REVIEW

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The preparation, stability, functionality and food enrichment ability of cinnamon oil-loaded nanoemulsion-based delivery systems: a review

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ABSTRACT

Even though cinnamon oil (CO) has functional and health effects in humans because of the presence of the antioxidant cinnamaldehyde (CIA), its food applications have been limited due to its poor water solubility. Encapsulation of CO in stable nanodroplets is a unique strategy to enhance the stability and bioavailability of hydrophobic molecules in the CO structure. A literature review has been conducted on the formation of stable nanoscale droplets using low- and high-energy nanoemulsification methods, physicochemical and antimicrobial characterization, and the food application efficiency of CO micro/nanoemulsions. Although high-energy emulsification technologies are more commonly used to produce CO nanoemulsions, there is considerable interest in the fabrication of these delivery systems using the low-energy techniques of spontaneous emulsification and phase-inversion temperature. Processing and formulation (oil phase composition and surfactant content) variables were optimized to produce the smallest droplet size and slowest CIA release rate. Cinnamon and CIA nanoemulsions can effectively control pathogens in functional foods during processing and storage. A strong inhibitory effect on many microorganisms can also be exerted by small nanodroplets encapsulating these bioactive compounds into edible films to significantly decrease the synthetic preservative content. The antibacterial and antifungal activity, nutritional value and physicochemical quality of foods can be improved by adding CO-enriched nanoemulsions.

Keywords

Cinnamon essential oil
Nanoencapsulation
Ostwald ripening
Antimicrobial
Fortification
Active packaging
Food preservation

Introduction

Secondary plant metabolites are a large class of naturally synthesized chemicals with health-promoting actions. Although most of these metabolites are non-nutritive dietary substances, they usually have positive effects on the human metabolism [1]. Essential oils (EOs) as one of the most important and promising secondary metabolites, are considered to be generally recognized as safe (GRAS) and are used in a wide range of food and beverage formulations as flavouring agents, natural preservatives and antioxidants. Their exceptional antimicrobial and antioxidant characteristics can guarantee the quality of food products and improve shelf-life [2]. Unfortunately, the considerable volatility, poor solubility and strong odour of EOs have restricted their direct incorporation into food systems [3]. However, encapsulation allows the protection and delivery of EOs in food matrixes [4] and is a useful process to trap bioactive components within a carrier material for improving the delivery of these molecules into foods [5]. Since there is a strong relationship between the delivery rate of any bioactive constituent and its particle size, the incorporation and absorption of EOs can be facilitated by forming droplets with nano-metre diameters [6].

Nanoemulsification is a novel technology to enhance the dispersibility of lipophilic ingredients in water with targeted release in the gastrointestinal tract. Nanoemulsions are an interesting group of colloidal delivery vehicles with nanoscale droplets and have attractive biophysical benefits such as improved physical stability, optical transparency, water solubility, and the in vitro and in vivo bioavailability of functional compounds [7]. In addition, the inclusion of an EO-loaded nanostructured emulsion into edible coatings and films can significantly improve the quality of stored food products by inhibiting physical change, nutritional loss, oxidative reactions and microbial spoilage [4, 8–10].

Cinnamon is native to Sri Lanka and is produced from the inner bark of trees from the genus *Cinnamomum*. This com-

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mon spice is used as a flavouring or aromatic condiment in many countries around the world. It has also been used for thousands of years in Iranian, Indian and Chinese traditional medicine to treat many disorders and diseases such as dental caries, periodontal disease and bad breath, poor blood circulation, damaged tissue, and disorders of the colon [11, 12]. It is also commonly consumed to heal wounds and to treat atrophy, bronchitis, the common cold, eye inflammation (e.g., chronic dry eye), rheumatism, nerve pain and vaginal inflammation [13, 14]. As cinnamon contains biologically active compounds such as cinnamic acid, protocatechuic acid, rutin, epicatechin, quercetin and cinnamyl aldehydes, it can greatly improve the healthiness, safety and functionality of foods [15]. Cinnamon oil (CO), which has a clear yellow to reddish brown colour, is a steam distillate of the bark, leaves and twigs of the cinnamon plant. Cinnamaldehyde (CIA), the main biocomponent of CO, is not toxic to mammals but as a natural preservative can be used to prevent the growth of various fungal and bacterial species [16]. Gupta *et al* [17] demonstrated that CO has stronger antimicrobial activity than cinnamon extract to preserve foods against food-borne microorganisms.

