relevant electrospinning parameters could be found in Table S1 in Supplementary Materials.

4. Conclusions

Growing consumer demand for safe and chemical-free natural products has improved the quality and safety of the products against pathogenic deterioration and lipid oxidation within their shelf life. Especial attention has been given to EOs as natural additives and antimicrobial and antioxidant agents classified as GRAS. In this regard, the study of EOs has great importance, since it has been proven that their antimicrobial activity can replace artificial preservatives. However, their low solubility in water, oxidation susceptibility, and volatilization have limited their use. The encapsulation technique is a beneficial way in improving the stability of EOs and thus their efficiency as antibacterial/antioxidant agents. The combination of electrospinning and nanoencapsulation EOs has allowed successful development of new antimicrobial packages for food preservation. These new nanoencapsulation techniques have attracted global interest in food packaging and research area due to the positive protection and environmental friendliness. As presented in the article, these new combinations take advantage of encapsulation and slow release properties of electrospun polymers as a potential new platform for stabilization of natural oils for food packaging.

While the initial results of loaded electrospun fibers for food packaging are promising, it should not be forgotten that

the composite nanofibers hugely depend on electrospinning process. Electrospinning despite various advantages has serious problems as well. Low production rate especially for aqueous polymeric solutions remains a major problem, along with limitations to selection of highly volatile organic solvents as well. Particularly, solvents must not have any adverse effect on the antimicrobial properties of the active ingredients or bring the risk of future side effects. Technical advancements in electrospinning in terms of process control and production rate within the last three decades have provided an opportunity to use nanofibers for more applications. However, electrospinning still needs lots of further innovations in order to upscale production rate and quality for food packaging application at industrial scale.

The current review demonstrated that electrospinning technology is a potential new platform for enhanced stabilization by encapsulation of natural oils in nanofibers. Whilst the initial results suggest great prospects for loaded nanofibers as food packaging, to produce a feasible product at industrial scale, loaded electrospun fibers require extensive processing.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supplementary Materials

Table S1: the electrospinning parameters used in related references. (*Supplementary Materials*)

References

- [1] P. Tice, *Packaging Materials: 4. Polyethylene for Food Packaging Applications*, ILSI, Washington, DC, USA, 2003.
- [2] S. Allahvaisi, *Polypropylene in the Industry of Food Packaging*, IntechOpen, London, UK, 2012.
- [3] K. Cassidy and S. Elyashiv-Barad, "US FDA's revised consumption factor for polystyrene used in food-contact applications," *Food Additives and Contaminants*, vol. 24, no. 9, pp. 1026–1031, 2007.
- [4] M. J. Elyashiv-Barad, S. Plant, and J. W. Strawbridge, *Plastics in Food Packaging*, John Wiley & Sons, Hoboken, NJ, USA, 2011.
- [5] S. Yildirim, B. Röcker, M. K. Pettersen et al., "Active packaging applications for food," *Comprehensive Reviews in Food Science and Food Safety*, vol. 17, no. 1, pp. 165–199, 2018.
- [6] A. Ocaña-Fuentes, E. Arranz-Gutiérrez, F. J. Señorans, and G. Reglero, "Supercritical fluid extraction of oregano (*Origanum vulgare*) essential oils: anti-inflammatory properties based on cytokine response on THP-1 macrophages," *Food and Chemical Toxicology*, vol. 48, no. 6, pp. 1568–1575, 2010.
- [7] V. S. Periasamy, J. Athinarayanan, and A. A. Alshatwi, "Anticancer activity of an ultrasonic nanoemulsion formulation of *Nigella sativa* L. essential oil on human breast cancer cells," *Ultrasonics Sonochemistry*, vol. 31, pp. 449–455, 2016.
- [8] H.-F. Yen, C.-T. Hsieh, T.-J. Hsieh, F.-R. Chang, and C.-K. Wang, "In vitro anti-diabetic effect and chemical component analysis of 29 essential oils products," *Journal of Food and Drug Analysis*, vol. 23, no. 1, pp. 124–129, 2015.
- [9] F. Brahmi, A. Abdenour, M. Bruno et al., "Chemical composition and in vitro antimicrobial, insecticidal and anti-oxidant activities of the essential oils of *Mentha pulegium* L. and *Mentha rotundifolia* (L.) Huds growing in Algeria," *Industrial Crops and Products*, vol. 88, pp. 96–105, 2016.
- [10] J. Fernández-López and M. Viuda-Martos, "Introduction to the special issue: application of essential oils in food systems," *Foods*, vol. 7, no. 4, p. 56, 2018.
- [11] C. M. Galanakis, "Recovery of high added-value components from food wastes: conventional, emerging technologies and commercialized applications," *Trends in Food Science & Technology*, vol. 26, no. 2, pp. 68–87, 2012.
- [12] A. Jaworek, "Micro- and nanoparticle production by electro-spraying," *Powder Technology*, vol. 176, no. 1, pp. 18–35, 2007.
- [13] A. Jaworek and A. T. Sobczyk, "Electrospraying route to nanotechnology: an overview," *Journal of Electrostatics*, vol. 66, no. 3-4, pp. 197–219, 2008.
- [14] J. Castro-Rosas, C. R. Ferreira-Grosso, C. A. Gómez-Aldapa et al., "Recent advances in microencapsulation of natural sources of antimicrobial compounds used in food—a review," *Food Research International*, vol. 102, pp. 575–587, 2017.
- [15] F. Kayaci and T. Uyar, "Encapsulation of vanillin/cyclodextrin inclusion complex in electrospun polyvinyl alcohol (PVA) nanowebs: prolonged shelf-life and high temperature stability of vanillin," *Food Chemistry*, vol. 133, no. 3, pp. 641–649, 2012.
- [16] Y. P. Neo, S. Swift, S. Ray, M. Gizdavic-Nikolaidis, J. Jin, and C. O. Perera, "Evaluation of gallic acid loaded zein sub-micron electrospun fibre mats as novel active packaging materials," *Food Chemistry*, vol. 141, no. 3, pp. 3192–3200, 2013.
- [17] W.-J. Li, C. T. Laurencin, E. J. Caterson, R. S. Tuan, and F. K. Ko, "Electrospun nanofibrous structure: a novel scaffold for tissue engineering," *Journal of Biomedical Materials Research*, vol. 60, no. 4, pp. 613–621, 2002.
- [18] R. A. Thakur, C. A. Florek, J. Kohn, and B. B. Michniak, "Electrospun nanofibrous polymeric scaffold with targeted drug release profiles for potential application as wound dressing," *International Journal of Pharmaceutics*, vol. 364, no. 1, pp. 87–93, 2008.
- [19] M. R. El-Aassar, "Functionalized electrospun nanofibers from poly (AN-co-MMA) for enzyme immobilization," *Journal of Molecular Catalysis B: Enzymatic*, vol. 85–86, pp. 140–148, 2013.
- [20] Q. Dong, G. Wang, H. Hu et al., "Ultrasound-assisted preparation of electrospun carbon nanofiber/graphene composite electrode for supercapacitors," *Journal of Power Sources*, vol. 243, pp. 350–353, 2013.
