Food Bioscience 57 (2024) 103470

Contents lists available at ScienceDirect

Food Bioscience

journal homepage: www.elsevier.com/locate/fbio

Recent advances in encapsulation techniques for cinnamon bioactive compounds: A review on stability, effectiveness, and potential applications

M.S. Culas [a,b], D.G. Popovich [b,c], A. Rashidinejad [a,*]

[a] Riddet Institute, Massey University, Private Bag 11 222, Palmerston North, 4442, New Zealand
[b] School of Food and Advanced Technology, Massey University, Private Bag 11222, Palmerston North, 4442, New Zealand
[c] School of Science Engineering & Technology, 702 Nguyen Van Linh, District 7, RMIT Vietnam, Ho Chi Mingh, Viet Nam

ARTICLE INFO

Keywords:
Cinnamon bioactive compounds
Delivery systems
Spray drying encapsulation
Physicochemical properties
Encapsulation challenges
Bioavailability enhancement

ABSTRACT

Cinnamon is renowned worldwide for its beneficial health-promoting properties. However, its application in the food industry faces significant challenges due to chemical instability, leading to the degradation of its bioactive compounds, as well as the development of undesirable sensory characteristics caused by the precipitation of salivary proteins by the bioactives. To address these issues, encapsulation methods (both micro and nano) have been developed and studied extensively. This review focuses on recent advances in such encapsulation techniques used to safeguard and deliver cinnamon bioactives, with special emphasis on the spray drying method. The methods employed to evaluate the physicochemical, rheological, and sensorial properties of nano and microparticles are also comprehensively reviewed. The review addresses the challenges associated with encapsulation, including encapsulation efficiency, long-term stability, and release kinetics, and proposes potential strategies to overcome these challenges. Furthermore, the paper presents future perspectives and research directions in cinnamon encapsulation, shedding light on novel materials, advanced characterization techniques, and hybrid encapsulation systems. Overall, encapsulation demonstrates the potential to preserve and harness the therapeutic benefits of cinnamon's bioactive compounds for a wide array of food, pharmaceutical, and nutraceutical applications. With ongoing research and advancements in encapsulation techniques, cinnamon bioactives can be effectively utilized to develop functional and health-enhancing products, catering to the diverse needs of consumers worldwide.

1. Introduction

Cinnamon, obtained from the bark, root, and leaves of *Cinnamomum* species, is renowned for its taste, aroma, and potential health benefits. Its bioactive constituents, including cinnamic acid, cinnamaldehyde, and diverse polyphenols, have demonstrated a range of therapeutic properties such as antioxidant (Mathew & Abraham, 2006), anti-inflammatory (Schink et al., 2018), anticarcinogenic (Holkem, Favaro-Trindade, & Lacroix, 2020), antidiabetic (Hayward et al., 2019), and anti-microbial effect (Gupta, Garg, Uniyal, & Kumari, 2008). Nevertheless, these bioactive compounds are inherently vulnerable to environmental elements such as light (Arias, Zapata, Rojano, & Arias, 2016), heat (Ferraz, Procopio, de Figueiredo Furtado, & Hubinger, 2022), oxygen (Osznianski, Sapis, & Jean, 1985), and moisture (Panceri, Gomes, De Gois, Borges, & Bordignon-Luiz, 2013). Consequently, ensuring the stability and bioavailability of cinnamon's bioactive components has become a significant challenge (Ríos-Pérez et al., 2023).

Encapsulation stands as a widely adopted technique to address these challenges effectively and to protect and deliver cinnamon bioactives, ensuring their controlled release and enhanced functionality in the human gastrointestinal tract (GIT). Encapsulation involves the entrapment of a bioactive material within a carrier material, forming a protective barrier that facilitates the effective delivery of the active ingredient in food applications (Nedovic, Kalusevic, Manojlovic, Levic, & Bugarski, 2011). The active ingredient that is entrapped is referred to as the core material, active agent, payload, fill, or internal phase, while the substance that is used to encapsulate is called the wall material, carrier, shell, external phase, or matrix (Zuidam & Shimoni, 2010). Through encapsulation, the bioactivity and therapeutic potential of cinnamon can be harnessed more effectively, opening new avenues for its utilization in various industries, including food, pharmaceuticals, and nutraceuticals.

* Corresponding author.
E-mail address: A.Rashidinejad@massey.ac.nz (A. Rashidinejad).

https://doi.org/10.1016/j.fbio.2023.103470
Received 24 September 2023; Received in revised form 7 December 2023; Accepted 9 December 2023
Available online 14 December 2023

Numerous studies have been conducted on the encapsulation of cinnamon bioactive compounds; however, to the best of our knowledge, there appears to be a notable gap in the literature, as a comprehensive review that effectively captures all pertinent aspects and confronts the complete range of possibilities and obstacles within this crucial realm of research is yet to be produced. We aim to provide a comprehensive overview of the recent advances in the encapsulation of cinnamon and its bioactive compounds. We explore the diverse encapsulation techniques, highlighting their advantages, limitations, and applications. The challenges associated with cinnamon encapsulation, such as encapsulation efficiency (EE), stability during storage, and release kinetics are discussed. Strategies to overcome these challenges, including the use of natural polymers, incorporation of antioxidants, and hybrid encapsulation systems, are also examined. Additionally, this review delves into the potential impact of encapsulation on the bioactivity and health benefits of cinnamon, shedding light on the improved stability and controlled release of its bioactive compounds. Moreover, we explore the influence of encapsulation on the sensory attributes of cinnamon, ensuring that encapsulated formulations maintain the characteristic flavor and aroma profiles sought after in various food products. Finally, we outline future directions and research perspectives in the field of cinnamon encapsulation. The exploration of novel encapsulation materials, incorporation of nanotechnology, and utilization of advanced characterization techniques hold promise for further enhancing the EE, stability, and release properties of cinnamon-based encapsulated systems. This review will provide researchers, food technologists, and pharmaceutical scientists with a comprehensive understanding of the encapsulation of cinnamon bioactive compounds, fostering further advancements and innovations in this field.

2. Cinnamon bioactive compounds and their chemical stability

Cinnamon belongs to the Lauraceae family and is from the genus *Cinnamomum*. It encompasses a diverse group of plant species, with over 250 known species. However, only a few species are commercially cultivated for various purposes (Das et al., 2022; El-Kader & Abu Hashish, 2020; Mishra & Srivastava, 2022; Satya, Prakash, & Meena, 2012). The commonly cultivated species include *Cinnamomum zeylanicum* (also known as *Cinnamomum verum*) from Sri Lanka, *Cinnamomum burmannii* from Indonesia, *Cinnamomum cassia* from China, *Cinnamomum tamala* from India, and *Cinnamomum loureiroii* from Vietnam (Vangalapati, Sree Satya, Surya Prakash, & Sumanjali, 2012).

Bioactive compounds in plants such as cinnamon are secondary plant metabolites that are often present in small amounts. Some compounds have been shown to decrease the risk of chronic diseases such as arthritis (Kometani et al., 2008), cancer (Holkem et al., 2020), and heart diseases (Tung et al., 2020). These compounds play a crucial role in regulating metabolic processes and exhibit various positive effects, such as elevated levels of GLUT 4 expression, enhanced glucose uptake through GLUT 1, increase in the production of GLP-1, increased PPAR activity, suppression of intestinal α-glucosidase and pancreatic α-amylase, inhibition of gluconeogenesis, and a delay in the emptying of the stomach (Santos, Saraiva, Vicente, & Moldão-Martins, 2019). Cinnamon extracts can stimulate glucogen synthase activation, enhance insulin receptor kinase activity to boost glucose uptake, block the action of glucogen synthase kinase-3, and prevent the dephosphorylation of the insulin receptor. These actions ultimately lead to the insulin receptor achieving its maximum level of phosphorylation. Cinnamon, through these described mechanisms, can effectively enhance insulin sensitivity (Viuda-Martos, Ruiz-Navajas, Fernández-López, & Pérez-Álvarez, 2010). In cinnamon, the bioactive compounds of interest are predominantly found in its essential oil, oleoresin, and water extract.

Cinnamon essential oil (CEO) is derived through hydro distillation of the plant's bark, leaf, or root, with each part yielding distinct components. The primary constituents of the bark, leaf, and root oils differ significantly, with cinnamaldehyde, eugenol, and camphor emerging as the predominant compounds in each respective part (Wijesekera, 1978). The other bioactive compounds found in the essential oil are cinnamate, cinnamyl acetate, 2-methoxy-cinnamaldehyde, cinnamic alcohol, and coumarin (Momtaz, Hassani, Khan, Ziaee, & Abdollahi, 2018). Some examples of such bioactive compounds in CEO with their related physiological functions are given in Table 1.

Cinnamon oleoresins are rich, deep reddish-brown liquids obtained through the organic solvent extraction of the bark, containing 50% or more volatile oil in their composition (Thomas & Kuruvilla, 2012). The volatile fraction of cinnamon oleoresin closely resembles the composition of CEO, as it is a blend of oil and resin (Khasanah et al., 2017). The flavor profile of oleoresins closely mirrors that of freshly ground spice, allowing for their usage in smaller quantities due to their high concentration compared to essential oils (Vaidya, Bhosale, & Singhal, 2006). Furthermore, they require less storage space than essential oils (Kurniasari & Kusumo, 2019). However, it is important to note that cinnamon oleoresins have a shorter shelf life as they can degrade in the presence of air, light, high temperature, and moisture (Vaidya et al., 2006). The specific composition of oleoresins varies based on their origin and the plant part from which they are extracted. For instance, when oleoresins are extracted from the bark of cinnamon, the main volatile components include cinnamaldehyde (65%–95%), benzaldehyde, cinnamic acid, coumarin, and cinnamyl acetate (Procopio et al., 2018). Eugenol is the predominant compound found in oleoresins extracted from cinnamon leaves, constituting approximately 87% of all (Singh, Maurya, DeLampasona, & Catalan, 2007). Cinnamon oleoresins exhibit favorable characteristics for food applications such as cakes and convenience foods, due to their anti-microbial and antioxidant properties (Khasanah et al., 2017).

The water extract of cinnamon contains a class of bioactive polyphenols called "proanthocyanidins" (PA), which are not present in the essential oil or oleoresin. PAs are the predominant type of polyphenol found in cinnamon. A PA molecule is composed of oligomers and polymers consisting of flavan-3-ol units (Gu et al., 2003). PAs have been well known to display a wide range of biological and pharmacological effects in combating the formation of free radicals and oxidative stress (de la Iglesia, Milagro, Campión, Boqué, & Martínez, 2010). PAs have demonstrated higher efficacy compared to resveratrol or ascorbic acid in their ability to scavenge free radicals (Li et al., 2015). Furthermore, PAs are also good antibacterial, anti-obesity, antidiabetic, and anti-cancer agents (Rauf et al., 2019; Tao et al., 2019). Additionally, the cinnamon water extract contains other bioactive compounds such as cinnamic acid, coumarin, cinnamaldehyde, cinnamyl alcohol, caffeic acid, ferulic acid, *p*-coumaric acid, protocatechuic acid, and vanillic acid (Jiao et al., 2013; Pramote et al., 2012; Shan, Cai, Sun, & Corke, 2005). Table 2 provides an overview of the physiological functions associated with various polyphenols found in cinnamon.