To the best of our knowledge, the present investigation is the first to review the fabrication techniques, physical stability, and antimicrobial and antioxidant activity of nanoemulsion delivery systems based on CO to optimally develop bioactive food and packaging systems.

Cinnamon oil: chemical constituents and health effects

Many researchers have reviewed the health effects of CO including its antibacterial, antifungal, nematicidal, insecticidal, mosquito larvicidal, antitermitic, antimycotic, antioxidant, anti-obesity, anticancer, antidiabetic, analgesic, antipyretic, anti-inflammatory and immunomodulating activity [11, 15, 18, 19]. Most of these bioactivities are attributed to the presence of CIA (the key flavonoid component in CO), which is naturally found in the form of the more stable *trans* isomer. The components responsible for the characteristic odour of COs obtained from bark and leaves are CIA (56–78%) and eugenol (60–77%), respectively [15]. The chemical structures of CIA (C_9H_8O, 132.16 g/mol) and eugenol ($C_{10}H_{12}O_2$, 164.2 g/mol) are shown in Fig. 1. The cinnamon species (there are ~250 species) and plant parts can significantly affect the amount of *trans*-CIA [18]. For instance, 80–90%, 60–80% and 84% *trans*-CIA was found in COs extracted from the barks/twigs of *Cinnamomum zeylanicum, Cinnamomum cassia* and *Cinnamomum burmannii*, respectively [20]. Furthermore, COs extracted from six batches of *C. osmophloeum* leaves of various origin contained 91.09% *trans*-CIA on average, while other bioactive compounds with high percentages were geranial, cinnamyl acetate and camphor [21]. Tung *et al* [22] also reported that *trans*-CIA (4.07%) constitutes only a small part of CO extracted from *Cinnamomum osmophloeum* twigs, with L-bornyl acetate, caryophyllene oxide, γ-eudesmol, β-caryophyllene, T-cadinol, δ-cadinene, *trans*-β-elemenone and cadalene at 15.89%, 12.98%, 8.03%, 6.60%, 5.49%, 4.79%, 4.25% and 4.19%, respectively, being more plentiful. The age and growth stage of the cinnamon plant also affect the yield and the chemical composition of extracted CO. Li *et al* [23] determined that the maximum CO yield of the 2-year branches of *C. verum* leaves was 5.81%. The presence of a large number of minor volatile compounds in CO confirms it has antioxidant and antimicrobial activity.