- [21] J. A. Bhushani and C. Anandharamkrishnan, "Electrospinning and electro-spraying techniques: potential food

- based applications," *Trends in Food Science & Technology*, vol. 38, no. 1, pp. 21–33, 2014.
- [22] R. Ribeiro-Santos, M. Andrade, N. R. d. Melo, and A. Sanches-Silva, "Use of essential oils in active food packaging: recent advances and future trends," *Trends in Food Science & Technology*, vol. 61, pp. 132–140, 2017.
- [23] A. São Pedro, I. E. Santo, C. V. Silva, C. Detoni, and E. Albuquerque, "The use of nanotechnology as an approach for essential oil-based formulations with antimicrobial activity," in *Microbial Pathogens and Strategies for Combating Them*, A. Méndez-Vilas, Ed., vol. 2, pp. 1364–1374, Formatex Research Center Publisher, Badajoz, Spain, 2013.
- [24] R. Pavela, "Essential oils for the development of eco-friendly mosquito larvicides: a review," *Industrial Crops and Products*, vol. 76, pp. 174–187, 2015.
- [25] K. Svoboda and R. Greenaway, "Investigation of volatile oil glands of *Satureja hortensis* L. (summer savory) and phytochemical comparison of different varieties," *The International Journal of Aromatherapy*, vol. 13, no. 4, pp. 196–202, 2003.
- [26] W. A. Wannes, B. Mhamdi, J. Sriti et al., "Antioxidant activities of the essential oils and methanol extracts from myrtle (*Myrtus communis* var. *italica* L.) leaf, stem and flower," *Food and Chemical Toxicology*, vol. 48, no. 5, pp. 1362–1370, 2010.
- [27] A. Dvaranauskaitė, P. Venskutonis, C. Raynaud, T. Talou, P. Viskelis, and A. Sasnauskas, "Variations in the essential oil composition in buds of six blackcurrant (*Ribes nigrum* L.) cultivars at various development phases," *Food Chemistry*, vol. 114, no. 2, pp. 671–679, 2009.
- [28] L. E. Hill, C. Gomes, and T. M. Taylor, "Characterization of beta-cyclodextrin inclusion complexes containing essential oils (trans-cinnamaldehyde, eugenol, cinnamon bark, and clove bud extracts) for antimicrobial delivery applications," *LWT—Food Science and Technology*, vol. 51, no. 1, pp. 86–93, 2013.
- [29] J. Lv, H. Huang, L. Yu et al., "Phenolic composition and nutraceutical properties of organic and conventional cinnamon and peppermint," *Food Chemistry*, vol. 132, no. 3, pp. 1442–1450, 2012.
- [30] C. Vallverdú, R. Vila, F. Tomi, M. Carhuapoma, J. Casanova, and S. Cañigueral, "Composition of the essential oil from leaves and twigs of *Luma chequen*," *Flavour and Fragrance Journal*, vol. 21, no. 2, pp. 241–243, 2006.
- [31] A. I. Hussain, F. Anwar, S. T. Hussain Sherazi, and R. Przybylski, "Chemical composition, antioxidant and antimicrobial activities of basil (*Ocimum basilicum*) essential oils depends on seasonal variations," *Food Chemistry*, vol. 108, no. 3, pp. 986–995, 2008.
- [32] M. Khajeh, Y. Yamini, N. Bahramifar, F. Sefidkon, and M. Reza Pirmoradei, "Comparison of essential oils compositions of *Ferula assa-foetida* obtained by supercritical carbon dioxide extraction and hydrodistillation methods," *Food Chemistry*, vol. 91, no. 4, pp. 639–644, 2005.
- [33] P. S. Negi, "Plant extracts for the control of bacterial growth: efficacy, stability and safety issues for food application," *International Journal of Food Microbiology*, vol. 156, no. 1, pp. 7–17, 2012.
- [34] L. Riahi, H. Chograni, M. Elferchichi, Y. Zaouali, N. Zoghliami, and A. Mliki, "Variations in Tunisian wormwood essential oil profiles and phenolic contents between leaves and flowers and their effects on antioxidant activities," *Industrial Crops and Products*, vol. 46, pp. 290–296, 2013.
- [35] F. Bakkali, S. Averbeck, D. Averbeck, and M. Idaomar, "Biological effects of essential oils—a review," *Food and Chemical Toxicology*, vol. 46, no. 2, pp. 446–475, 2008.
- [36] K.-K. Li, S.-W. Yin, X.-Q. Yang, C.-H. Tang, and Z.-H. Wei, "Fabrication and characterization of novel antimicrobial films derived from thymol-loaded zein-sodium caseinate (SC) nanoparticles," *Journal of Agricultural and Food Chemistry*, vol. 60, no. 46, pp. 11592–11600, 2012.
- [37] D. Dainelli, N. Gontard, D. Spyropoulos, E. Zondervan-van den Beuken, and P. Tobback, "Active and intelligent food packaging: legal aspects and safety concerns," *Trends in Food Science & Technology*, vol. 19, pp. S103–S112, 2008.
- [38] M. Ozdemir and J. D. Floros, "Active food packaging technologies," *Critical Reviews in Food Science and Nutrition*, vol. 44, no. 3, pp. 185–193, 2004.
- [39] P. Suppakul, K. Sonneveld, S. W. Bigger, and J. Miltz, "Efficacy of polyethylene-based antimicrobial films containing principal constituents of basil," *LWT—Food Science and Technology*, vol. 41, no. 5, pp. 779–788, 2008.
- [40] L. Vermeiren, F. Devlieghere, M. van Beest, N. de Kruijf, and J. Debevere, "Developments in the active packaging of foods," *Trends in Food Science & Technology*, vol. 10, no. 3, pp. 77–86, 1999.
- [41] A. A. M. d. Melo, R. M. Geraldine, M. F. A. Silveira et al., "Microbiological quality and other characteristics of refrigerated chicken meat in contact with cellulose acetate-based film incorporated with rosemary essential oil," *Brazilian Journal of Microbiology*, vol. 43, no. 4, pp. 1419–1427, 2012.
- [42] A. C. Souza, G. E. O. Goto, J. A. Mainardi, A. C. V. Coelho, and C. C. Tadini, "Cassava starch composite films incorporated with cinnamon essential oil: antimicrobial activity, microstructure, mechanical and barrier properties," *LWT—Food Science and Technology*, vol. 54, no. 2, pp. 346–352, 2013.
- [43] Y. Peng and Y. Li, "Combined effects of two kinds of essential oils on physical, mechanical and structural properties of chitosan films," *Food Hydrocolloids*, vol. 36, pp. 287–293, 2014.
- [44] M. Oussalah, S. Caillet, S. Salmiéri, L. Saucier, and M. Lacroix, "Antimicrobial effects of alginate-based films containing essential oils on *Listeria monocytogenes* and *Salmonella typhimurium* present in bologna and ham," *Journal of Food Protection*, vol. 70, no. 4, pp. 901–908, 2007.
- [45] J. Hafsa, M. a. Smach, M. R. Ben Khedher et al., "Physical, antioxidant and antimicrobial properties of chitosan films containing *Eucalyptus globulus* essential oil," *LWT—Food Science and Technology*, vol. 68, pp. 356–364, 2016.