Despite the numerous beneficial bioactive compounds present in

Table 1
The main bioactive compounds from cinnamon essential oil with their relevant biological activity (modified from Momtaz et al. (2018)).

Bioactive compound	Main biological activity/ function
Cinnamate, cinnamaldehyde, coumarin, eugenol	Antioxidant
cinnamaldehyde	Anti-diabetic
Cinnamate	Improves hepatic liver metabolism
Cinnamaldehyde, coumarin	Anti-cancer
Cinnamaldehyde, eugenol	Anti-microbial
Cinnamaldehyde, cinnamyl acetate, cinnamic alcohol, coumarin, eugenol	Anti-inflammatory
Cinnamaldehyde	Hypolipidemic
Cinnamic alcohol, coumarin, eugenol	Antifungal
Coumarin	Anti-coagulant
2-methoxy-cinnamaldehyde	Nematocidal activity
Cinnamic alcohol	Antiproliferative

Table 2
The bioactive compounds from cinnamon water extract with their related biological activity/function (modified from Momtaz et al. (2018)).

Bioactive	Main biological activity/ function
Cinnamic acid, catechins, quercetin, proanthocyanidins (PAs)	Antioxidant
Cinnamic acid, PAs	Anti-diabetic
Cinnamic acid, quercetin	Anti-cancer
Cinnamic acid	Anti-microbial
Cinnamic acid, catechins, quercetin	Anti-inflammatory
PAs	Hypolipidemic
Catechins, PAs	Antiproliferative
Cinnamic acid	Cardioprotective

cinnamon, their functionality is limited due to various factors. These include degradation reactions in aqueous mediums, undesirable sensory characteristics (e.g., astringency), interactions with food components/ matrix, volatility, and sensitivity to environmental factors such as oxygen and light (Bennick, 2002; Hofmann et al., 2006; Hyldgaard, Mygind, & Meyer, 2012; Mohammadi, Hosseini, & Hashemi, 2020; Zakharova et al., 2016). The use of cinnamon in its dry form (i.e., cinnamon powder) may prevent degradation reactions but it can result in a high concentration of PA, leading to astringency, which restricts its application in large quantities (De Souza et al., 2018). Furthermore, the polyphenol-rich cinnamon extract has poor oral bioavailability due to its limited water solubility and significant instability during thermal processing, leading to only a fraction of the administered polyphenol reaching the blood circulation (Helal, Tagliazucchi, Verzelloni, & Conte, 2014; Xu, Wu, Jin, & Campanella, 2018).

Thermal processing can cause a substantial loss of polyphenols, thereby hindering their utilization in functional foods. Cinnamaldehyde, another bioactive compound in cinnamon, which is primarily responsible for the distinct flavor and aroma of cinnamon, is highly volatile and prone to degradation at high temperatures, resulting in the formation of unwanted end-products such as benzene (Kuehl et al., 2022) and loss of the original flavor (Hermanto, Khasanah, Atmaka, Manuhara, & Utami, 2016). Additionally, cinnamaldehyde's inhibitory effect on yeasts can negatively impact the leavening process in products where fermentation plays a role (Pattison & Von Holy, 2001). Further, although cinnamaldehyde exhibits potent anti-microbial activity against food-borne pathogens, its low flavor threshold, lipophilic nature, and limited contact with pathogens in high-moisture foods restrict its use (Carvalho, Estevinho, & Santos, 2016; Kalemba & Kunicka, 2003; Merino et al., 2019).

3. Encapsulation techniques used for cinnamon bioactive compounds

Encapsulation involves the process of enclosing materials within capsules before introducing them into a system, enabling the packaging of entire cells or bioactive molecules, such as antioxidants, enzymes, polyphenols, and micronutrients, within protective wall materials. This technique effectively creates encapsulated materials, providing protection and controlled delivery for these sensitive components (Saifullah, Shishir, Ferdowsi, Rahman, & Van Vuong, 2019). Depending on the particle size, the process is classified as microencapsulation (ranging from 3 to 800 μm) or nanoencapsulation (ranging from 10 to 1000 nm) (Jeon, Lee, & Lee, 2016). Encapsulation increases the bioavailability of these bioactives, as the process provides an outer shielding that protects the core material from harsh environmental factors while allowing controlled release in the GIT which allows maximum absorption of the bioactives (Kwak, 2014).

Therefore encapsulation techniques effectively address the limitations in the functionality of cinnamon by safeguarding cinnamon bioactive compounds against degradation reactions, improving their solubility and stability even under adverse environmental conditions, enhancing bioavailability, concealing undesirable characteristics, facilitating controlled release, and ultimately augmenting bioactivity (Bora, Ma, Li, & Liu, 2018; De Souza et al., 2018; Ghaderi-Ghahfarokhi, Barzegar, Sahari, & Azizi, 2016; Madene, Jacquot, Scher, & Desobry, 2006; Majeed et al., 2015; Sanguansri & Augustin, 2006).

Various encapsulation techniques have been employed for cinnamon bioactives, including spray drying, coacervation, precipitation, freeze drying, ionic gelation, ultrasonication, and molecular inclusion. Each technique has its core principles, effective methodological parameters, advantages, disadvantages, limitations, potential applications, and relevant literature reviews listed in Table 3. Among these techniques, this article particularly emphasizes spray drying, providing a comprehensive overview of its application in cinnamon encapsulation.

3.1. Ionic gelation

Ionic gelation is the process of synthesizing micro or nanoparticles using the electrostatic interaction between oppositely charged particles (Fig. 1), where at least one of the particles is under mechanical stirring conditions (Hoang et al., 2022). Chitosan is a biopolymer that has been extensively used to synthesize nanoparticles through ionic gelation due to its favorable biocompatibility, biodegradability, and unique bioactive release properties (Debnath, Kumar, & Babu, 2011). This process of producing nano/microparticles is simple and cost-effective, does not use organic solvents, and requires less time and equipment. The possible toxicity of reagents and other undesirable effects are avoided as reversible physical cross-linking is formed rather than permanent chemical cross-linking (Debnath et al., 2011).

We found several studies that produced nano/micro cinnamon particles using ionic gelation. Most of these studies focused on investigating the anti-microbial properties of the resulting capsules. One of the studies utilized the capsules to assess the shelf life of cucumbers (Mohammadi, Hashemi, & Hosseini, 2015), while the remaining studies primarily focused on characterizing the particles produced via ionic gelation. All the studies focused on encapsulating the cinnamon oil, while only one study focused on encapsulating the ethanolic extract of cinnamon.

Zhang, Jung, and Zhao (2017) highlighted that β chitosan is a stable loading system, as a wall material for CEO and cellulose nanocrystals as a film-forming material that can stabilize and distribute the loaded β chitosan beads in a film to form an antibacterial packaging material. Another study utilized a combination of grape seed extract and chitosan-encapsulated CEO to create nanoparticles through ionic gelation. These nanoparticles demonstrated the ability to inhibit oral bacteria responsible for dental caries. The wall materials used in this study were chitosan and carrageenan. The nano-encapsulated cinnamon particles exhibited significantly increased antibacterial activity against Streptococcus mutans and *Streptococcus sobrinus*, with minimum inhibitory concentrations ranging from 1.00 to 2.00 mg/mL. This finding suggests that they hold promising potential as a component to enhance oral health (Choi, Lee, & Lee, 2023). These researchers discovered that a binary system of β-cyclodextrin/chitosan (β-CD/chitosan) nanoparticles, and a single system of chitosan nanoparticles loaded with CEO, were synthesized through ionic gelation, and examined for their *in vitro* release behavior. The binary system exhibited a higher CEO release of 71% compared to 49% for the single system. The highest EE was observed when the β-CD/chitosan was prepared at 55 °C, which was 2.9 times higher than the EE observed for the optimized chitosan nanoparticles. This increase can be attributed to β-CD's effective loading of poorly water-soluble compounds into its cavity, leading to enhanced EE. Furthermore, the EE increased with rising temperatures up to 55 °C, but beyond that point, a decline in EE was observed with further temperature increase. This phenomenon might be attributed to the dissociation of the ionic bond between chitosan and tripolyphosphate (TPP), resulting in the exposure of chitosan's free, positively charged amino groups and subsequently increasing the zeta potential.

Table 3
Recent advances in encapsulation techniques for cinnamon bioactive compounds.

Core material	Encapsulation technique(s)	Wall material	The main aim of the study	Main findings	References
Cinnamon essential oil (CEO)	Ionic gelation	Chitosan (CS)	To encapsulate CEO with hydroxypropyl methylcellulose/ hydroxypropyl starch nanocomposite film.	The formed films exhibited desirable antioxidant and anti-microbial properties with enhanced mechanical and barrier properties. Sustained release of CEO. Encapsulation efficiency (EE) ranged from 45 % to 50%.	Yu et al. (2023)
CEO	Precipitation	CS and whey protein isolate (WPI)	Preparation and characterization of nanocapsules containing CEO and to compare the volatile components and antibacterial effectiveness of CEO before and after encapsulation.	CEO nanocapsules had EE of 91.74 ± 1.10%. The nanocapsules had higher thermal stability and high long-term anti-bacterial activity.	Yang et al. (2021)
CEO	Freeze drying	β- cyclodextrin (β-CD), α- cyclodextrin, hydroxypropyl-β-CD, Maltodextrin (MD)	To encapsulate cinnamon oil in cyclodextrin (CD) nanosponges and the potential application of these CEO nanocapsules in antimicrobial food packaging.	α and β CD nanosponges were able to encapsulate more CEO (around 80 μg of cinnamaldehyde/mg of nanosponges). CD nanosponges were able to provide a controlled release of volatile compounds and show antibacterial action.	Simionato et al. (2019)
Cinnamon ethanol extract	Anti-solvent precipitation	xanthan gum	To determine the stability and functionality of xanthan gum shellac nanoparticles in encapsulating cinnamon bark extract.	Xanthan gum were able to stabilize shellac nanoparticles at gastric pH by electro-steric stabilization. A decrease in EE was observed when a higher level of cinnamon extract loading was used. The release study showed that more than 90% of cinnamon polyphenol was released at the intestinal pH. The polyphenol retention after heat treatment (90 °C, 20 min) was still higher than 90%.	Muhammad et al. (2020)
CEO	Droplet-based millifluidic technique	Sodium alginate (SA) and CS	Optimization and physiochemical characterization of the droplet-based millifluidic technique for encapsulation of CEO.	The produced capsules showed an EE of 98.96%.	Farahmand et al. (2022)
Cinnamaldehyde	Ultrasonication	CS and pectin	To mask cinnamon flavor using ultrasonic encapsulation.	Cinnamaldehyde microcapsules had higher flavor retention at baking temperatures than pure cinnamaldehyde. Cinnamaldehyde microcapsules had lower cinnamaldehyde loss than pure cinnamaldehyde.	Gong et al. (2020)
CEO	Ionic gelation	CS	To evaluate the effects of CS nano encapsulated CEO on the diet, performance, immune response, and intestinal bacteria population of broiler chicken.	An EE of 69.7% was achieved.	Nouri (2019)
Cinnamon oleoresin	Spray drying	Gum arabic (GA), MD, modified starch (MS)	To microencapsulate cinnamon oleoresin using different wall materials.	GA was a better wall material than other wall materials. However, the blend of GA:MD:MS in the ratio of 4:1:1 was more efficient than even 100% GA.	Vaidya et al. (2006)
Cinnamon leaf essential oil (CLEO)	Precipitation	β-CD	To encapsulate CLEO in β-CD.	The major oil constituent in CLEO was Eugenol. The highest eugenol content was achieved at the CLEO:β-CD ratio of 16:84. The moisture sorption in the microcapsules was lower than the β-CD. Hydrogen bonds were detected between β-CD and CLEO. CLEO microcapsules were stable natural anti-microbial compounds.	Ayala-Zavala et al. (2008)
Cinnamon infusions	Spray drying	MD	To encapsulate cinnamon infusions using spray drying.	The inlet temperature and feed rate for the best protection for cinnamon infusions were 160 °C	Santiago-Adame et al. (2015)