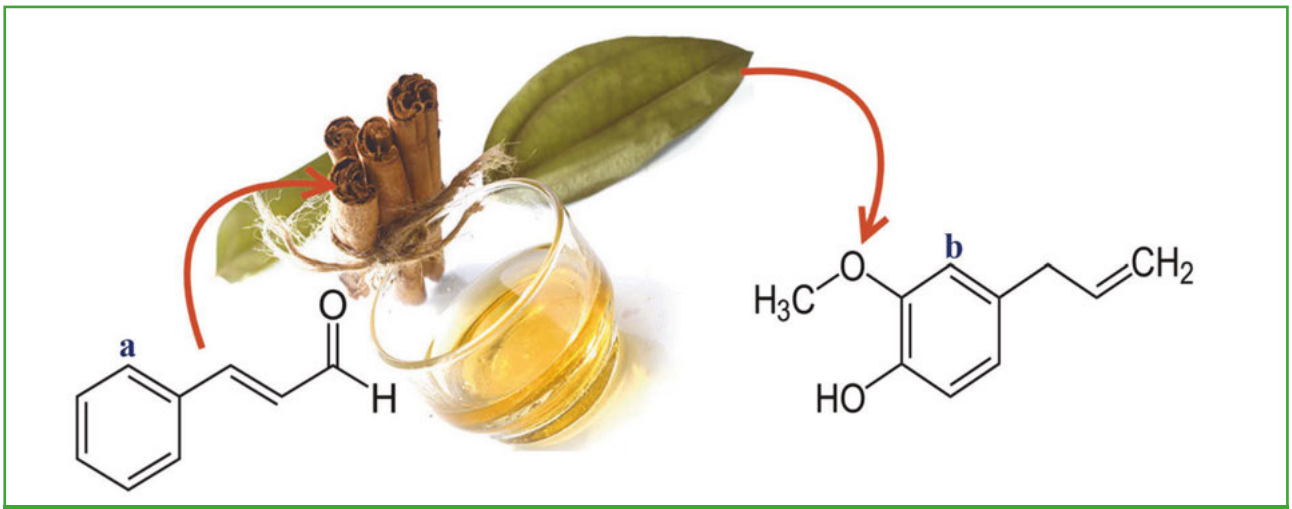

Figure 1 - Structure of (**a**) *trans*-cinnamaldehyde (*trans*-CIA) and (**b**) eugenol found in cinnamon oil

Preparation of cinnamon oil-based nanoemulsions

There are low- and high-energy methods for nanoemulsifying EOs. The low-energy approach includes spontaneous emulsification (SE), the emulsion inversion point (EIP) method, the phase inversion composition (PIC) technique and the phase inversion temperature (PIT) process, while the high-energy approach includes the rotor-stator system (RSS), high-pressure homogenization (HPH), ultrasound-assisted emulsification (UAE) and microfluidization (MF). Both low- and high-energy emulsification methods use mechanical devices and the internal chemical energy of the system to produce nanoemulsions. In general, low-energy methods are preferred due to the low processing cost for large emulsion volumes [24].

The methods to fabricate CO-based nanoemulsions are summarized in Table 1. UAE (at 20 kHz and 750 W) using sonotrode probes was applied to fabricate CO-based nanoemulsions encapsulating the angiotensin-converting enzyme (ACE) inhibitor ramipril [25] and the antifungal drug fluconazole [26]. RSS at different agitation rates (7,000–24,000 rpm) and times (2–60 min) and HPH at various pressures (137.9–200 MPa) and cycles (three to five) were applied to prepare coarse and fine CO-based emulsions (Table 1). Yildirim *et al* [27] used MF (at 900 bar for three passes) to nanoemulsify