- [46] A. C. Seydim and G. Sarikus, "Antimicrobial activity of whey protein based edible films incorporated with oregano, rosemary and garlic essential oils," *Food Research International*, vol. 39, no. 5, pp. 639–644, 2006.
- [47] M. Jouki, F. T. Yazdi, S. A. Mortazavi, and A. Koocheki, "Quince seed mucilage films incorporated with oregano essential oil: physical, thermal, barrier, antioxidant and antibacterial properties," *Food Hydrocolloids*, vol. 36, pp. 9–19, 2014.
- [48] D. A. Botre, N. d. F. F. Soares, P. J. P. Espitia, S. de Sousa, and I. R. T. Renhe, "Avaliação de filme incorporado com óleo essencial de orégano para conservação de pizza pronta," *Revista Ceres*, vol. 57, no. 3, pp. 283–291, 2015.
- [49] V. Otero, R. Becerril, J. A. Santos, J. M. Rodríguez-Calleja, C. Nerín, and M.-L. García-López, "Evaluation of two antimicrobial packaging films against *Escherichia coli* O157:H7

- strains in vitro and during storage of a Spanish ripened sheep cheese (Zamorano),” *Food Control*, vol. 42, pp. 296–302, 2014.
- [50] Z. K. Emiroğlu, G. P. Yemiş, B. K. Coşkun, and K. Candoğan, “Antimicrobial activity of soy edible films incorporated with thyme and oregano essential oils on fresh ground beef patties,” *Meat Science*, vol. 86, no. 2, pp. 283–288, 2010.
- [51] K. G. Zinoviadou, K. P. Koutsoumanis, and C. G. Biliaderis, “Physico-chemical properties of whey protein isolate films containing oregano oil and their antimicrobial action against spoilage flora of fresh beef,” *Meat Science*, vol. 82, no. 3, pp. 338–345, 2009.
- [52] P. N. Takala, K. D. Vu, S. Salmieri, R. A. Khan, and M. Lacroix, “Antibacterial effect of biodegradable active packaging on the growth of *Escherichia coli*, *Salmonella typhimurium* and *Listeria monocytogenes* in fresh broccoli stored at 4°C,” *LWT—Food Science and Technology*, vol. 53, no. 2, pp. 499–506, 2013.
- [53] P. Tongnuanchan, S. Benjakul, and T. Prodpran, “Physico-chemical properties, morphology and antioxidant activity of film from fish skin gelatin incorporated with root essential oils,” *Journal of Food Engineering*, vol. 117, no. 3, pp. 350–360, 2013.
- [54] S. Shojaee-Aliabadi, H. Hosseini, M. A. Mohammadifar et al., “Characterization of antioxidant-antimicrobial κ-carrageenan films containing *Satureja hortensis* essential oil,” *International Journal of Biological Macromolecules*, vol. 52, pp. 116–124, 2013.
- [55] M. Oussalah, S. Caillet, S. Salmiéri, L. Saucier, and M. Lacroix, “Antimicrobial and antioxidant effects of milk protein-based film containing essential oils for the preservation of whole beef muscle,” *Journal of Agricultural and Food Chemistry*, vol. 52, no. 18, pp. 5598–5605, 2004.
- [56] J. Gómez-Estaca, A. López de Lacey, M. E. López-Caballero, M. C. Gómez-Guillén, and P. Montero, “Biodegradable gelatin-chitosan films incorporated with essential oils as antimicrobial agents for fish preservation,” *Food Microbiology*, vol. 27, no. 7, pp. 889–896, 2010.
- [57] P. R. Salgado, M. E. López-Caballero, M. C. Gómez-Guillén, A. N. Mauri, and M. P. Montero, “Sunflower protein films incorporated with clove essential oil have potential application for the preservation of fish patties,” *Food Hydrocolloids*, vol. 33, no. 1, pp. 74–84, 2013.
- [58] W. S. Choi, S. Singh, and Y. S. Lee, “Characterization of edible film containing essential oils in hydroxypropyl methylcellulose and its effect on quality attributes of “Formosa” plum (*Prunus salicina* L.),” *LWT*, vol. 70, pp. 213–222, 2016.
- [59] J. Yun, X. Fan, X. Li, T. Z. Jin, X. Jia, and J. P. Mattheis, “Natural surface coating to inactivate *Salmonella enterica* serovar Typhimurium and maintain quality of cherry tomatoes,” *International Journal of Food Microbiology*, vol. 193, pp. 59–67, 2015.
- [60] K. D. Vu, R. G. Hollingsworth, E. Leroux, S. Salmieri, and M. Lacroix, “Development of edible bioactive coating based on modified chitosan for increasing the shelf life of strawberries,” *Food Research International*, vol. 44, no. 1, pp. 198–203, 2011.
- [61] Á. Perdonés, I. Escriche, A. Chiralt, and M. Vargas, “Effect of chitosan-lemon essential oil coatings on volatile profile of strawberries during storage,” *Food Chemistry*, vol. 197, pp. 979–986, 2016.
- [62] S. Ramakrishna, K. Fujihara, W.-E. Teo, T. Yong, Z. Ma, and R. Ramaseshan, “Electrospun nanofibers: solving global issues,” *Materials Today*, vol. 9, no. 3, pp. 40–50, 2006.
- [63] Z.-M. Huang, Y.-Z. Zhang, M. Kotaki, and S. Ramakrishna, “A review on polymer nanofibers by electrospinning and their applications in nanocomposites,” *Composites Science and Technology*, vol. 63, no. 15, pp. 2223–2253, 2003.
- [64] L. Wannatong, A. Sirivat, and P. Supaphol, “Effects of solvents on electrospun polymeric fibers: preliminary study on polystyrene,” *Polymer International*, vol. 53, no. 11, pp. 1851–1859, 2004.
- [65] V. Lassalle and M. L. Ferreira, “PLA nano- and microparticles for drug delivery: an overview of the methods of preparation,” *Macromolecular Bioscience*, vol. 7, no. 6, pp. 767–783, 2007.
- [66] L. G. Gómez-Mascaraque, G. Sanchez, and A. López-Rubio, “Impact of molecular weight on the formation of electrospun chitosan microcapsules as delivery vehicles for bioactive compounds,” *Carbohydrate Polymers*, vol. 150, pp. 121–130, 2016.
- [67] S. Torres-Giner, A. Martínez-Abad, M. J. Ocio, and J. M. Lagaron, “Stabilization of a nutraceutical omega-3 fatty acid by encapsulation in ultrathin electrospun zein prolamine,” *Journal of Food Science*, vol. 75, no. 6, pp. N69–N79, 2010.
- [68] S. M. Jafari, *Nanoencapsulation Technologies for the Food and Nutraceutical Industries*, Academic Press, Cambridge, MA, USA, 2017.
- [69] A. A. Almetwally, M. El-Sakhawy, M. Elshakankery, and M. Kasem, “Technology of nano-fibers: production techniques and properties-critical review,” *Journal of the Textile Association*, vol. 78, pp. 5–14, 2017.