(*continued on next page*)

Table 3 (*continued*)

Core material	Encapsulation technique(s)	Wall material	The main aim of the study	Main findings	References
				and 180 °C and 10 mL/min. The EE was found to be up to 85%.	
Cinnamon oil	Spray drying	GA, WPI/MD, or polyvinyl alcohol (PVA)	To develop insect-resistant food packaging film using cinnamon oil.	The EE of GA, WPI/MD, and PVA were 90.4%, 94.6%, and 80.7%, respectively.	Kim et al. (2013)
CEO	Spray drying	WPI, MD, SA	To understand the effects of wall material and storage conditions on microcapsules properties.	The optimum formulation for wall material:core material was 70:30. The EE was over 93%. Retention during storage was over 95% at 50 °C for 30 days.	Hu et al. (2020)
CEO	Complex coacervation	Gelatin and GA (0.3% tannic acid as curing agent)	To prepare and characterize CEO that is extracted by deep eutectic solvent.	EE was 85.88 ± 0.24%. The thermogravimetric analysis showed that microencapsulation improved the thermal stability of the oil.	Liu et al. (2023)
CEO	Saturated aqueous solution method, molecular inclusion, ultrasonic method	Highland barley starch	To microencapsulate cinnamon oil with highland barley starch.	The microcapsules formed by molecular inclusion were the best with EE of 88.2%, a yield of 79.1%, and a release rate of 11.5% after 25 days of storage.	Li et al. (2020)
CEO	Spray drying	GA, MD, and inulin (IN)	To optimize microencapsulation using GA, MD, and IN.	The optimum concentration for the wall is 27.87% GA, 27.59% MD, and 44.53% IN.	Shahidi Noghabi and Molaveisi (2020a, 2020b)
CEO	Spray drying	MD and GA	To determine the physical characteristics of cinnamon microcapsules.	Water content, bulk density, surface oil, and microencapsulation efficiency vary with ratio changes in wall material.	Hermanto et al. (2016)
Cinnamon and oregano essential oil	Simple coacervation	SA	To microencapsulate cinnamon and introduce it to reduce Listeria monocytogenes.	The encapsulated oil showed inhibition of *L. monocytogenes* significantly. EE was 98.36%.	Gottardo et al. (2022)
CEO	Spray drying	SA	To prepare and characterize free and encapsulated CEO. To determine the antidermatophytic activity.	The minimum inhibitory concentration of free CEO and microencapsulated cinnamon oil was 125–250 μg/mL and 220.5–440.5 μg/mL, respectively.	Makimori et al. (2020)
CEO	Spray drying	GA, WPI, and MD	To determine the thermal stability and physiochemical characteristics of microcapsules of CEO produced by spray drying.	The best wall material is a combination of GA and MD. Thermogravimetric curves showed higher thermal stability with WPI. The blend of GA and MD had better retention of cinnamaldehyde. The blend of MD and WPI produced more spherical particles.	Felix et al. (2017)
CEO	Coprecipitation and CS adsorption	β-CD	To determine *in vivo* anti-microbial activity of encapsulated cinnamon oil in yacon roots.	EE was affected by the wall material. Higher temperatures and humidity could affect the release rate.	Xing et al. (2016)
CEO	Spray drying	GA and MD	To determine the effect of storage temperature on the microcapsule's stability.	The highest EE was in the blend of GA and MD in the ratio of 1:1. EE was 84.62%. The shelf life at 30 °C was 20 weeks.	Pratiwi et al. (2016)
CEO	Simple coacervation	β-CD and CS	To assess the anti-bacterial efficacy of active packaging using microencapsulated cinnamon oil combined with ZnO-coated Polyvinyl chloride.	Microencapsulated cinnamon showed substantial antibacterial activity against *E. coli and S. aureus*.	Xing, Xu, Sun, Li, and Li (2011)
CEO	Precipitation	β-CD	To determine the physical characteristics and antifungal properties of β-CD microcapsules and nanofiber films incorporating cinnamon and oregano essential oils.	Microencapsulated CEO had higher anti-microbial efficiency compared to oregano.	Munhuweyi, Caleb, Van Reenen, and Opara (2018)
CEO	Complex coacervation	SA	To microencapsulate a plant essential oil and evaluate its anti-microbial activity against *Ralstonia solanacearum*.	Cinnamon had the highest anti-bacterial activity of the 10 experimented essential oils.	Tu et al. (2020)
Aqueous extract of cinnamon	Spray drying	MD and acacia gum	To determine the antioxidant capacity and physicochemical properties of microencapsulated aqueous extracts of cinnamon (*Cinnamon zeylanicum*) using spray drying.	The presence of bioactive compounds were dependent on the concentration of the aqueous extract. The blend containing 5% MD and acacia gum had the highest antioxidant capacity.	Ríos-Pérez et al. (2023)

(*continued on next page*)

Table 3 (*continued*)

Core material	Encapsulation technique(s)	Wall material	The main aim of the study	Main findings	References
Aqueous-ethanol extract of cinnamon	Complex coacervation	Gelatin and five polysaccharides (GA, pectin, cashew tree gum, carboxymethylcellulose, and κ-carrageenan)	To use complex coacervation as a technique for protecting bioactive compounds and reducing astringency and strong flavors.	Complex coacervation with gelatin/GA and gelatin/κ-carrageenan were able to mask undesirable taste and astringency. Gelatin/κ-carrageenan and gelatin/cashew tree gum pirs had greater stability for total phenolic compounds and proanthocyanidin.	De Souza et al. (2020)
CEO	Spray drying	GA and MD	To determine the hygroscopic, thermal, and chemical properties of CEO microcapsules produced by spray drying.	Degradation onset temperature for the wall material was close to 200 °C, regardless of the relative storage humidity. Samples stored at 4 °C showed the best antioxidant activity. Substantial oil retention was noted in the first 45 days.	Campelo et al. (2017)
Trans-cinnamaldehyde, eugenol, cinnamon bark, and clove bud extracts	Freeze drying (Molecular inclusion)	β-CD	To characterize inclusion complexes of essential oils with β-CD for their potential use in anti-microbial delivery applications.	The entrapment efficiencies ranged from 41.7% to 84.7%, with pure compounds being higher than extracts. Except for free eugenol, all other essential oil (EO)-β-CD complexes exhibited anti-microbial activities. Encapsulation increased EOs' water solubility and protected them from oxidation.	Hill et al. (2013)
Cinnamon oleoresin	Spray drying	GA and MD	To examine the sensory and physicochemical properties of a dark chocolate bar that incorporates microcapsules of cinnamon (*Cinnamomum burmannii*) bark oleoresin.	The addition of oleoresin microcapsules significantly affected the lightness (L*), texture, total phenol content, and antioxidant activity IC50. The higher the amount of added cinnamon bark oleoresin microcapsules, the higher the total phenol content and antioxidant activity IC50 of the dark chocolate bars.	Praseptiangga, Invicta, and Khasanah (2019)
CEO	Molecular inclusion	βαCD	To investigate the anti-microbial activity of α- or β-CD complexes containing *trans*-cinnamaldehyde against *Staphylococcus aureus* and *Escherichia coli*.	The β-CDcomplexes were larger than the α complexes but with a lower polydispersity index. All complexes showed over 90% EE. The complexes were more effective against *Escherichia coli* than *Staphylococcus aureus*.	Chun et al. (2015)
CEO	Molecular inclusion	β-CD	To investigate the antioxidant properties of a β-CD complex containing *trans*-cinnamaldehyde.	The nitric oxide (NO) or reactive oxygen species (ROS) were significantly lowered by both the *trans*-cinnamaldehyde and the *trans*-cinnamaldehyde β-CD inclusion complex. The EE was 85% and high retention of the active *trans*-cinnamaldehyde for four weeks.	Davaatseren et al. (2017)

In their study, Yu, Yang, Liu, Jin, and Jiao (2023) noted that the size of the nanoparticles increased with higher concentrations of cinnamon essential oil (CEO). In other words, the particle size grew larger as the concentration of essential oil (EO) in the capsule increased. Concurrently, the zeta potential, which provides an estimate of the surface charge of the nanoparticles, was observed to decrease with rising EO concentration. This decrease in zeta potential is attributed to the weakening of repulsive forces, as the particle sizes increased due to the higher EO concentration. According to another study (Honary & Zahir, 2013), dispersions with a zeta potential greater than +30 mV are considered stable, while those with a zeta potential greater than +20 mV only provide short-term stability. In the research conducted by Yu et al. (2023), the observed zeta potentials ranged from approximately +25.3 mV (at the highest EO concentration) to around +31.2 mV (at the lowest EO concentration). Therefore, these findings suggest that the stability of the formed dispersions decreases with increasing concentrations of EO in a nanodispersion.