Nanoemulsion type	Formulation parameters		Emulsion preparation		
	Φ_{Oil} (%)	Emulsifier/surfactant/stabilizer (%)	Method	Operating conditions	Reference
Ramipril-loaded CO/W	6	Tween 80 (6, 12 and 18)	UAE (13 mm probe)	20 kHz, 750 W	[25]
CO/W microemulsion	6	Tween 20 (6, 12, 18, 24 and 30)	SE	Magnetic stirring (400 rpm)	[16]
CIA/W	2	Tween 80 (1.5)	RSS (Ultra-Turrax®)	7,000, 12,000 or 16,000 rpm for 4 min	[10]
Fluconazole-loaded CO/W	6	Tween 80 (18)	UAE (13 mm probe)	20 kHz, 750 W	[26]
CO+coconut oil/W	10	Tween 80 (10)	MF, RSS, UAE and SE	MF: 900 bar for 3 passes	[27]
				RSS: 10,000 rpm for 2 min	
				UAE: 75 W for 10 min	
				SE: CO titration at a rate of 1 ml/min	
CO+SO/W	10	Lecithin (3), Pea proteins (3), sucrester (1), Tween 20 (0.5)+glycerol monooleate (0.5)	RSS+HPH	RSS: 24,000 rpm for 5 min	[28]
				HPH: 150 MPa, with 5 cycles	
CO+SO/W	4	Tween 80 (T80) or WPI (1)	RSS+HPH	RSS: 24,000 rpm for 4 min	[29]
				HPH: 200 MPa, with 3 cycles	
trans-CIA/W	0.2	Tween 20 (0.6)	RSS+HPH	RSS: 10,000 rpm for 5 min	[30]
				HPH: 20,000 psi (~137.9 MPa)	
Fluconazole-loaded CO/W microemulsion	5	Tween 20 (25)	SE	Gentle mixing by hand	[31]
CO+MCT/W	10	Tween 80 (2.5–15)	SE	Magnetic stirring (400 rpm) for 15 min	[32]
CO/W	6	Tween 80 (6, 12 and 18)	UAE (13 mm probe)	20 kHz, 750 W, 10–30 min	[33]
CO+Acetem/W	1.67	Tween 60 (0.5)	PIC	Stirring for 6 hours	[8]
CO/W	0.5, 1, 5	Tween 80 (0.5), Span 20 (0.5)	RSS	17,000 rpm for 1 hour	[34, 35]
CO+MCT/W	10	Tween 80 (10)	PIT	Temperature decrease, rapid cooling and continuous stirring for 3 min	[36]
CO+BPO (1:1)/W	1	Sodium alginate (1)	UAE, HPH	UAE: 20 kHz, 750 W, 30% amplitude with pulses of 5×5 s for 12 min	[37]
		Span 20, Tween 20, 40 and 80		HPH: 150 MPa, with 5 cycles	
CO+CLO/W	4	Tween 80 (27), ethanol (9)	PIC	Addition of water to the oil–surfactant mixture	[38]
CO/W	1	Tween 20, 80 (3), LAE (0–0.375)	RSS	15,000 rpm for 4 min	[39]
CO/W	5	Lecithin, Tween 8, Span 80	UAE (13 mm probe)	20 kHz, 750 W	[44]

BPO black pepper oil, *CIA* cinnamaldehyde, *CLO* clove oil, *CO* cinnamon oil, *HPH* high-pressure homogenization, *LAE* lauric arginate, *MCT* medium chain triglyceride, *MF* microfluidization, *PIC* phase inversion composition, *PIT* phase inversion temperature, *RSS* rotor-stator system, *SE* spontaneous emulsification, *SO* sunflower oil, *UAE* ultrasound-assisted emulsification, *W* water, *WPI* whey protein isolate

Table 1 - Formulation and nanoemulsification conditions for cinnamon oil-based emulsions fabricated by low- and high-energy methods

an oil phase containing CO and coconut oil as they found that MF compared with RSS, UAE and SE resulted in the smallest mean particle size. Other researchers employed a combination of RSS and HPH to achieve stable and ultrafine *trans*-CIA and CO nanoemulsions [28–30]. SE was the most common low-energy process used to nanoemulsify CO [16, 27, 31, 32] due to the mild processing conditions and fast formation of nanodroplets. The quick molecular movement of surfactants and solvents from the dispersed to the continuous phase without alteration in surfactant curvature or phase shift can easily facilitate the formation CO nanoemulsions [32].

Physical stability of cinnamon oil-based nanoemulsions

Effect of formulation components

Table 1 shows the types and concentrations of surfactants, emulsifiers and stabilizers used to produce stable CO-nanoemulsion delivery systems. The non-ionic, single tail surfactant of Tween 80 (polyoxyethylene (20) sorbitan monooleate) was the most common surfactant used in the formulation of CO nanoemulsions (Table 1). Due to the high value of its hydrophilic–lipophilic balance (HLB=15), this small-molecule surfactant can easily minimize the diameter of emulsion droplets in oil/water (O/W) nanoemulsions because of their fast adsorption onto the droplet surface [33–36]. Tian *et al* [32] reported that an increase in Tween 80 content from 5% to 15% results in considerable stability against creaming or oiling off and a decreased droplet size from 130 to 30 nm. Ghosh *et al* [33] also stated that an increase in Tween 80 concentration from 6% to 18% can lead to a significant decrease in droplet diameter from 254 to 65 nm. Previously, Ghosh *et al* [16] had used different concentrations of Tween 20 (6–30%) in surfactant–oil ratios (SORs) of 1:1 to 5:1 CO to fabricate CO microemulsions. A gradual reduction in droplet size was found as Tween 20 content was increased to 24% (SOR, 4:1). As SOR was increased from 1:1 to 5:1, the viscosity of nanoemulsions increased while their turbidity decreased, so that samples with SORs of 4:1 and 5:1 with the maximum viscosity and the minimum turbidity showed the highest thermal stability [16]. Increasing the SOR resulted in an increase in area and a decrease in tension at the oil–water interface, thus producing smaller droplets and stabilizing nanoemulsions [4, 6]. The volume fraction of the dispersed phase of CO nanoemulsions changed from 0.5% to 10% (Table 1).