- [70] S. Chakraborty, I.-C. Liao, A. Adler, and K. W. Leong, “Electrohydrodynamics: a facile technique to fabricate drug delivery systems,” *Advanced Drug Delivery Reviews*, vol. 61, no. 12, pp. 1043–1054, 2009.
- [71] A. López-Rubio, E. Sanchez, S. Wilkanowicz, Y. Sanz, and J. M. Lagaron, “Electrospinning as a useful technique for the encapsulation of living bifidobacteria in food hydrocolloids,” *Food Hydrocolloids*, vol. 28, no. 1, pp. 159–167, 2012.
- [72] R. Pérez-Masiá, J. M. Lagaron, and A. Lopez-Rubio, “Morphology and stability of edible lycopene-containing micro- and nanocapsules produced through electrospinning and spray drying,” *Food and Bioprocess Technology*, vol. 8, no. 2, pp. 459–470, 2015.
- [73] M. Eltayeb, P. K. Bakhshi, E. Stride, and M. Edirisinghe, “Preparation of solid lipid nanoparticles containing active compound by electrohydrodynamic spraying,” *Food Research International*, vol. 53, no. 1, pp. 88–95, 2013.
- [74] K. A. Rieger and J. D. Schiffman, “Electrospinning an essential oil: cinnamaldehyde enhances the antimicrobial efficacy of chitosan/poly(ethylene oxide) nanofibers,” *Carbohydrate Polymers*, vol. 113, pp. 561–568, 2014.
- [75] K. Feng, P. Wen, H. Yang et al., “Enhancement of the antimicrobial activity of cinnamon essential oil-loaded electrospun nanofilm by the incorporation of lysozyme,” *RSC Advances*, vol. 7, no. 3, pp. 1572–1580, 2017.
- [76] J. Wróblewska-Krepsztul, T. Rydzkowski, I. Michalska-Požoga, and V. K. Thakur, “Biopolymers for biomedical and pharmaceutical applications: recent advances and overview of alginate electrospinning,” *Nanomaterials*, vol. 9, no. 3, p. 404, 2019.
- [77] K. A. Rieger, N. P. Birch, and J. D. Schiffman, “Electrospinning chitosan/poly(ethylene oxide) solutions with

- essential oils: correlating solution rheology to nanofiber formation,” *Carbohydrate Polymers*, vol. 139, pp. 131–138, 2016.
- [78] I. Katouzian and S. M. Jafari, “Nano-encapsulation as a promising approach for targeted delivery and controlled release of vitamins,” *Trends in Food Science & Technology*, vol. 53, pp. 34–48, 2016.
- [79] M. Shrestha, T. M. Ho, and B. R. Bhandari, “Encapsulation of tea tree oil by amorphous beta-cyclodextrin powder,” *Food Chemistry*, vol. 221, pp. 1474–1483, 2017.
- [80] J.-h. Cheng, Y.-n. Hu, Z.-g. Luo, W. Chen, H.-m. Chen, and X.-c. Peng, “Preparation and properties of octenyl succinate β -cyclodextrin and its application as an emulsion stabilizer,” *Food Chemistry*, vol. 218, pp. 116–121, 2017.
- [81] E. N. Faikoh, Y.-H. Hong, and S.-Y. Hu, “Liposome-encapsulated cinnamaldehyde enhances zebrafish (*Danio rerio*) immunity and survival when challenged with *Vibrio vulnificus* and *Streptococcus agalactiae*,” *Fish & Shellfish Immunology*, vol. 38, no. 1, pp. 15–24, 2014.
- [82] Z. Fang and B. Bhandari, “Encapsulation of polyphenols—a review,” *Trends in Food Science & Technology*, vol. 21, no. 10, pp. 510–523, 2010.
- [83] R. E. Conn, J. J. Kolstad, J. F. Borzelleca et al., “Safety assessment of polylactide (PLA) for use as a food-contact polymer,” *Food and Chemical Toxicology*, vol. 33, no. 4, pp. 273–283, 1995.
- [84] P. Wen, D.-H. Zhu, H. Wu, M.-H. Zong, Y.-R. Jing, and S.-Y. Han, “Encapsulation of cinnamon essential oil in electrospun nanofibrous film for active food packaging,” *Food Control*, vol. 59, pp. 366–376, 2016.
- [85] G. Chen and B. Liu, “Cellulose sulfate based film with slow-release antimicrobial properties prepared by incorporation of mustard essential oil and β -cyclodextrin,” *Food Hydrocolloids*, vol. 55, pp. 100–107, 2016.
- [86] C. López-de-Dicastillo, M. Jordá, R. Catalá, R. Gavara, and P. Hernández-Muñoz, “Development of active polyvinyl alcohol/ β -cyclodextrin composites to scavenge undesirable food components,” *Journal of Agricultural and Food Chemistry*, vol. 59, no. 20, pp. 11026–11033, 2011.
- [87] M. Jawaid and S. K. Swain, *Bionanocomposites for Packaging Applications*, Springer, Berlin, Germany, 2018.
- [88] C. Sebaaly, C. Charcosset, S. Stainmesse, H. Fessi, and H. Greige-Gerges, “Clove essential oil-in-cyclodextrin-in-liposomes in the aqueous and lyophilized states: from laboratory to large scale using a membrane contactor,” *Carbohydrate Polymers*, vol. 138, pp. 75–85, 2016.
- [89] E. M. M. Del Valle, “Cyclodextrins and their uses: a review,” *Process Biochemistry*, vol. 39, no. 9, pp. 1033–1046, 2004.
- [90] J. Szejtli, “Introduction and general overview of cyclodextrin chemistry,” *Chemical Reviews*, vol. 98, no. 5, pp. 1743–1754, 1998.
- [91] C. Samperio, R. Boyer, W. N. Eigel et al., “Enhancement of plant essential oils’ aqueous solubility and stability using alpha and beta cyclodextrin,” *Journal of Agricultural and Food Chemistry*, vol. 58, no. 24, pp. 12950–12956, 2010.
- [92] H. M. C. de Azeredo, “Antimicrobial nanostructures in food packaging,” *Trends in Food Science & Technology*, vol. 30, no. 1, pp. 56–69, 2013.
- [93] H. Samsudin, H. Soto-Valdez, and R. Auras, “Poly(lactic acid) film incorporated with marigold flower extract (*Tagetes erecta*) intended for fatty-food application,” *Food Control*, vol. 46, pp. 55–66, 2014.
- [94] P. Wen, D.-H. Zhu, K. Feng et al., “Fabrication of electrospun polylactic acid nanofilm incorporating cinnamon essential oil/ β -cyclodextrin inclusion complex for antimicrobial packaging,” *Food Chemistry*, vol. 196, pp. 996–1004, 2016.
- [95] Y. Liu, S. Wang, R. Zhang, W. Lan, and W. Qin, “Development of poly(lactic acid)/chitosan fibers loaded with essential oil for antimicrobial applications,” *Nanomaterials*, vol. 7, no. 7, p. 194, 2017.