3.2. Molecular inclusion

Molecular inclusion (Fig. 2) is the process by which a guest molecule (active ingredient) is encapsulated within a host molecule to create an inclusion complex. Cyclodextrin (CD), which is an enzymatically modified saccharide has a 3D shape with different polarities internally and externally and is used as a carrier molecule for most active ingredients (Cid-Samamed, Rakmai, Mejuto, Simal-Gandara, & Astray, 2022). This unique structure of CD with a hydrophobic interior and a hydrophilic exterior, enables them to complex the bioactive in the hydrophobic cavity to form a large, organized structure. This process is well known as CD-based bioactive supra-molecular assemblies (Chen &

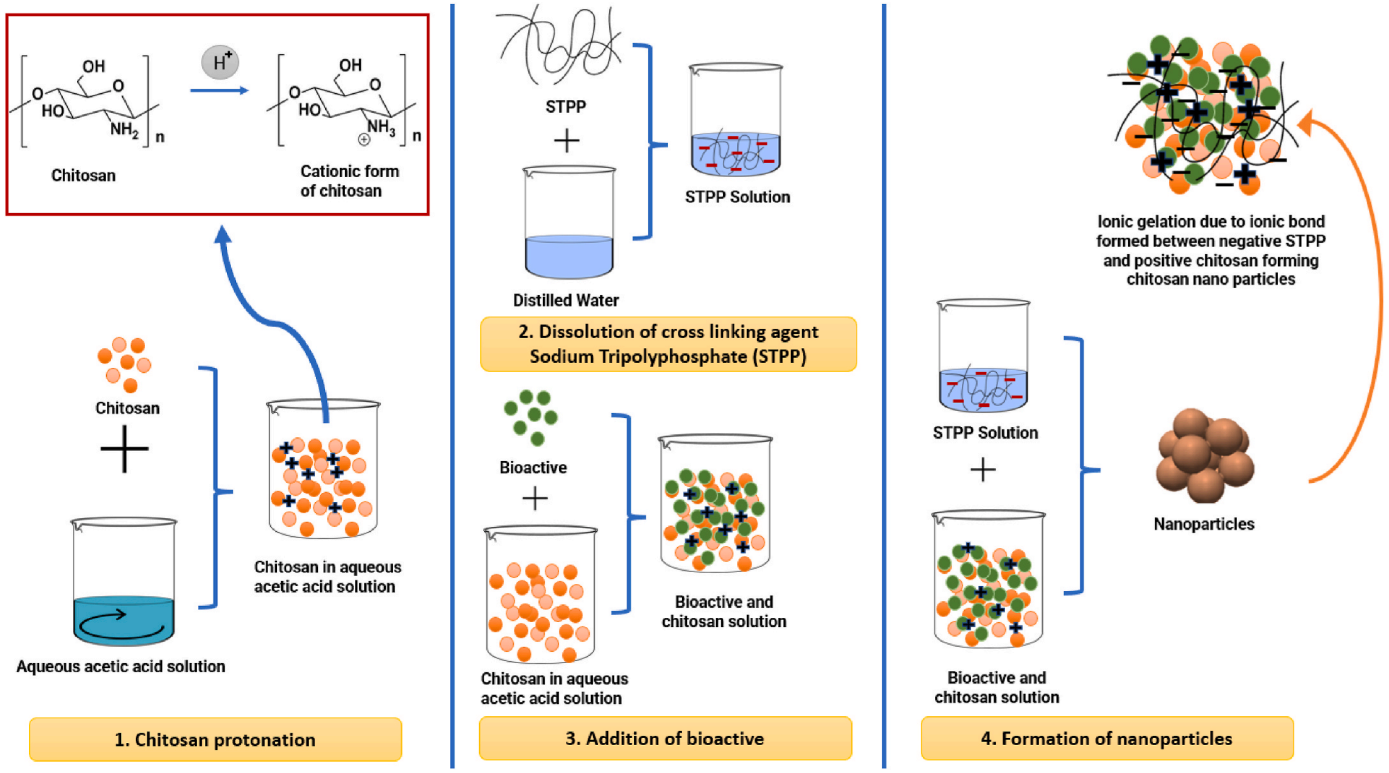

Fig. 1. Diagrammatic representation of the process of ionic gelation of bioactives.

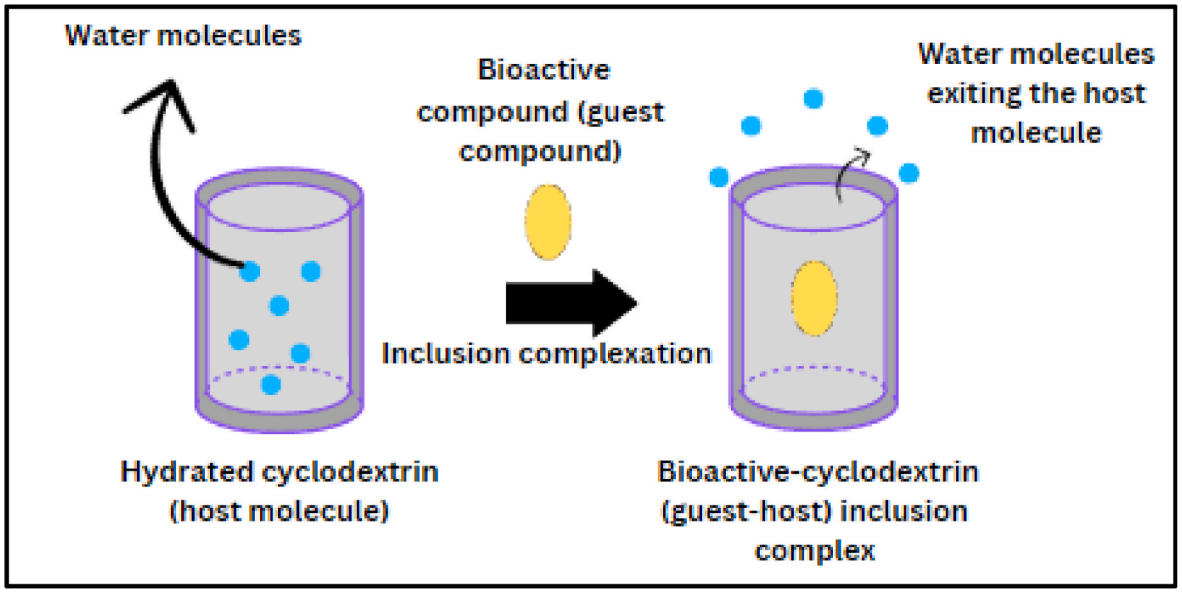

Fig. 2. Diagrammatic representation of the inclusion complexation process of a guest bioactive compound. CD: cyclodextrin.

Liu, 2010). The truncated cone structure of CD with a hydrophilic outer surface and a lipophilic inner cavity safeguards bioactive components from oxidation, light-induced reactions, sublimation, decomposition, and loss of volatility (Krishnaswamy, Orsat, & Thangavel, 2012). Furthermore, it helps eliminate or minimize undesired taste, odors, microbial contaminants, hygroscopicity, and other unwanted components while trapping poorly water-soluble compounds, regulating the release of active compounds, and improving the dissolution rate and bioavailability as the hydrophobic bioactives can be encapsulated within the lipophilic cavities of cyclodextrin. β-CD has been successfully used to encapsulate CEO. There are several methods available for preparing inclusion complexes of CD with guest molecules, including co-precipitation, kneading, supercritical carbon dioxide, grinding, microwave irradiation, solvent evaporation, solid dispersion, and spray-drying (Cid-Samamed et al., 2022). Hill, Gomes, and Taylor (2013) produced inclusion complexes by freeze drying and found that the β-CD EO complex was able to inhibit some bacterial strains (*Salmonella enterica* serovar Typhimurium LT2 and *Listeria innocua*) at lower concentrations more effectively than the free oil. This could be due to the increased water solubility in the inclusion complex giving rise to

better contact between the pathogen and the oil. Chun, Jo, Bjrapha, Choi, and Min (2015) also found that the manufactured cinnamon-CD complex was effective against microorganisms such as *Staphylococcus aureus* and *Escherichia coli*. Davaatseren et al. (2017) produced *trans*-cinnamaldehyde inclusion complexes with β-CD and compared the anti-inflammatory and antioxidant activities against the free *trans*-cinnamaldehyde. It was observed that the oxidation of *trans*-cinnamaldehyde was prevented during prolonged storage by the CD inclusion complex.

3.3. Spray drying

Spray drying is a microencapsulation technique where suspensions are atomized into powdered particles comprised of a wall material and a core (Santiago-Adame et al., 2015). Some wall materials that have been used in spray drying for the microencapsulated CEO are maltodextrins, whey protein isolates, sodium caseinate, sodium alginate (SA), acacia gum, and CDs (Desai & Park, 2005; Hu et al., 2020). The obtained microparticles can protect the core from exposure to oxygen while encapsulating it's aroma and flavor and then releasing the core in the lower part of the GIT (Pourashouri et al., 2014). So, this type of encapsulation will be beneficial in increasing polyphenol stability and protecting their bioactivity during storage (Khazaei, Jafari, Ghorbani, & Kakhki, 2014; Mahdavi, Jafari, Ghorbani, & Assadpoor, 2014). A summary of the previous research on the spray drying encapsulation of cinnamon bioactives is given in Table 4. Several factors can impact the stability of these compounds and the efficiency of encapsulation during the spray drying process; e.g., wall material:core material ratio, wall material type, feed/flow rate, bioactive concentration, and the inlet temperature.

3.3.1. The wall material:core ratio

Various research studies have utilized different ratios between the wall material and the core material, leading to varied encapsulation efficiencies. Desai and Jin Park (2005) highlighted that a single wall material cannot meet all the requirements, advocating for combined mixtures to produce superior microcapsules compared to those in pure form. In line with this, Vaidya et al. (2006) investigated the efficiencies of three wall materials (gum Arabic, modified starch, and maltodextrin) for cinnamon oleoresin (Table 5). Their findings showed that gum Arabic outperformed maltodextrin and modified starch as a single wall material, with respect to the half-life (t1/2) of volatile (Total volatiles minus the non-volatile portion of the sample extracted with ether), entrapped cinnamaldehyde (cinnamaldehyde within the microcapsule), and total cinnamaldehyde (cinnamaldehyde within the microcapsule and on the surface of the microcapsule). However, when gum Arabic was combined with maltodextrin and modified starch, the $t_{1/2}$ of constituents increased with higher gum Arabic concentrations, while gum Arabic used as a ternary blend resulted in better encapsulation than gum Arabic used alone. The optimal ratio of the three wall materials (i.e., gum Arabic: maltodextrin: modified starch) for improved $t_{1/2}$ and constituent retention of cinnamaldehyde was found to be 4:1:1.

Conversely, Felix, Birchal, Botrel, Marques, and Borges (2017) presented contradictory results in their study, which assessed pure and combined blends of wall materials, excluding ternary blends. They measured EE in terms of entrapped cinnamaldehyde and found that the blend of gum Arabic and maltodextrin (50:50) had higher entrapped cinnamaldehyde than other blends (100% gum Arabic, 100% whey protein isolate, 50% maltodextrin, and 50% whey protein isolate). Notably, Vaidya et al. (2006) did not use whey protein isolate in their study, but they evaluated gum Arabic in pure form and in combination with maltodextrin in the same ratio. The differences in the results between the two studies raise questions about the influence of core materials (oleoresin vs. EO) used in encapsulation. Furthermore, Ascheri, Marquez, and Martucci (2003) conducted a study on orange EO and observed that an increase in gum Arabic concentration led to a

Table 4
Summary of the research on spray drying encapsulation of cinnamon bioactive compounds.