Ostwald ripening is an important mechanism causing instability in nanoemulsions based on EOs, but can be prevented by adding highly hydrophobic agents. Some triglycerides (e.g., sunflower oil (SO) and coconut oil) and medium chain triglycerides (MCT) acting as ripening inhibitor agents were formulated in the dispersed oil phase of CO nanoemulsions, resulting in the presence of two lipid components (CO and triglyceride) in the dispersed phase. CO as a relatively water-soluble oil makes nanoemulsions susceptible to Ostwald ripening. In this situation, CO molecules tend to diffuse from small to large droplets and thus there will be more CO molecules in the larger droplets than in the smaller ones. The incorporation of appropriate amounts of highly water-insoluble oils into the droplets can delay or inhibit Ostwald ripening in nanoemulsions owing to an entropy of mixing effect that inhibits droplet growth due to differences in curvature [4, 6]. Although the application of stabilizers generally to produce CO nanoemulsions is uncommon, sodium alginate and whey protein isolate were used to stabilize oil phases containing CO and SO [29], and CO and black pepper oil (BPO) [37].

Effect of processing parameters

Table 1 summarizes the parameters used in low- and high-energy methods to fabricate CO nanoemulsions. Otoni *et al* [10] applied high-shear mixing rates for 4 min to prepare CO nanoemulsions. Results showed that all rotation speeds (Table 1) were able to overcome Laplace pressure to break droplets into smaller sizes on a nano-scale (20–500 nm). Nonetheless, a larger polydispersity index for emulsion droplets produced at 7,000 rpm compared to higher rotation speeds (12,000 and 16,000 rpm) was detected. The authors attributed this finding to the lower energy input in the nanoemulsification process [10]. Jiménez *et al* [37] have recently reported that UAE (40–50 nm) is more efficient than HPH (50–70 nm) for preparing smaller emulsion droplets. A high number of cycles should be used in HPH in order to attain small droplet size with a uniform distribution [28, 29, 37]. The smaller emulsion droplets produced by UAE are the result of ultrasonication, whereby large oil droplets are initially formed through an interfacial destabilization mechanism, and then smaller droplets are produced by the collapse of microbubbles formed by cavitation-induced turbulence [24]. Yildirim *et al* [27] showed that there was no significant difference between the size of emulsion droplets produced by UAE and by SE. However, MF was the most efficient method for nanoemulsifying CO, with a droplet size of 35.9 nm. Ghosh *et al* [33] proved that droplet size can be significantly decreased by increasing sonication time by 10–30 min. The

smaller droplet size seen with reduced UAE time is due to the increased shear forces. The low polydispersity index of nanoemulsion droplets is probably due to the adsorption rate and surface activity of the surfactant (Tween 80) on droplet surfaces [7]. However, prolonged UAE can also result in increased droplet size and lipid oxidation rate due to the generation of free radicals and localized heat. Therefore, UAE process variables should be optimized for manufacturing physicochemically stable CO nanoemulsions [7, 33].

Functionality of cinnamon oil-based nanoemulsions

The functionality of CO nanoemulsions was studied in terms of antimicrobial and antioxidant activity. The antimicrobial activity of CO nanoemulsions against a wide range of Gram-negative (e.g., *Escherichia coli, Salmonella enterica, Salmonella typhimurium* and *Helicobacter pylori*) and Gram-positive (e.g., *Staphylococcus aureus*, *Listeria monocytogenes*, *Lactobacillus delbrueckii*, *Bacillus cereus* and *Bacillus subtilis*) bacteria and yeasts/moulds (e.g., *Saccharomyces cerevisiae* and *Aspergillus niger*) was investigated (Table 2). The different CO-nanoemulsion formulations demonstrated high antimicrobial potential against foodborne and spoilage microorganisms.