- [96] M. Kashiri, Y. Maghsoudlo, and M. Khomeiri, “Incorporating *Zataria multiflora* Boiss. essential oil and sodium bentonite nano-clay open a new perspective to use zein films as bioactive packaging materials,” *Food Science and Technology International*, vol. 23, no. 7, pp. 582–596, 2017.
- [97] L. Lin, Y. Dai, and H. Cui, “Antibacterial poly(ethylene oxide) electrospun nanofibers containing cinnamon essential oil/ β -cyclodextrin proteoliposomes,” *Carbohydrate Polymers*, vol. 178, pp. 131–140, 2017.
- [98] M. C. Ribeiro, M. da Silva Fernandes, A. Yoshiteru Kuaye, R. Jimenez-Flores, and M. Gigante, “Preconditioning of the stainless steel surface affects the adhesion of *Bacillus cereus* spores,” *International Dairy Journal*, vol. 66, pp. 108–114, 2017.
- [99] S. Kumari and P. K. Sarkar, “*Bacillus cereus* hazard and control in industrial dairy processing environment,” *Food Control*, vol. 69, pp. 20–29, 2016.
- [100] İ. Ünal, F. Korel, and A. Yemencioğlu, “Active packaging of ground beef patties by edible zein films incorporated with partially purified lysozyme and Na₂EDTA,” *International Journal of Food Science & Technology*, vol. 46, no. 6, pp. 1289–1295, 2011.
- [101] K. S. Doosh and S. M. Abdul-Rahm, “Effect of lysozyme isolated from hen egg white in elongation the shelf life of Iraqi soft cheese made from buffalo milk,” *Pakistan Journal of Nutrition*, vol. 13, no. 11, pp. 635–641, 2014.
- [102] C. B. Amara, N. Eghbal, P. Degraeve, and A. Gharsallaoui, “Using complex coacervation for lysozyme encapsulation by spray-drying,” *Journal of Food Engineering*, vol. 183, pp. 50–57, 2016.
- [103] L. Ge, Y.-s. Zhao, T. Mo, J.-r. Li, and P. Li, “Immobilization of glucose oxidase in electrospun nanofibrous membranes for food preservation,” *Food Control*, vol. 26, no. 1, pp. 188–193, 2012.
- [104] D.-z. Yang, Y.-h. Long, and J. Nie, “Release of lysozyme from electrospun PVA/lysozyme-gelatin scaffolds,” *Frontiers of Materials Science in China*, vol. 2, no. 3, pp. 261–265, 2008.
- [105] P. Shao, Z. Yan, H. Chen, and J. Xiao, “Electrospun poly(vinyl alcohol)/permutite fibrous film loaded with cinnamaldehyde for active food packaging,” *Journal of Applied Polymer Science*, vol. 135, no. 16, p. 46117, 2018.
- [106] J. Wu, C. Yu, and Q. Li, “Regenerable antimicrobial activity in polyamide thin film nanocomposite membranes,” *Journal of Membrane Science*, vol. 476, pp. 119–127, 2015.
- [107] A. Baselice, F. Colantuoni, D. A. Lass, G. Nardone, and A. Stasi, “Trends in EU consumers’ attitude towards fresh-cut fruit and vegetables,” *Food Quality and Preference*, vol. 59, pp. 87–96, 2017.
- [108] M. Oliveira, M. Abadias, J. Usall, R. Torres, N. Teixidó, and I. Viñas, “Application of modified atmosphere packaging as a safety approach to fresh-cut fruits and vegetables—a review,” *Trends in Food Science & Technology*, vol. 46, no. 1, pp. 13–26, 2015.
- [109] J. Xiao, C. Shi, H. Zheng et al., “Kafirin protein based electrospun fibers with tunable mechanical property, wettability, and release profile,” *Journal of Agricultural and Food Chemistry*, vol. 64, no. 16, pp. 3226–3233, 2016.

- [110] H. H. Kara, F. Xiao, M. Sarker et al., "Antibacterial poly(lactic acid) (PLA) films grafted with electrospun PLA/allyl isothiocyanate fibers for food packaging," *Journal of Applied Polymer Science*, vol. 133, no. 2, 2016.
- [111] S. Phunpee, S. Saesoo, I. Sramala et al., "A comparison of eugenol and menthol on encapsulation characteristics with water-soluble quaternized β -cyclodextrin grafted chitosan," *International Journal of Biological Macromolecules*, vol. 84, pp. 472–480, 2016.
- [112] K. P. Anthony, S. A. Deolu-Sobogun, and M. A. Saleh, "Comprehensive assessment of antioxidant activity of essential oils," *Journal of Food Science*, vol. 77, no. 8, pp. C839–C843, 2012.
- [113] H. Cetin Babaoglu, A. Bayrak, N. Ozdemir, and N. Ozgun, "Encapsulation of clove essential oil in hydroxypropyl β -cyclodextrin for characterization, controlled release, and antioxidant activity," *Journal of Food Processing and Preservation*, vol. 41, no. 5, Article ID e13202, 2017.
- [114] H. M. C. Marques, "A review on cyclodextrin encapsulation of essential oils and volatiles," *Flavour and Fragrance Journal*, vol. 25, no. 5, pp. 313–326, 2010.
- [115] T. Uyar, J. Hacıoğlu, and F. Besenbacher, "Electrospun polyethylene oxide (PEO) nanofibers containing cyclodextrin inclusion complex," *Journal of Nanoscience and Nanotechnology*, vol. 11, no. 5, pp. 3949–3958, 2011.
- [116] F. Kayaci, Y. Ertas, and T. Uyar, "Enhanced thermal stability of eugenol by cyclodextrin inclusion complex encapsulated in electrospun polymeric nanofibers," *Journal of Agricultural and Food Chemistry*, vol. 61, no. 34, pp. 8156–8165, 2013.
- [117] F. Kayaci, H. S. Sen, E. Durgun, and T. Uyar, "Functional electrospun polymeric nanofibers incorporating geraniol-cyclodextrin inclusion complexes: high thermal stability and enhanced durability of geraniol," *Food Research International*, vol. 62, pp. 424–431, 2014.
- [118] Z. Aytac, S. Y. Dogan, T. Tekinay, and T. Uyar, "Release and antibacterial activity of allyl isothiocyanate/ β -cyclodextrin complex encapsulated in electrospun nanofibers," *Colloids and Surfaces B: Biointerfaces*, vol. 120, pp. 125–131, 2014.
- [119] Z. Aytac, S. I. Kuskü, E. Durgun, and T. Uyar, "Quercetin/ β -cyclodextrin inclusion complex embedded nanofibres: slow release and high solubility," *Food Chemistry*, vol. 197, pp. 864–871, 2016.
- [120] Z. Aytac, Z. I. Yildiz, F. Kayaci-Senirmak, N. O. San Keskin, T. Tekinay, and T. Uyar, "Electrospinning of polymer-free cyclodextrin/geraniol-inclusion complex nanofibers: enhanced shelf-life of geraniol with antibacterial and antioxidant properties," *RSC Advances*, vol. 6, no. 52, pp. 46089–46099, 2016.
- [121] Z. Aytac, Z. I. Yildiz, F. Kayaci-Senirmak et al., "Fast-dissolving, prolonged release, and antibacterial cyclodextrin/limonene-inclusion complex nanofibrous webs via polymer-free electrospinning," *Journal of Agricultural and Food Chemistry*, vol. 64, no. 39, pp. 7325–7334, 2016.