Core material	Wall material	Results	References
Cinnamon oleoresin	Gum arabic (GA), maltodextrin (MD), modified starch (MS)	GA is a better wall material than other wall materials. However, the blend of GA:MD:MS in the ratio of 4:1:1 was more efficient than even 100% GA.	Vaidya et al. (2006)
Cinnamon infusions	MD	The inlet temperature and feed rate that gave the best protection for cinnamon infusions were 160 °C and 180 °C and 10 mL/min. The encapsulation efficiency (EE) was found to be up to 85%.	Santiago-Adame et al. (2015)
Cinnamon oil	GA, whey protein isolate (WPI)/MD, or Polyvinyl alcohol (PVA)	The EE of GA, WPI/MD, and PVA were 90.4%, 94.6%, and 80.7%, respectively.	Kim et al. (2013)
Cinnamon essential oil (CEO)	WPI, MD, Sodium alginate (SA)	The optimum formulation for wall material:core material was 70:30. The EE was over 93%. Retention during storage was over 95% at 50 °C for 30 days.	Hu et al. (2020)
CEO	GA, MD, and Inulin (IN)	The optimum concentration for the wall was 27.87% GA, 27.59% MD, and 44.53% IN.	Shahidi Noghabi and Molaveisi (2020a, 2020b)
CEO	MD and GA	Water content, bulk density, surface oil, and microencapsulation efficiency vary with ratio changes in wall material.	Hermanto et al. (2016)
CEO	SA	The minimum inhibitory concentration of free CEO and microencapsulated cinnamon oil was 125–250 μg/mL and 220.5–440.5 μg/mL respectively.	Makimori et al. (2020)
CEO	GA, WPI, and MD	The best wall material is a combination of GA and MD. Thermogravimetric curves showed higher thermal stability with WPI. The blend of GA and MD had better retention of cinnamaldehyde. The blend of MD and WPI produced more spherical particles.	Felix et al. (2017)
CEO	GA and MD	The highest EE was in the blend of GA and MD in the ratio of 1:1. EE was 84.62%. The shelf life at 30 °C was 20 weeks.	Pratiwi et al. (2016)
Aqueous extract of cinnamon	MD and acacia gum	The stability of bioactive depends on the concentration of the aqueous extract. The blend containing 5% MD and acacia gum had the highest antioxidant capacity.	Ríos-Pérez et al. (2023)

(*continued on next page*)

Table 4 (*continued*)

Core material	Wall material	Results	References
CEO	GA and MD	Degradation onset temperature for the wall material was close to 200 °C, regardless of the relative storage humidity. Samples stored at 4 °C showed the best antioxidant activity. Approximately 2.5% of cinnamaldehyde retention was noted in the first 45 days.	Campelo et al. (2017)
Cinnamon oleoresin	GA and MD	The lightness, texture, total phenol content, and antioxidant activity were significantly affected by the addition of cinnamon microcapsules. The total phenol content and antioxidant activity increased with the addition of cinnamon oleoresin microcapsules.	Praseptiangga et al. (2019)
Cinnamon ethanol extract	MD	The astringency of cinnamon was masked when atomized with MD. MD increased the stability of proanthocyanidin.	Ostroschi et al. (2018)
Cinnamon oleoresin	MD and WPI	EE was greater than 83% 3MD:1WPI was the best formulation.	Ferraz et al. (2022)

Table 5
Entrapped cinnamaldehyde with different wall ratios (modified from Vaidya et al. (2006)).

The ratio of GA:MD:MS	Entrapped cinnamaldehyde ($t_{1/2}$)
100:0:0	150.65
0:100:0	58.24
25:75:0	70.00
50:50:0	100.43
0:0:100	49.50
25:0:75	55.00
50:0:50	66.63
1:1:1	99.00
4:1:1	154
1:1:4	66

significant loss of EO (more than 80%). This loss was attributed to a possible interaction between the EO and gum Arabic. These findings highlight the importance of understanding how the effectiveness of wall materials can vary with different core materials. Therefore, there exists a gap in the literature regarding the reactivity of cinnamon oil and oleoresins with the chosen wall materials used in encapsulation.

Additionally, there is a lack of research comparing various wall materials for the aqueous extract of cinnamon. Further investigations should focus on using different blends of wall materials with different bioactives present in the oleoresin, essential oil, and aqueous extract to determine if each bioactive exhibits distinct reactivity with the chosen wall material used in encapsulation. Such studies will contribute to a comprehensive understanding of encapsulation processes and aid in optimizing encapsulation efficiency for various applications.

3.3.2. The impact of the wall material used for encapsulation

The choice of different wall materials can significantly impact the morphology of the resulting microcapsules. According to Vaidya et al. (2006), microcapsules formed using gum Arabic were nearly spherical with only a few dents, suggesting a well-formed structure. Conversely, when maltodextrin was employed as the wall material, the observed microcapsules appeared broken and incomplete, indicating poor EE. However, the use of a ternary blend consisting of gum Arabic, maltodextrin, and modified starch resulted in spherical microcapsules with a smooth surface, indicating that the ternary blend offers a more suitable solution for effectively encapsulating cinnamon oleoresin.

In another study conducted by Pratiwi, Darmadji, and Hastuti (2016), Fourier transform infrared (FTIR) spectra were analyzed to investigate the interaction between wall materials maltodextrin and gum Arabic. The results indicated that there was no change in absorption at specific positions, suggesting that the interaction between maltodextrin and gum Arabic was purely physical, and no chemical reaction or cross-linking occurred between the two materials. This information can be valuable in understanding the behavior of different wall materials and their suitability for specific encapsulation applications. Therefore, the selection of appropriate wall material plays a crucial role in determining the morphology and efficacy of microcapsules. Combining different wall materials, as demonstrated by Vaidya et al. (2006), can lead to improved microcapsule structures and EE. Meanwhile, studies like Pratiwi et al. (2016) shed light on the nature of interactions between wall materials, providing valuable insights for designing effective encapsulation systems in the future.

3.3.3. The feed rate and the inlet temperature

The research conducted by Santiago-Adame et al. (2015) highlighted the significant impact of feed rate and inlet temperature during spray drying on the percent yield of dried product produced. The study found that the best conditions for encapsulating cinnamon infusion microcapsules were achieved at 160 and 180 °C with a feed rate of 10 mL/min. These conditions effectively preserved both the phenolic content and antioxidant capacity of the microcapsules. Furthermore, the feed rate and inlet temperature also influenced the morphology of the resulting microcapsules. The different rates of water evaporation during spray drying at varying temperatures (160 and 180 °C) could be attributed to the irregular morphology observed. Conversely, smoother surfaces without evident cracks were observed at higher temperatures. This observation was consistent with the findings of Santiago-Adame et al. (2015).

Vaidya et al. (2006) noted different morphologies of microcapsules with changes in the wall material used. However, Santiago-Adame et al. (2015) solely utilized maltodextrins as the wall material and still obtained varying morphologies. This suggests that irregularity in microcapsule morphology may be due to differences in inlet temperature rather than the wall material itself. It becomes evident that the morphology of microcapsules is dependent on multiple factors, including the choice of wall material, the ratio of each wall material, inlet temperature, and the core material.

3.4. Complex coacervation

Complex coacervation is a widely used microencapsulation technique, and several studies employing this method for encapsulating cinnamon bioactives have demonstrated enhanced stability during storage (Comunian et al., 2017; De Souza, Thomazini, Chaves, Ferro-Furtado, & Favaro-Trindade, 2020). The process involves interactions between oppositely charged polyions in an aqueous medium, leading to the formation of coacervates (De Kruif, Weinbreck, & de Vries, 2004).

In the food industry, complex coacervation has gained significant recognition for its versatility in encapsulating hydrophobic compounds, including aromas. However, its applicability extends beyond that, as it can effectively encapsulate various types of compounds such as water-soluble vitamins, sweeteners, and phenolic compounds (De Souza et al., 2018). The use of proteins and polysaccharides as polymers is

common in complex coacervation. For instance, a proanthocyanidin-rich extract encapsulated via complex coacervation exhibited high antioxidant activity and demonstrated the potential to inhibit digestive enzymes (De Souza et al., 2018). The resulting particles from complex coacervation also successfully masked undesirable sensorial characteristics (De Souza et al., 2020).

One of the key advantages of complex coacervation is its ability to achieve controlled and prolonged release of bioactive compounds within the gastrointestinal tract, effectively preventing the undesirable burst release often observed in alternative delivery systems (Johnson & Wang, 2014). Additionally, even when loaded with a high payload of bioactive compounds, complex coacervation maintains an impressive EE of up to 99%, ensuring a significant amount of the compounds are effectively encapsulated (Timilsena, Akanbi, Khalid, Adhikari, & Barrow, 2019). Researchers, such as Holkem and Favaro-Trindade (2020), have successfully produced coacervates by mixing proteins and polysaccharides at a ratio of 6:1, with a pH of 4.2. Utilizing complex coacervation with gelatin and pectin for microencapsulation of cinnamaldehyde demonstrated a substantial increase in the degradation temperature, from 180–220 °C to 350–400 °C (Muhoza et al., 2019).

The advantages of complex coacervation make it a sought-after method for the microencapsulation of EOs, providing benefits such as achieving high payload, enhancing thermal stability, and facilitating the sustained release of the core material (Muhoza et al., 2022). However, this approach also comes with certain constraints, including sensitivity to pH and salt levels, as well as the tendency to generate aggregates with a significant average particle size (Ifeduba & Akoh, 2015). Thorough exploration is required to effectively utilize complex coacervates and understand the impact of protein and cinnamon bioactive interactions on the properties, stability, and release characteristics of micro/-nanocapsules (Muhoza et al., 2023).

3.5. Liposome entrapment

Liposomes are highly desirable systems for encapsulating a wide range of substances, offering improved stability against environmental factors, enzymes, and chemicals. They exhibit resilience against extreme pH levels, temperature changes, and variations in ionic strength, making them extensively employed in the pharmaceutical and food industries. Their compatibility with living organisms, natural degradation, lack of toxicity, small size, and ability to transport diverse bioactive compounds have led to their application in delivering cinnamon bioactive compounds within food systems (Cui, Li, Li, Vittayapadung, & Lin, 2016).

Composed of a spherical lipid bilayer, with hydrophilic groups forming the aqueous core and lipophilic groups constituting the hydrophobic outer layer, liposomes function as colloidal carriers with several advantages, including biocompatibility, enhanced bioavailability, solubilization of insoluble compounds, and the capacity for sustained-release properties (Kim & Baianu, 1991). This technique often yields lower encapsulation efficiencies. In the research conducted by Cui et al. (2016), the entrapment efficiencies ranged from 18% to 29%.

Despite the lower entrapment efficiency, liposomes obtained in the study had a small average particle size (144.3 ± 1.08 nm) and a high Zeta potential (<−30 mV), indicating favorable dispersibility and stability. Additionally, liposomes demonstrated the ability to effectively entrain a sufficient concentration of antibacterial agents. For example, the liposome entrapment process retained 40%–50% of eugenol, whereas the direct emulsification method only retained 1%–2% of eugenol. This underscores the effectiveness of encapsulating volatile active compounds in liposomes for obtaining antimicrobial films enriched with EOs (Valencia-Sullca et al., 2016).

The benefits of liposomal encapsulation extend to various applications, such as in broiler chickens where liposome-encapsulated CEO exhibited antioxidant and antibacterial properties. It also improved tight junction proteins, gut barrier functions, and digestive enzymes in poultry, making it a promising dietary inclusion for poultry farming (Meligy et al., 2023). Liposome-encapsulated cinnamaldehyde also demonstrated prolonged antibacterial activity by disrupting cell membrane integrity, proving to be more effective than pure cinnamaldehyde. Even after 28 days of storage, the antibacterial efficiency remained greater than 90% (Chen, Cheng, Swing, Xia, & Zhang, 2019; Wang et al., 2021). However, liposome entrapment does come with inherent limitations, including a relatively short half-life, hydrolysis of the phospholipid bilayer, leakage of the encapsulated material, and fusion of the liposome core. Additionally, producing liposomes on a large scale presents challenges, particularly in achieving both low average particle size and high EE (Muhoza et al., 2023). Nevertheless, ongoing research and development in this field may help address these limitations and unlock the full potential of liposomes for various encapsulation applications in the future.