This is due to the large numbers of bioactive components present in CO such as CIA, eugenol, linalool, cinnamyl acetate, cinnamic acid, benzoic acid and benzaldehyde [38–43]. As discussed earlier, CIA is the main component in CO [17, 20]. This highly electronegative compound can inter-

Emulsion type	z Diameter (nm)	Evaluated microorganisms	Antimicrobial activity	Reference
CO/W	41.32–271.95	*Escherichia coli, Staphylococcus aureus, Listeria monocytogenes*, and *Salmonella enterica* serovar Choleraesuis	Higher antimicrobial activity in nanoemulsions with lower droplet size Gram-positive bacteria more susceptible to CO nanoemulsions than Gram-negative bacteria	[10]
CO/W microemulsion	5.7	*S. aureus*	Whole cell inhibition after 1 min treatment with undiluted CO microemulsions Log2 cell reduction after 45 min treatment with diluted CO microemulsions (1:100)	[16]
CO+coconut oil/W	~100	*E. coli*	CO content in nanoemulsions had a stronger effect on *E. coli* inhibition than the preparation method MF did not improve *E. coli* inactivation but SE and UAE did	[27]
CO+SO/W	130–293	*E. coli, Lactobacillus delbrueckii* and *Saccharomyces cerevisiae*	Complete inactivation of *E. coli* after 24 hours with CO nanoemulsions containing glycerol monooleate-Tween 20 and sugar ester	[28]
CO+SO/W	79–83.5	*Aspergillus niger*	Total prevention of mycelial growth at 0.25 mg/g of CO nanoemulsion Lower growth inhibition of *A. niger* by free CO at the same concentration (~75%)	[29]
trans-CIA/W	<200	*E. coli* O157:H7 933, *S. aureus* and *Salmonella typhimurium*	Inhibition rate: *S. aureus*>*S. typhimurium*>*E. coli* Growth inhibition at low nanoemulsion levels	[30]
CO+MCT/W	<200	*E. coli* and *S. aureus*	Long-term inhibition by CO nanoemulsion of *E. coli* growth compared with pure CIA	[32]
CO/W	65–254	*Bacillus cereus*	No viable microbial cells after 1 min treatment with undiluted CO nanoemulsion A 60% reduction in the number of viable cells after 2-hour contact with diluted CO nanoemulsions (1:1000)	[33]
BPO+CO/W	96.34–166.45	*E. coli, S. aureus, L. monocytogenes* and *S. enterica* serovar Typhimurium	CO nanoemulsions had better antimicrobial activity against *E. coli* and *L. monocytogenes* than BPO nanoemulsions	[37]
CO+CLO/W	8.69	*E. coli, B. subtilis, S. aureus* and *S. typhimurium*	Nanoemulsions showed higher antimicrobial activity than their non-nanoemulsion equivalents	[38]
CO/W	~100	*E. coli* O157:H7, *Salmonella enteritidis* and *L. monocytogenes* Scott A	Nanoemulsions containing LAE, Tween 80 and CO had lower antibacterial activity than the same levels of free LAE and CO	[39]
CO/W	101.6	*E. coli* and *Helicobacter pylori*	Nanoemulsions showed higher antimicrobial activity than free CO	[44]

BPO black pepper oil, *CIA* cinnamaldehyde, *CLO* clove oil, *CO* cinnamon oil, *LAE* lauric arginate, *MCT* medium chain triglyceride, *MF* microfluidization, *SE* spontaneous emulsification, *SO* sunflower oil, *UAE* ultrasound-assisted emulsification, *W* water