- [122] Z. Aytac, Z. I. Yildiz, F. Kayaci-Senirmak, T. Tekinay, and T. Uyar, "Electrospinning of cyclodextrin/linalool-inclusion complex nanofibers: fast-dissolving nanofibrous web with prolonged release and antibacterial activity," *Food Chemistry*, vol. 231, pp. 192–201, 2017.
- [123] A. Celebioglu, F. Kayaci-Senirmak, S. İpek, E. Durgun, and T. Uyar, "Polymer-free nanofibers from vanillin/cyclodextrin inclusion complexes: high thermal stability, enhanced solubility and antioxidant property," *Food & Function*, vol. 7, no. 7, pp. 3141–3153, 2016.
- [124] A. Celebioglu, Z. I. Yildiz, and T. Uyar, "Fabrication of electrospun eugenol/cyclodextrin inclusion complex nanofibrous webs for enhanced antioxidant property, water solubility, and high temperature stability," *Journal of Agricultural and Food Chemistry*, vol. 66, no. 2, pp. 457–466, 2018.
- [125] D. Pornpattananankul, L. Zhang, S. Olson et al., "Bacterial toxin-triggered drug release from gold nanoparticle-stabilized liposomes for the treatment of bacterial infection," *Journal of the American Chemical Society*, vol. 133, no. 11, pp. 4132–4139, 2011.
- [126] G. A. T. Kaminski, M. R. Sierakowski, R. Pontarolo, L. A. d. Santos, and R. A. d. Freitas, "Layer-by-layer polysaccharide-coated liposomes for sustained delivery of epidermal growth factor," *Carbohydrate Polymers*, vol. 140, pp. 129–135, 2016.
- [127] W. Liu, W. Liu, A. Ye et al., "Environmental stress stability of microencapsules based on liposomes decorated with chitosan and sodium alginate," *Food Chemistry*, vol. 196, pp. 396–404, 2016.
- [128] L. M. P. Montenegro, J. B. Griep, F. C. Tavares, D. H. de Oliveira, D. Bianchini, and R. G. Jacob, "Synthesis and characterization of imine-modified silicas obtained by the reaction of essential oil of *Eucalyptus citriodora*, 3-aminopropyltriethoxysilane and tetraethylorthosilicate," *Vibrational Spectroscopy*, vol. 68, pp. 272–278, 2013.
- [129] J. H. Cui, Y. Liang, D. Yang, and Y. Liu, "Facile fabrication of rice husk based silicon dioxide nanospheres loaded with silver nanoparticles as a rice antibacterial agent," *Scientific Reports*, vol. 6, no. 1, p. 21423, 2016.
- [130] K. Okada, T. Tomita, Y. Kameshima, A. Yasumori, and K. J. D. MacKenzie, "Porous properties of coprecipitated Al_2O_3 - SiO_2 xerogels prepared from aluminium nitrate nonhydrate and tetraethylorthosilicate," *Journal of Materials Chemistry*, vol. 9, no. 6, pp. 1307–1312, 1999.
- [131] H. Ziyang, Z. Lan, and L. Guangchao, "Study on fabrication and properties of porous HA/ SiO_2 composite coating on titanium substrate," *Acta Chimica Sinica*, vol. 70, no. 3, pp. 235–240, 2012.
- [132] Z. Li, H. Kang, N. Che et al., "Controlled release of liposome-encapsulated Naproxen from core-sheath electrospun nanofibers," *Carbohydrate Polymers*, vol. 111, pp. 18–24, 2014.
- [133] N. C. Wickremasinghe, V. A. Kumar, and J. D. Hartgerink, "Two-step self-assembly of liposome-multidomain peptide nanofiber hydrogel for time-controlled release," *Biomacromolecules*, vol. 15, no. 10, pp. 3587–3595, 2014.
- [134] I. Peinado, M. Mason, A. Romano, F. Biasioli, and M. Scampicchio, "Stability of β -carotene in polyethylene oxide electrospun nanofibers," *Applied Surface Science*, vol. 370, pp. 111–116, 2016.
- [135] H. Cui, L. Yuan, W. Li, and L. Lin, "Antioxidant property of SiO_2 -eugenol liposome loaded nanofibrous membranes on beef," *Food Packaging and Shelf Life*, vol. 11, pp. 49–57, 2017.
- [136] B. Munteanu, L. Sacarescu, A.-L. Vasiliu et al., "Antioxidant/antibacterial electrospun nanocoatings applied onto PLA films," *Materials*, vol. 11, no. 10, p. 1973, 2018.
- [137] K. Divya, S. Vijayan, T. K. George, and M. S. Jisha, "Antimicrobial properties of chitosan nanoparticles: mode of action and factors affecting activity," *Fibers and Polymers*, vol. 18, no. 2, pp. 221–230, 2017.
- [138] M. Gällstedt, A. Brottman, and M. S. Hedenqvist, "Packaging-related properties of protein- and chitosan-coated

- paper," *Packaging Technology and Science*, vol. 18, no. 4, pp. 161–170, 2005.
- [139] S.-I. Hong, J.-W. Lee, and S.-M. Son, "Properties of polysaccharide-coated polypropylene films as affected by biopolymer and plasticizer types," *Packaging Technology and Science*, vol. 18, no. 1, pp. 1–9, 2005.
- [140] C. H. Lee, D. S. An, H. J. Park, and D. S. Lee, "Wide-spectrum antimicrobial packaging materials incorporating nisin and chitosan in the coating," *Packaging Technology and Science*, vol. 16, no. 3, pp. 99–106, 2003.
- [141] H. Berrougui, M. Cloutier, M. Isabelle, and A. Khalil, "Phenolic-extract from argan oil (*Argania spinosa* L.) inhibits human low-density lipoprotein (LDL) oxidation and enhances cholesterol efflux from human THP-1 macrophages," *Atherosclerosis*, vol. 184, no. 2, pp. 389–396, 2006.
- [142] M. Kouidri, A. K. Saadi, A. Noui, and F. Medjahed, "The chemical composition of argan oil," *International Journal of Advanced Studies in Computers, Science and Engineering*, vol. 4, no. 1, p. 24, 2015.
- [143] K. Chaieb, H. Hajlaoui, T. Zmantar et al., "The chemical composition and biological activity of clove essential oil, *Eugenia caryophyllata* (*Syzygium aromaticum* L. Myrtaceae): a short review," *Phytotherapy Research*, vol. 21, no. 6, pp. 501–506, 2007.
- [144] B. Melendez-Rodriguez, K. J. Figueroa-Lopez, A. Bernardos et al., "Electrospun antimicrobial films of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) containing eugenol essential oil encapsulated in mesoporous silica nanoparticles," *Nanomaterials*, vol. 9, no. 2, p. 227, 2019.
- [145] H. Cui, M. Bai, M. M. A. Rashed, and L. Lin, "The antibacterial activity of clove oil/chitosan nanoparticles embedded gelatin nanofibers against *Escherichia coli* O157:H7 biofilms on cucumber," *International Journal of Food Microbiology*, vol. 266, pp. 69–78, 2018.