3.6. Emulsions

An emulsion is formed by combining two liquids that do not mix, typically oil and water, where one liquid is dispersed in the form of tiny spherical droplets within the other. A system containing dispersed oil droplets within an aqueous phase is referred to as an oil-in-water (O/W) emulsion, whereas a system with water droplets dispersed within an oil phase is termed a water-in-oil (W/O) emulsion (Lu, Kelly, & Miao, 2016). Various methods, including homogenization, sonication, high-pressure homogenization, and phase inversion, are employed to create emulsions with varying particle size distributions (Zhang, Liu, Wang, Jiang, & Quek., 2016).

Emulsions offer a solution to the limited application of cinnamon essential oils as natural preservatives due to their hydrophobic nature (Jiménez, Domínguez, Pascual-Pineda, Azuara, & Beristain, 2018). Surfactant-free emulsions using Cinnamon cassia oil (C. cassia oil) and partially deacetylated chitin nanofiber (ChNF) as a stabilizer exhibited improved antibacterial effects and diffusion efficiency, proving to be efficient encapsulated delivery system, for essential oils (Huang, Liu, Liu, & Li, 2020). The concentration of the essential oil and the pH can influence the encapsulation efficiency, droplet size, zeta potential, and morphology (Jiménez et al., 2018). The average particle size increased with the increased concentration of the essential oil (Razavi et al., 2020). Jiménez et al. (2018) found that nano emulsions of cinnamon essential oil exhibited greater physical stability compared to micro emulsions. The same study also highlighted that the nanoemulsion of cinnamon essential oil processed with ultrasound method exhibited improved physicochemical stability and enhanced antimicrobial efficacy against *Listeria monocytogenes* and *Escherichia coli*. Thus, emulsions have the potential to serve as effective delivery systems for cinnamon essential oil in antimicrobial applications, contributing to food safety and preservation (Wang et al., 2018).

4. Stability of encapsulated cinnamon bioactive compounds

Despite the well-documented benefits of cinnamon bioactives, their practical utilization encounters substantial challenges due to inherent instability during storage and processing. Factors such as exposure to light, temperature fluctuations, and oxygen can lead to the degradation of cinnamon bioactives over time giving rise to challenges such as light-induced degradation, a short shelf life, low solubility, poor permeability, uncontrolled release leading to leakages and slow diffusion, bioactive degradation during handling, storage, and processing, as well as volatile loss and lipid oxidation Additionally, interactions with the food matrix may further compromise their overall stability. Considering these challenges, encapsulation has emerged as a promising solution to overcome the issues of instability while enhancing the functionality of bioactives by improving benefits such as improved antioxidant activity, improved anti-inflammatory activity and anti-diabetic activity. By entrapping the cinnamon bioactives within protective matrices, encapsulation can effectively shield them from external influences, leading to

improved preservation and sustained release, thus unlocking their full potential for various applications.

The stability assessment of encapsulated compounds involves evaluating various parameters to gauge their physical, chemical, and functional stability. Physical stability encompasses the ability of the encapsulated product to retain its physical characteristics, such as particle size, morphology, and dispersibility. To assess physical stability, previous studies have utilized particle size analysis, morphology examination, sedimentation analysis, and rheological measurements. On the other hand, chemical stability refers to the capability of the encapsulated compounds to resist degradation. This aspect is assessed through compound degradation analysis, oxidation analysis, and pH stability evaluation.

Meanwhile, functional stability is evaluated by conducting *in vitro* or *in vivo* assays to determine the bioactivity and effectiveness of the encapsulated products. Additionally, release kinetics analysis and storage stability analysis are carried out to understand the release patterns of the encapsulated compounds over time and their stability during storage, respectively. By comprehensively assessing these different stability parameters, researchers can gain valuable insights into the performance and effectiveness of the encapsulation process, helping to optimize the encapsulation technique for various applications.

4.1. Morphology

The morphology of microparticles plays a crucial role in determining the physical stability of the capsules, as the presence of cracks can lead to the loss of volatile compounds from the microcapsules. Scanning

Table 6
Morphology of micro/nanoparticles containing cinnamon bioactives manufactured using different wall materials.

Wall material	Morphology	Discussion	References
Maltodextrin (MD) and gum arabic (GA)	Not completely spherical, most have a deflated shape.	The deflated shape was due to the water vapor formation at high temperatures during spray drying. Loss of volatile components can happen during this process.	Pratiwi et al. (2016)
GA, whey protein isolate (WPI), and MD	GA produced spherical particles, WPI produced rougher particles, and MD lowered the roughness with WPI but increased the roughness for GA. No cracks were evident. Particle size distribution was from 1.65 to 1.92 μm.	This can be because the GA sample had the essential oil (EO) concentrated in the center giving it a spherical appearance. The other samples showed the oil dispersed over the wall material giving it an irregular shape.	Felix et al. (2017)
GA, MD, and modified starch (MS)	The microcapsules formed from GA:MD:MS (4:1:1) were spherical and had a smooth surface. The particles formed from GA were nearly spherical but with dents. The particles from MD and MS were broken and not complete.	The obtained smooth surface shows that the blend of GA: MD:MS was much more suitable for encapsulation rather than being used individually.	Vaidya et al. (2006)
Gelatin, pectin, cashew gum, carboxymethyl cellulose, k-carrageenan	An irregular shape was observed.	The irregularity may be because of the interaction between polyphenol rich cinnamon extract (PRCE) and the wall material. A more regular shape was observed when the extract concentration was lowered. Thus, there may be an interaction between PRCE and wall material, especially gelatin.	De Souza et al. (2018)
Sodium alginate (SA)	A spherical homogenous surface with no evident cracks was observed.	This morphology is advantageous to increase Cinnamon essential oil (CEO) protection and retention and reduce CEO permeability.	Makimori et al. (2020)
	Spherical with a slight crack. GA:MD:Inulin (IN) (27.87:27.59:44.53) showed a higher smooth surface.	Particles consisting of IN were more smooth, spherical, and dent-free. This may be because IN has good elasticity.	Shahidi Noghabi and Molaveisi (2020a, 2020b)
WPI, MD, and SA	Single discrete particles. Irregularly shaped particles were formed with increasing WPI/MD ratio. Smoother particles with low WPI/MD ratio.	The level of the essential oil on the surface is very low because the high level of oil on the surface can lead to agglomeration. When MD is present a softer and more porous crust. The Crust appears denser after SA is added. Porosity can be improved by adding SA.	Hu et al. (2020)
WPI, MD	Irregular surfaces with cavities. Particles having WPI only presented smoother surfaces. Some particles showed shrinkage of structure (MD:WPI, 3MD:1WPI, 1MD:3WPI). MD treatments produced particles with pores.	Particles with hollows are characteristic of spray-dried microparticles. Shrinkage of structure was due to water evaporation during atomization. The reduced emulsifying capacity of MD was due to the absence of proteins.	Ferraz et al. (2022)
MD	Deflated balloon shape, rough surfaces with cavities, and structural cracks. The temperature of 160 and 180 °C and feed rate of 10 mL/min produced defined semi-spherical particles with no evident cracks. Particles produced at the rate of 8 -mL/min produced irregular surfaces and particle agglomeration.	Surface irregularities could be due to the water evaporation rates during spray drying. Smoother and defined surfaces were observed at higher temperatures as faster evaporation happened.	Santiago-Adame et al. (2015)
MD	Microparticles were spherical with or without MD. Concavities were observed and the particles were of various sizes. No cracks or fissures on external surfaces even without a carrier. However, the ones produced with carriers had fewer concavities and were more spherical. Particles produced at higher temperatures with MD had less shrinkage. One formulation presented broken walls (MD 10 DE 20 g/100 g of PRCE, T = 160 °C).	The particles were more spherical with fewer concavities with MD because of the larger expansion capacity during dehydration in the presence of MD. Lesser shrinkage was observed with MD because higher temperatures induce a higher coefficient of heat transfer leading to higher expansion, less shrinkage, and thin walls. The broken particles show that the walls were too thin for that formulation (approximately 1.5 μm).	Ostroschi et al. (2018)
GA, WPI/MD, polyvinyl alcohol (PVA)	GA produced the smallest particle. WPI/MD particles were the largest. The diameter was greater than 10 μm. Those made of WPI/MD and PVA were spherical. While those from GA were hollow.	Hollow particles are due to the formation of vapor bubbles inside the emulsion.	Kim et al. (2013)
MD, GA	Ratio variations of the coating agents significantly affected physical characteristics, especially water solubility. Microcapsules ranged from 1.92 to 30.8 μm. Microcapsules created through spray drying, with polysaccharide used as the coating material, exhibited a distinct surface.	This phenomenon can be attributed to various factors, including the composition of the coating agents, the atomization and drying process, the formation of irregular wrinkles during the initial drying stage, and the influence of the solution's surface tension.	Hermanto et al. (2016)

electron microscopy (SEM) is a valuable tool for observing both the internal and external morphology of the formed capsules, providing essential insights into their structural integrity.

The choice of encapsulation technique and wall material significantly influences the resulting morphologies, underscoring the importance of selecting appropriate parameters to achieve the desired encapsulation outcomes. Table 6 provides a summary of the different morphologies attained using various encapsulation techniques and wall materials for cinnamon compounds, helping to compare and understand the effectiveness of different approaches in preserving the integrity and stability of the encapsulated bioactive compounds. By carefully considering and optimizing the morphological characteristics of the microcapsules, researchers can enhance the overall performance and efficacy of the encapsulation process for cinnamon compounds and other similar applications.

4.2. Particle size

Particle size is a critical characteristic of formed microcapsules with implications for encapsulation confirmation and overall product stability. Generally, the particle size increases after coating, which is often verified through laser diffraction analysis. The amount of core material used affects particle size, subsequently influencing emulsion stability (Gong, Lee, Godec, Zhang, & Abbaspourrad, 2020). Larger particle sizes (>63 μm) reported by Jafari, He, and Bhandari (2007) retain more volatiles, while smaller particles (<38 μm) exhibit more unencapsulated oil on their surface. In the application of food ingredients, particle size plays a significant role as excessively large particles may lead to an undesirable mouthfeel, although larger particles can be intentionally desired for products with visible particles (De Souza et al., 2018).

Changes in average particle size can cause coalescence and flocculation, impacting system color, stability, and heat resistance (Mao, Roos, Biliaderis, & Miao, 2017; Mcclements, 2007). Larger particles exhibit improved heat stability due to thick interfacial membranes, while smaller particles tend to have higher antimicrobial activity due to a larger surface area facilitating easy interaction with bacterial membranes. Moreover, larger particles allow for prolonged release of active compounds, sustaining the desired effects over an extended period (Trinh, Shaari, Basit, & Azeem, 2014). Conversely, smaller particles promote rapid diffusion and core release (McClements & Li, 2010). For instance, in a study by Yang et al. (2021), CEO nanocapsules were obtained using the nanoprecipitation method with chitosan and whey protein isolate as wall materials, resulting in a particle size range between 100 and 200 nm. De Souza et al. (2018) observed a wide range of particle sizes (26–149 μm) when employing different combinations of wall materials in their research. The smallest particle size was achieved using gelatin and cashew gum as wall materials, while the largest particle size was obtained with gelatin and carrageenan. These findings underscore the significant influence of selected wall materials on determining particle size and, consequently, the stability of the encapsulated product. Accordingly, understanding and controlling particle size through appropriate wall material selection and encapsulation techniques are crucial steps in achieving desired functional and stability attributes of microcapsules for various applications.