Table 2 - The antimicrobial efficiency of CO-based nanoemulsion delivery systems

fere with biological processes participating in the electron transfer mechanism and can react with nitrogen-containing molecules (such as proteins and nucleic acids), preventing the growth of microbial cells via the diffusion and leakage of ions and other cell contents [17]. Likewise, inhibition of mycelium germination using CO nanoemulsions is due to a set of complex mechanisms including the prevention or inactivation of intracellular and extracellular enzymes in the cell membrane, the breakdown of cytoplasmic membrane and cytoplasmic granulation [40]. Hence, an increase in the concentration of CO encapsulated into nanoemulsions can significantly enhance the antimicrobial effect of nanoemulsions, thus providing acceptable microbial lethality at low nanoemulsion levels [27]. In other words, an undiluted CO microemulsion has better antimicrobial efficacy against bacteria, especially Gram-positive bacteria (e.g., *B. cereus* and *S. aureus*) than a diluted microemulsion [16, 33]. Compared with Gram-negative bacteria, Gram-positive bacteria showed lower sensitivity to the antimicrobial CO nanoemulsions as a result of the greater thickness of their peptidoglycan wall and different phospholipid composition [4, 6, 7]. Jiménez *et al* [37] have recently found that the antibacterial activity of CO nanoemulsions against *E. coli* and *L. monocytogenes* is stronger than that of BPO-based nanoemulsions. It seems that, compared with its counterpart in BPO (piperine), the main component of CO (*trans*-CIA) has lower antimicrobial activity against these foodborne bacteria. These findings demonstrated that the antimicrobial activity of nanoemulsions is stronger than that of free CO at the same concentration [29, 32, 38, 44]. Ribes *et al* [29] explained that nanoemulsion systems likely considerably enhance the water-dispersibility/solubility and physicochemical stability of CO, thus improving its antifungal activity against *A. niger*. Under this condition, *trans*-CIA probably interferes with the enzymatic reactions involved in cell wall synthesis and subsequently affects the morphogenesis and growth of *A. niger* [45].

The formulation components (e.g., CO concentration, surfactant type and SOR) and processing factors play a key role in reducing droplet size and improving the antimicrobial activity of the prepared nanoemulsions [6, 7, 27, 30]. It has been demonstrated that nanoemulsions with smaller droplet size have better antimicrobial efficacy [10]. Yildirim *et al* [27] compared the antibacterial performance of CO-based nanoemulsions fabricated by SE, MF and UAE and found that the use of UAE and SE can improve *E. coli* eradication [27]. However, because of the localized heating induced by cavitation, UAE can also destroy bioactive components of CO such as *trans*-CIA, leading to decreased antimicrobial potential even in smaller droplets [46]. Microbial analysis of *trans*-CIA nanoemulsions manufactured by Jo *et al* [30] using the combined methods of RSS and HPH showed that the *trans*-CIA concentration did not have a significant effect on activity against *E. coli*. The authors postulated that the high temperature generated during the relatively high pressures and mechanical shear damages *trans*-CIA even when it is present in high concentrations [30]. Therefore, control of process variables involved in high-energy emulsification methods allows manufacturers to develop nanoemulsion-based delivery systems with smaller droplet size and better antimicrobial activity [24, 47].

The antioxidant activity of CO-based nanoemulsions has been less studied than their antimicrobial activity. Owing to the presence of the *trans*-CIA flavonoid component and other polyphenolic ingredients, CO can effectively quench free radicals by donating hydroxyl groups. It seems that nanoemulsion systems by encapsulating functional CO compounds into the stable droplets inhibit lipid–metal interactions and reduce the lipid oxidation rate even at relatively high temperatures [7]. Jiménez *et al* [37] have recently emphasized that UAE- and HPH-mediated nanoemulsions create a strong barrier around CO bioactive compounds and can also provide stronger antiradical activity with a lower CO content compared with conventional emulsions. The apparent increased antioxidant activity of nanoemulsion delivery systems may be due to the presence of smaller droplets with a larger surface area allowing the bioactive lipophilic compounds to react with oxygen molecules [48].