- [146] H. Cui, C. Ma, C. Li, and L. Lin, "Enhancing the antibacterial activity of thyme oil against *Salmonella* on eggshell by plasma-assisted process," *Food Control*, vol. 70, pp. 183–190, 2016.
- [147] A. Marchese, I. E. Orhan, M. Daglia et al., "Antibacterial and antifungal activities of thymol: a brief review of the literature," *Food Chemistry*, vol. 210, pp. 402–414, 2016.
- [148] L. Rivas, M. J. McDonnell, C. M. Burgess et al., "Inhibition of verocytotoxigenic *Escherichia coli* in model broth and rumen systems by carvacrol and thymol," *International Journal of Food Microbiology*, vol. 139, no. 1-2, pp. 70–78, 2010.
- [149] M. A. Numpaque, L. A. Oviedo, J. H. Gil, C. M. Garcia, and D. L. Durango, "Thymol and carvacrol: biotransformation and antifungal activity against the plant pathogenic fungi *Colletotrichum acutatum* and *Botryodiplodia theobromae*," *Tropical Plant Pathology*, vol. 36, no. 1, pp. 3–13, 2011.
- [150] P. S. Chavan and S. G. Tupe, "Antifungal activity and mechanism of action of carvacrol and thymol against vineyard and wine spoilage yeasts," *Food Control*, vol. 46, pp. 115–120, 2014.
- [151] L.-H. Wang, Z.-H. Zhang, X.-A. Zeng, D.-M. Gong, and M.-S. Wang, "Combination of microbiological, spectroscopic and molecular docking techniques to study the antibacterial mechanism of thymol against *Staphylococcus aureus*: membrane damage and genomic DNA binding," *Analytical and Bioanalytical Chemistry*, vol. 409, no. 6, pp. 1615–1625, 2017.
- [152] D. Valero, J. M. Valverde, D. Martínez-Romero, F. Guillén, S. Castillo, and M. Serrano, "The combination of modified atmosphere packaging with eugenol or thymol to maintain quality, safety and functional properties of table grapes," *Postharvest Biology and Technology*, vol. 41, no. 3, pp. 317–327, 2006.
- [153] C. O. Pérez-Alfonso, D. Martínez-Romero, P. J. Zapata, M. Serrano, D. Valero, and S. Castillo, "The effects of essential oils carvacrol and thymol on growth of *Penicillium digitatum* and *P. italicum* involved in lemon decay," *International Journal of Food Microbiology*, vol. 158, no. 2, pp. 101–106, 2012.
- [154] L. Lin, Y. Zhu, and H. Cui, "Electrospun thyme essential oil/gelatin nanofibers for active packaging against *Campylobacter jejuni* in chicken," *LWT*, vol. 97, pp. 711–718, 2018.
- [155] P. Umaraw, A. Prajapati, A. K. Verma, V. Pathak, and V. P. Singh, "Control of *Campylobacter* in poultry industry from farm to poultry processing unit: a review," *Critical Reviews in Food Science and Nutrition*, vol. 57, no. 4, pp. 659–665, 2017.
- [156] W. C. Silva, B. N. Targino, R. S. Mendonça, A. S. Sant'Ana, and H. M. Hungaro, "Campylobacter: an overview of cases, occurrence in food, contamination sources, and antimicrobial resistance in Brazil," *Food Reviews International*, vol. 34, no. 4, pp. 364–389, 2018.
- [157] A. Pant and J. S. Negi, "Novel controlled ionic gelation strategy for chitosan nanoparticles preparation using TPP- β -CD inclusion complex," *European Journal of Pharmaceutical Sciences*, vol. 112, pp. 180–185, 2018.
- [158] H. Lu, L. Zou, Y. Xu, and Y. V. Li, "Controlled dispersion of multiwalled carbon nanotubes modified by hyperbranched polylysine," *Journal of Applied Polymer Science*, vol. 135, no. 19, p. 46249, 2018.
- [159] M. Rizwan, R. Yahya, A. Hassan et al., "Synthesis of a novel organosoluble, biocompatible, and antibacterial chitosan derivative for biomedical applications," *Journal of Applied Polymer Science*, vol. 135, no. 9, p. 45905, 2018.
- [160] Z. Aytac, S. Ipek, E. Durgun, T. Tekinay, and T. Uyar, "Antibacterial electrospun zein nanofibrous web encapsulating thymol/cyclodextrin-inclusion complex for food packaging," *Food Chemistry*, vol. 233, pp. 117–124, 2017.
- [161] Z. Li, M. Wang, F. Wang et al., " γ -cyclodextrin: a review on enzymatic production and applications," *Applied Microbiology and Biotechnology*, vol. 77, no. 2, pp. 245–255, 2007.
- [162] P. A. P. Cevallos, M. P. Buera, and B. E. Elizalde, "Encapsulation of cinnamon and thyme essential oils components (cinnamaldehyde and thymol) in β -cyclodextrin: effect of interactions with water on complex stability," *Journal of Food Engineering*, vol. 99, no. 1, pp. 70–75, 2010.
- [163] Z. Aytac and T. Uyar, "Antioxidant activity and photostability of α -tocopherol/ β -cyclodextrin inclusion complex encapsulated electrospun polycaprolactone nanofibers," *European Polymer Journal*, vol. 79, pp. 140–149, 2016.
- [164] F. Tao, L. E. Hill, Y. Peng, and C. L. Gomes, "Synthesis and characterization of β -cyclodextrin inclusion complexes of thymol and thyme oil for antimicrobial delivery applications," *LWT—Food Science and Technology*, vol. 59, no. 1, pp. 247–255, 2014.
- [165] I. Mourtzinou, N. Kalogeropoulos, S. E. Papadakis, K. Konstantinou, and V. T. Karathanos, "Encapsulation of nutraceutical monoterpenes in β -cyclodextrin and modified starch," *Journal of Food Science*, vol. 73, no. 1, pp. S89–S94, 2008.
- [166] Y. Zhang, Y. Zhang, Z. Zhu, X. Jiao, Y. Shang, and Y. Wen, "Encapsulation of thymol in biodegradable nanofiber via coaxial electrospinning and applications in fruit

- preservation," *Journal of Agricultural and Food Chemistry*, vol. 67, no. 6, pp. 1736–1741, 2019.
- [167] H. K. Makadia and S. J. Siegel, "Poly lactic-co-glycolic acid (PLGA) as biodegradable controlled drug delivery carrier," *Polymers*, vol. 3, no. 3, pp. 1377–1397, 2011.
- [168] C. Gomes, R. G. Moreira, and E. Castell-Perez, "Poly (DL-lactide-co-glycolide) (PLGA) nanoparticles with entrapped trans-cinnamaldehyde and eugenol for antimicrobial delivery applications," *Journal of Food Science*, vol. 76, no. 2, pp. N16–N24, 2011.
- [169] L. M. Silva, L. E. Hill, E. Figueiredo, and C. L. Gomes, "Delivery of phytochemicals of tropical fruit by-products using poly (DL-lactide-co-glycolide) (PLGA) nanoparticles: synthesis, characterization, and antimicrobial activity," *Food Chemistry*, vol. 165, pp. 362–370, 2014.