4.3. Oxidation analysis

The application of spray drying and lyophilization processes to proanthocyanidin-rich cinnamon extract resulted in a reduction in phenolic compounds and their antimicrobial activity compared to the original liquid extract. This decline can be attributed to the high temperatures used during the drying process, which may lead to the thermal degradation of the bioactive compounds. However, these processes led to an enhancement in antioxidant capacity and the inhibition of digestive enzymes, specifically α-amylase and α-glycosidase, particularly evident in the dry extract obtained through spray drying (Santiago-Adame et al., 2015). It is noteworthy that the antioxidant capacity and enzyme inhibition properties were positively influenced by the drying techniques.

Microencapsulation, as observed in the research by Hu et al. (2020), played a vital role in protecting the CEO during storage. The higher fluorescence intensity of the free CEO compared to the encapsulated CEO, stored under similar conditions, suggests that microencapsulation effectively shielded the CEO from degradation and oxidative processes. Furthermore, Shahidi Noghabi and Molaveisi (2020a, 2020b) demonstrated that encapsulated cinnamon oil exhibited more antioxidant stability compared to its free counterpart. This observation was evident in the reduction of inhibitory percentage and the steeper slope observed in the free cinnamon oil, indicating that the encapsulated form retained greater antioxidant stability over time.

The findings from these studies highlight the potential of microencapsulation techniques, such as spray drying and lyophilization, in preserving and enhancing the functional properties of cinnamon bioactives. By protecting the bioactive compounds from degradation and enhancing their antioxidant capacity and enzyme inhibition properties, microencapsulation proves to be a valuable approach for ensuring the stability and efficacy of cinnamon extracts and EOs for various applications.

4.4. Rheological measurements

Rheology is the study of the deformation and flow of fluids and materials and their response to applied strain or stress (Rao & Rao, 2014). Rheological measurements can provide valuable insights into the microscopic arrangement of a fluid as it undergoes shear or heat treatment, allowing for the assessment of its flow properties (Ahmed, 2018). In encapsulation processes, the rheological characteristics of polysaccharides, proteins, and lipids are of utmost importance as these biopolymers are commonly employed as protective wall materials for the core substance (Rao & Rao, 2014).

As demonstrated by Santiago-Adame et al. (2015), temperature significantly impacts the shear flow rate stability of cinnamon infusions during the spray drying process. The observed effect was attributed to thermal degradation or oxidation of the microparticles during the drying process. The research findings revealed that spray-dried cinnamon infusions exhibited high viscosity and a more stable mechanical response when subjected to 160 °C. Therefore, understanding the rheological behavior of materials used in encapsulation processes is essential for optimizing formulation and processing conditions, leading to improved stability and performance of the encapsulated products. Rheological studies offer valuable data to tailor encapsulation techniques and choose appropriate wall materials for specific applications, ensuring the successful protection and delivery of bioactive compounds like cinnamon infusions.

4.5. Release profile

Achieving sustained release of bioactive compounds is a crucial objective in encapsulation. Particles are designed and encapsulated to release the bioactives under specific environmental conditions, and understanding the release profile is essential to determine the expected storage duration and release behavior of the encapsulated core. In a study by Santiago-Adame et al. (2015), high feed rates during the encapsulation process led to higher concentrations of the bioactive inside the microcapsules, resulting in approximately a 10% increase. The release of the core lasted for approximately 36 h, which was influenced, in part, by the mechanical stability required for proper flow during the encapsulation process.

The release behavior of polyphenols from dried nanoparticles was investigated under different pH conditions (Muhammad et al., 2020). A rapid release of approximately 40% was observed in the first 15 min, attributed to the loosely attached polyphenols on the surface.

Subsequently, the release levels remained constant. However, when the pH increased to 7.4 (alkaline), the release of phenolic content increased significantly, reaching 90%. This pH sensitivity in the release profile allows for controlled release, restricting uncontrolled release and enabling targeted release triggered by the alkaline pH of the intestines.

In a study by Makimori et al. (2020), the *in vitro* release profile of free and microencapsulated CEO) was analyzed. The free EO rapidly released within 360 min, while encapsulated CEO using hydroxypropyl-β-CD exhibited a slower release profile. The encapsulated form achieved a release rate of 21.18% until 100 min, indicating the effectiveness of encapsulation in slowing down the release. Moreover, by increasing the concentration of hydroxypropyl-β-CD from 10 to 30 g/L, an extended-release time was achieved, extending from 240 to 360 min. These studies demonstrate the significance of understanding the release profiles of encapsulated bioactive compounds. By tailoring the encapsulation process and formulation to control release, researchers can achieve sustained and targeted release of bioactive compounds, enhancing the efficacy and applications of encapsulated products.

4.6. Compound degradation analysis

Encapsulation efficiency (EE) is a crucial parameter that indicates the amount of bioactive effectively encapsulated, serving as an indicator of compound protection against environmental stress factors like oxygen, moisture, pH, and temperature. Table 3 provides an overview of the encapsulation efficiencies obtained in different studies. A high EE is desirable as it reflects a strong level of protection for the encapsulated bioactive. The interaction between the core and wall material, along with the concentration and preparation technique, plays a pivotal role in determining EE.

Various studies employ different methods to determine EE based on the bioactive of interest. For instance, Yang et al. (2021) extracted surface oil and total oil from freeze-dried particles to determine the EE of cinnamon oil, while De Souza et al. (2018) determined the EE of the aqueous extract based on the percentage of phenolics present. Some studies express EE in terms of cinnamaldehyde percentage, as it is the primary component in the oil (Farahmand, Emadzadeh, Ghorani, & Poncelet, 2022). The concentration of both core material and wall material can impact EE. Muhammad et al. (2020) observed a reduction in EE with increasing concentrations of core material and wall material. This decrease was attributed to an increase in viscosity resulting from higher concentrations of the wall material (xanthan gum). Additionally, the reduction in EE was directly proportional to the loading capacity. In contrast, Farahmand et al. (2022) found that increasing alginate concentration could enhance EE by forming thick and dense shells, effectively preventing oil leakage.

Yu et al. (2023) reported the highest EE (50.19% ± 0.38) in particles with an EO concentration of 50 μL/mL, with a weak encapsulation interaction observed at lower EO concentrations. The EE can be influenced by various factors such as the ratio of the carrier material to the bioactive and the solubility of the encapsulant within the polymer matrices (Yu et al., 2023). Additionally, Ferraz et al. (2022) noted significant compound degradation at 45 °C, leading to color changes and increased moisture, underscoring the importance of considering temperature effects on EE. Accordingly, the knowledge of EE and its optimization is critical in ensuring the effectiveness and stability of encapsulated bioactives, contributing to the successful utilization of encapsulation techniques for various applications.

4.7. Zeta potential

The zeta potential measurement is a crucial indicator used to assess the stability of colloidal systems. Various factors, including pH, particle composition, and the ionic strength of the medium, significantly contribute to the zeta potential, which represents the surface charge and potential distribution at the interface of a colloidal particle in a liquid medium. A zeta potential value ranging from ±30 to ±60 mV indicates a high electrostatic repulsion between particles, leading to better dispersion and enhanced stability of the colloidal suspension. Conversely, a low zeta potential of ±20 mV suggests reduced colloidal stability, and a change in its value towards zero can result in particle agglomeration and sedimentation, leading to decreased stability of the colloidal system (Honary & Zahir, 2013).

The zeta potential of particles also influences the diffusion of the core material and its interaction with bacterial cell membranes (Muhoza et al., 2023), further emphasizing its importance in encapsulation systems. Table 7 provides examples of obtained zeta potential values for cinnamon bioactives, showcasing their colloidal stability and potential applications. Hence, understanding and controlling the zeta potential of colloidal systems can help researchers optimize the stability and functionality of encapsulated bioactives, ensuring their successful delivery and potential applications in various fields.

4.8. Storage stability

Numerous studies in the literature have investigated the storage stability of encapsulated cinnamon bioactives by assessing the retention rate of these compounds in the encapsulated product under various

Table 7
Examples of zeta potential of encapsulated cinnamon bioactives.

Method of encapsulation	Zeta Potential	Discussion	References
Ion gelation	<30 mV	The zeta potential decreased with the increase in cinnamon essential oil (CEO) concentration. This is because larger particles were formed with increasing CEO, resulting in the weakening of repulsive forces.	Yu et al. (2023)
Precipitation	31.7 ± 1.27 mV	CEO nanocapsules were stable when produced with chitosan (CS) and whey protein isolate (WPI).	Yang et al. (2021)
Antisolvent precipitation	Zeta potential > −40 mV	The increase in xanthan gum concentration had a significant influence on the zeta potential of the nanoparticles. Since xanthan gum is a negatively charged biopolymer with a high surface charge density, a higher percentage of xanthan gum resulted in more negative zeta potential values.	Muhammad et al. (2020)
Spray drying	Zeta potential < −30 mV	The system with WPI provided negative zeta potentials less than −30 mV.	Hu et al. (2020)
Saturated aqueous solution, molecular inclusion, and ultrasonic methods	Zeta potential< ±30 mV	The presence of cinnamaldehyde, the main component of CEO, with its positively charged carbonyl group, exhibited an affinity towards the negatively charged Highland barley starch, resulting in the neutralisation of some of the negative charge. Overall, those produced via molecular inclusion had better stability.	Li et al. (2020)

temperatures and over specific periods. The consistent findings across these studies demonstrate that encapsulation serves as a protective measure, effectively preventing degradation and extending the shelf life and usability of the product. Notably, storage at 25 °C is considered favorable for preserving cinnamon bioactives (Hou et al., 2021; Hu et al., 2020; Yin et al., 2019). Table 8 provides examples of selected studies that have examined the storage stability of cinnamon bioactives.

Collectively, these studies underscore the efficacy of encapsulation techniques in safeguarding the bioactives present in cinnamon, ensuring their stability and functionality over extended storage periods. However, there is still a need for further research to explore additional encapsulation methods and optimize storage conditions for cinnamon bioactives. Table 8 presents an overview of some of the work conducted on the storage stability of cinnamon bioactives, highlighting the progress made in this area. As a result, further exploration into the storage stability of encapsulated cinnamon bioactives holds the key to unleashing the complete potential of these compounds across diverse applications. This endeavor guarantees their excellence and efficacy throughout the entire duration of their shelf life.

Table 8
Example of experimentations of storage stability of cinnamon bioactives.