Cinnamon oil-based nanoemulsions in food and packaging applications

CO-based nanoemulsions have been applied as antioxidant/antimicrobial agents to enrich liquid and semi-solid foods, and edible packaging films. Jo *et al* [30] evaluated the antimicrobial characteristics of *trans*-CIA nanoemulsions in watermelon juice (WMJ). Due to its high content of sugars, vitamins and minerals and its optimal pH, WMJ is an ideal medium for the growth of pathogenic and spoilage bacteria. Consequently, the incorporation of nanoemulsions encapsulating antimicrobial constituents into commercial WMJ formulations can significantly improve its nutritional, sensorial and antimicrobial properties. The addition of *trans*-CIA nanoemulsions into WMJ resulted in better inhibition of *S. typhimurium* than of *S. aureus* or *E. coli* [30]. This may be due to the weaker ability of *S. typhimurium* to adapt to

the new medium (as an environmental stress) since it has a longer lag phase than *S. aureus* or *E. coli*. Zhang *et al* [38] fortified a mushroom sauce with 0.5 g/kg nanoemulsion prepared by blending CO and clove essential oil. This addition significantly increased the sauce's bioactive and flavour compounds such as cinnamic aldehyde, eugenol and methyl salicylate, without any significant changes in flavour. Hilbig *et al* [39] recently stated that the addition of nanoemulsions containing 500 ppm CO and 187.5 ppm lauric arginate (N-alpha-lauroyl-L-arginine ethyl ester monohydrochloride, LAE) to 2% milk can completely inhibit the growth of *L. monocytogenes*. An investigation by dos Santos *et al* [34] in dairy cows also showed that, even at low concentrations, CO-based nanoemulsions have a strong acaricidal effect.

Otoni *et al* [10] added CIA-based nanoemulsions to pectin-based film-forming solutions to cast edible films and found that these nanoemulsions significantly improve the structural rigidity and reduce the water vapour permeability (WVP) of edible pectin films. A significant increase in the strength and elongation of pectin-based nanocomposites enriched with CO-based nanoemulsions containing smaller droplets was also reported by Moura *et al* [9]. Bilbao-Sáinz *et al* [8] incorporated nanoemulsions containing oregano oil and CO into soy protein-based edible films and reported that composite films formulated with oregano oil nanoemulsions had better mechanical strength and WVP than those formulated with CO nanoemulsions. Otoni *et al* [10] also reported that the inclusion of CO nanoemulsions into packaging films can substantially improve their protective capacity against the foodborne microorganisms *E. coli, S. aureus, S. enterica* and *L. monocytogenes*. They pointed out that the increased surface area of nanoscale droplets allowed higher delivery of bioactive compounds such as *trans*-CIA and eugenol [10]. Therefore, the use of these delivery vehicles encapsulating CO can effectively provide safe food products with lower levels of preservatives for consumers.

Conclusion

This review has confirmed that CO-loaded nanoemulsions are highly efficient vehicles for the delivery of biologically active substances such as *trans*-CIA to food and packaging systems. Low-energy nanoemulsification methods have been recently developed for fabricating nano-scaled droplets. However, recent studies have highlighted that there are few low-energy processes, so the fabrication of droplets needs to be optimized to achieve the best stability, antimicrobial properties and bioavailability, and for industrial applicability. Results showed that selection of the correct type and concentration of the surfactant/emulsifier and the exact ratio of oil phase composition (CO and the carrier oil) can ensure high storage stability without phase separation. More research should be conducted on emulsion-based delivery systems designed to inhibit Ostwald ripening so as to understand its role in changing droplet size, storage and thermal stability, and antimicrobial potential. As CO-enriched nanoemulsions showed better antibacterial activity than pure CO, the production of functional foods and green packaging systems based on these water-soluble matrices is strongly recommended. The efficiency of different methods to extract EOs from cinnamon has been investigated in the literature but there is very little information about the in vitro digestion, kinetic release, bioavailability and absorption of CO encapsulated into these nanoemulsion systems under simulated gastrointestinal conditions.

Conflict of interest

The author declares no conflicts of interest.

Human and animal rights

This article does not contain any studies with human or animal subjects.

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