- [170] R. F. Lins, W. R. Lustri, S. Minharro, A. Alonso, and D. de Sousa Neto, "On the formation, physicochemical properties and antibacterial activity of colloidal systems containing tea tree (*Melaleuca alternifolia*) oil," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 497, pp. 271–279, 2016.
- [171] D. J. Ireland, S. J. Greay, C. M. Hooper et al., "Topically applied *Melaleuca alternifolia* (tea tree) oil causes direct anti-cancer cytotoxicity in subcutaneous tumour bearing mice," *Journal of Dermatological Science*, vol. 67, no. 2, pp. 120–129, 2012.
- [172] O. Catanzano, M. C. Straccia, A. Miro et al., "Spray-by-spray in situ cross-linking alginate hydrogels delivering a tea tree oil microemulsion," *European Journal of Pharmaceutical Sciences*, vol. 66, pp. 20–28, 2015.
- [173] F. d. S. Oliveira, T. S. d. Freitas, R. P. d. Cruz et al., "Evaluation of the antibacterial and modulatory potential of α -bisabolol, β -cyclodextrin and α -bisabolol/ β -cyclodextrin complex," *Biomedicine & Pharmacotherapy*, vol. 92, pp. 1111–1118, 2017.
- [174] H. Cui, M. Bai, and L. Lin, "Plasma-treated poly(ethylene oxide) nanofibers containing tea tree oil/ β -cyclodextrin inclusion complex for antibacterial packaging," *Carbohydrate Polymers*, vol. 179, pp. 360–369, 2018.
- [175] F. A. P. Scacchetti, E. Pinto, and G. M. B. Soares, "Functionalization and characterization of cotton with phase change materials and thyme oil encapsulated in β -cyclodextrins," *Progress in Organic Coatings*, vol. 107, pp. 64–74, 2017.
- [176] Y. Tang, Y. Zhou, X. Lan et al., "Electrospun gelatin nanofibers encapsulated with peppermint and chamomile essential oils as potential edible packaging," *Journal of Agricultural and Food Chemistry*, vol. 67, no. 8, pp. 2227–2234, 2019.
- [177] R. Liang, S. Xu, C. F. Shoemaker, Y. Li, F. Zhong, and Q. Huang, "Physical and antimicrobial properties of peppermint oil nanoemulsions," *Journal of Agricultural and Food Chemistry*, vol. 60, no. 30, pp. 7548–7555, 2012.
- [178] I. Liakos, L. Rizzello, H. Hajiali et al., "Fibrous wound dressings encapsulating essential oils as natural antimicrobial agents," *Journal of Materials Chemistry B*, vol. 3, no. 8, pp. 1583–1589, 2015.
- [179] B. P. Chumpitazi, G. L. Kearns, and R. J. Shulman, "Review article: the physiological effects and safety of peppermint oil and its efficacy in irritable bowel syndrome and other functional disorders," *Alimentary Pharmacology & Therapeutics*, vol. 47, no. 6, pp. 738–752, 2018.
- [180] M. H. H. Roby, M. A. Sarhan, K. A.-H. Selim, and K. I. Khalel, "Antioxidant and antimicrobial activities of essential oil and extracts of fennel (*Foeniculum vulgare* L.) and chamomile (*Matricaria chamomilla* L.)," *Industrial Crops and Products*, vol. 44, pp. 437–445, 2013.
- [181] S. Agatonovic-Kustrin, D. Babazadeh Ortakand, D. W. Morton, and A. P. Yusof, "Rapid evaluation and comparison of natural products and antioxidant activity in calendula, feverfew, and German chamomile extracts," *Journal of Chromatography A*, vol. 1385, pp. 103–110, 2015.
- [182] F. Duman, I. Ocsoy, and F. O. Kup, "Chamomile flower extract-directed CuO nanoparticle formation for its antioxidant and DNA cleavage properties," *Materials Science and Engineering: C*, vol. 60, pp. 333–338, 2016.
- [183] A. Cvetanović, J. Švarc-Gajić, P. Mašković, S. Savić, and L. Nikolić, "Antioxidant and biological activity of chamomile extracts obtained by different techniques: perspective of using superheated water for isolation of biologically active compounds," *Industrial Crops and Products*, vol. 65, pp. 582–591, 2015.
- [184] Z. A. N. Hanani, Y. H. Roos, and J. P. Kerry, "Use and application of gelatin as potential biodegradable packaging materials for food products," *International Journal of Biological Macromolecules*, vol. 71, pp. 94–102, 2014.
- [185] F. M. Fakhouri, D. Costa, F. Yamashita et al., "Comparative study of processing methods for starch/gelatin films," *Carbohydrate Polymers*, vol. 95, no. 2, pp. 681–689, 2013.
- [186] S. F. Hosseini, M. Rezaei, M. Zandi, and F. Farahmandghavi, "Bio-based composite edible films containing *Origanum vulgare* L. essential oil," *Industrial Crops and Products*, vol. 67, pp. 403–413, 2015.
- [187] M. Ahmad, S. Benjakul, T. Prodpran, and T. W. Agustini, "Physico-mechanical and antimicrobial properties of gelatin film from the skin of unicorn leatherjacket incorporated with essential oils," *Food Hydrocolloids*, vol. 28, no. 1, pp. 189–199, 2012.
- [188] P.-D. Duh, "Antioxidant activity of water extract of four Harnng Jyur (*Chrysanthemum morifolium* Ramat) varieties in soybean oil emulsion," *Food Chemistry*, vol. 66, no. 4, pp. 471–476, 1999.
- [189] C.-K. Lii, Y.-P. Lei, H.-T. Yao et al., "Chrysanthemum morifolium Ramat. reduces the oxidized LDL-induced expression of intercellular adhesion molecule-1 and E-selectin in human umbilical vein endothelial cells," *Journal of Ethnopharmacology*, vol. 128, no. 1, pp. 213–220, 2010.
- [190] F. Khallouki, M. Hmamouchi, C. Younos, R. Soulimani, J. M. Bessiere, and E. M. Essassi, "Antibacterial and molluscicidal activities of the essential oil of *Chrysanthemum viscidifolium*," *Fitoterapia*, vol. 71, no. 5, pp. 544–546, 2000.
- [191] L. Lin, X. Mao, Y. Sun, G. Rajivgandhi, and H. Cui, "Antibacterial properties of nanofibers containing chrysanthemum essential oil and their application as beef packaging," *International Journal of Food Microbiology*, vol. 292, pp. 21–30, 2019.
- [192] M. Nadeem and M. Imran, "Promising features of Moringa oleifera oil: recent updates and perspectives," *Lipids in Health and Disease*, vol. 15, no. 1, p. 212, 2016.
- [193] L. Lin, Y. Gu, and H. Cui, "Moringa oil/chitosan nanoparticles embedded gelatin nanofibers for food packaging against *Listeria monocytogenes* and *Staphylococcus aureus* on cheese," *Food Packaging and Shelf Life*, vol. 19, pp. 86–93, 2019.