Storage Temperature (°C)	Storage Days	Result and Discussion	References
25 and 45	90 days	Bioactive compounds significantly degraded at 45 °C, resulting in color change, increased moisture, water activity, and particle size. Those containing a higher proportion of whey protein isolate (WPI) had better protection than maltodextrin (MD).	Ferraz et al. (2022)
30 to 70	4 weeks	Total oil content reduced with the increasing temperature. Surface oil, Total oil, and entrapped oil were reduced with the increase in the length of time of storage.	Pratiwi et al. (2016)
25	14 days	The microcapsules produced in the study exhibited uniform size and achieved the sustained release of essential oil for over 168 h. The coated mangoes inhibited the decline in titratable acid, soluble solids, and vitamin C contents and slowed the rate of weight loss and pH increase, delayed the occurrence of mango respiration peaks, and maintained firmness during storage conditions of 25 °C and 50% relative humidity.	Yin et al. (2019)
25, 37 and 50	1, 7, 15, 30, 60, 90 days	The capsules stored at 25 °C were the most stable ones with a retention rate of 95.9% after 90 days. The capsules stored at 50 °C were the most unstable with a retention rate below 87.1% for the same period.	Hu et al. (2020)
4 and 25	9 weeks	The wall materials can have an impact on storage stability. When comparing the wall materials inulin (IN), MD, and gum arabic (GA), a formulation consisting of IN and MD has better stability of compounds, compared to wall materials of only GA.	Shahidi Noghabi and Molaveisi (2020a, 2020b)
4, 25, and 40	60 days	The nanoemulsion maintained its stability throughout a 60-day storage duration at 4, 25, and 40 °C.	Hou et al. (2021)

The examination of stability indicates that factors such as choice of encapsulation method, encapsulation matrix, chemical interactions, storage conditions, and duration of storage have a notable impact on the overall stability of the encapsulated compounds and demand meticulous attention and consideration.

5. Effectiveness of encapsulated cinnamon bioactive compounds

Various delivery systems, including liposomes, emulsions, nanoparticles, complex coacervation, molecular inclusion, and spray drying, have been successfully utilized for encapsulating cinnamon bioactives, providing enhanced stability and sustained release. Each delivery system offers distinct advantages and considerations. The application of spray drying though rapid, can result in the degradation and reduction of certain heat-sensitive compounds in cinnamon bioactives, especially cinnamaldehyde.

Complex coacervation, involving the interaction of oppositely charged polyelectrolytes, enables high payload and sustained release of core materials but may lead to irregular powder formation and poor solubility (Prata & Grosso, 2015). Research conducted by De Souza et al. (2018) confirmed that complex coacervation can be used to mask the undesirable sensorial characteristics of cinnamon bioactives. To preserve heat-sensitive compounds, it is advisable to opt for freeze-drying rather than spray drying during the final stage of production when drying the coacervate. Research findings have indicated a noticeable loss of proanthocyanidins when spray drying was employed after coacervation.

Liposomes, characterized by their cell-like membrane structure, high biocompatibility, and targeted release capabilities, have shown promise as carriers for bioactive compounds. However, the susceptibility to phospholipid layer oxidation and hydrolysis poses limitations to their application in encapsulating cinnamaldehyde giving rise to lower encapsulation efficiencies (Cui et al., 2016).

Molecular inclusion enhances the solubility, stability, and bioaccessibility of poorly water-soluble bioactive compounds. It masks taste and odor, reduces volatility and irritation, and provides improved chemical stability (Nedovic et al., 2011). However, challenges arise due to host-guest recognition, compatibility of reactants, and limited solubility of CD in water.

Each encapsulation technique has its advantages and limitations (Table 9), and the choice depends on factors such as the desired release profile, stability requirements, and the specific characteristics of the cinnamon bioactive compounds. It is important to consider these factors and conduct further research and experimentation to determine the most suitable encapsulation technique for a particular application.

Factors such as bioaccessibility, chemical stability, compatibility with the food matrix, scalability, and cost should be considered when choosing an encapsulation system for cinnamon bioactives. The alignment of the method with the desired physicochemical properties of the wall materials and the specific goals of the encapsulation process is an important parameter.

6. Potential applications of encapsulated cinnamon bioactive compounds

Encapsulated cinnamon bioactives have garnered recognition in various applications due to their enhanced stability, controlled release, and improved dispersibility. They find utility in diverse industries such as food and beverages, nutraceuticals, pharmaceuticals, cosmetics, and personal care products. Numerous studies have demonstrated the strong

Table 9
Comparison of the advantages and disadvantages of different encapsulation techniques.

Encapsulation method	Advantages	Disadvantages
Spray drying	• High encapsulation efficiency •Scalability •Production of fine particles •Improved stability	•Thermal degradation of compounds •Loss of volatile compounds •Equipment complexity and cost
Molecular inclusion	•Improved stability •Retention of bioactivity •Versatility •Selective encapsulation •Increases water solubility of core material •Protection of heat-sensitive compounds	•Host-guest compatibility issues •Encapsulation selectivity •Difficulty in controlled release •The cost associated with specific host molecules
Complex coacervation	•Protection of bioactive compounds •Controlled release •High encapsulation efficiency •Versatile encapsulation	•Additional steps for cross-linking •Limited scalability •Sensitivity to process parameters •Wider particle sizes
Ionic gelation	•Involves mild process conditions. •Scalability •Controlled release •Biocompatibility •Versatile	•Limited stability •Diffusion limitations •Gel brittleness •Limited compatibility with bioactive •Challenges of crosslinking optimization
Emulsification	•Versatile •Efficient encapsulation •Enhanced stability •Controlled release •Compatibility	•Emulsion instability •Selection of emulsifier •The challenge of achieving homogeneity •Sensitivity to process conditions
Liposome entrapment	•Biocompatibility •Versatile •Controlled release •Enhanced stability •Retards thermal decomposition •hydrophobic, hydrophilic and amphiphilic molecules can be incorporated	•Complexity of preparation •Limited encapsulation efficiency •Physical instability •High cost of production •Particle size not controllable

antimicrobial activity of encapsulated CEO against fungi, bacteria, and viruses (Chen et al., 2019; Hill et al., 2013; Wang et al., 2021). One study observed that encapsulated cinnamon showed bacteriostatic action against *B. thermosphacta*, *L. monocytogenes*, and *E. coli*, and bactericidal action against *Y. enterocolitica*. The controlled release of CEO from the encapsulated form allowed for effectiveness even at lower concentrations (Simionato, Domingues, Nerin, & Silva, 2019), making cinnamon bioactives a potential natural antimicrobial agent. Encapsulated CEO finds applications in active food packaging, where stable active agent formulations are required. Research has also shown that edible biofilms with enhanced antimicrobial activity can be developed using cinnamon (Sharma, Dhanjal, & Mittal, 2017). These coatings have the potential to slow down biochemical reactions and increase the shelf life of products.

Cinnamon is known to possess numerous health benefits, such as treating diseases like Parkinson's and Alzheimer's, diabetes, cardiovascular diseases, oxidative stress, and cancer (Błaszczyk, Rosiak, & Kałużna-Czaplińska, 2021). This makes cinnamon a potential natural pharmaceutical for the treatment of several health issues. And a hopeful ingredient for functional foods (Gunes-Bayir, Bilgin, Guclu, Pogda, & Dadak, 2022; Muhammad & Dewettinck, 2017). However, the low bioavailability and fast systemic clearance of the bioactive compound limit its *in vivo* activities (Han, Koo, & Choi, 2022). Encapsulation of cinnamon has proven to overcome these limitations and enhance its bioavailability (Fachriyah, Eviana, Eldiana, Amaliyah, & Sektianingrum, 2017).

A study by Meghani et al. (2018) demonstrated that oil-in-water nanoemulsions of cinnamon oil have cytotoxic, genotoxic, and antibacterial potential in murine cell lines, making them a potential carrier for lipophilic nutraceuticals like vitamin D. Research with CEO has also shown that stable nano creams can be prepared, which find interesting applications in the cosmetic industry, given that cinnamon oil contains a high percentage of eugenol with antioxidant, antimicrobial, and anti-inflammatory properties (Zainol, Ming, & Darwis, 2015).

The application of CEO on fruits has shown promising results, including delayed post-harvest senescence, inhibition of molds and yeasts, reduced loss of soluble dry matter, decreased reactive oxygen species, and positive effects on antioxidant metabolism (Piechowiak & Skóra, 2023). Cinnamon thus contributes significantly to fruit preservation and enhances fruit quality during storage, extending shelf life (Carvalho et al., 2016; Piechowiak, Grzelak-Błaszczyk, Sójka, Skóra, & Balawejder, 2022; Piechowiak & Skóra, 2023). Researchers have also explored this application on fresh fish and meat and have observed increased refrigeration shelf life (Fernández-Pan, Carrión-Granda, & Maté, 2014; Joukar, Hosseini, Moosavi-Nasab, Mesbahi, & Behzadnia, 2017). Moreover, a study by Nguyen, Tran, and Vu (2022) observed that cinnamon nanoemulsions can be used to protect plants from *Alternaria alternata* due to their antifungal activity, making them a useful application against leaf spot disease that causes reduced crop yield and weakens the plant in horticulture. The efficacy of encapsulated cinnamaldehyde was carried out against *Pseudomonas syringae* pv. *pisi,* the pathogen responsible for pea bacterial blight. The results indicated a notable improvement in its biocidal activity, as evidenced by a substantial 143.58% increase in the number of symptomless plants observed within twenty days after sowing (Cadena et al., 2018). Encapsulation can also be used to protect the cinnamon flavor and provide heat stability during baking applications while reducing the cinnamaldehyde's ability to inhibit the growth of yeast in bakery products (Gong et al., 2020). Cinnamon oil emulsion droplets have demonstrated protection against Fumonisin B1 and aflatoxin B1, which are common fungal metabolites frequently found together in food items and recognized as the causative agents of mycotoxicosis and various forms of primary cancers (Abdel-Wahhab, El-Nekeety, Hassan, Gibriel, & Abdel-Wahhab, 2018). Overall, the encapsulation of cinnamon bioactives offers a multitude of valuable applications across various industries, and ongoing research in this area continues to unveil new possibilities for harnessing the potential benefits of cinnamon in different fields.

7. Challenges and future perspectives toward the use of encapsulated cinnamon bioactives

While the utilization of encapsulated cinnamon bioactives offers a range of benefits, several challenges can be noted with its application. One concern is related to the potential risks of nanoparticles penetrating biological membranes and accumulating in organs, such as the liver (Barlow et al., 2009). Although the wall materials used in encapsulation are generally considered food-grade, there may still be risks associated with converting them into nano and microparticles, potentially leading to harmful imbalances in homeostasis when consumed in concentrations greater than what is typically found in a normal diet (Jafari & McClements, 2017; Rashidinejad & Singh, 2021). To mitigate these concerns, it is advisable to use carriers of natural origin, such as proteins and polysaccharides, that are digestible and less likely to cause harm.

Additionally, inhalation of nanoparticles can cause inflammatory reactions, fibrosis, and necrosis of lung tissues (Inoue & Takano, 2011). Studies have also indicated that nanoparticles may accumulate in the brain, especially if they are very small (<10 nm) and/or the blood-brain barrier is compromised (Najahi-Missaoui, Arnold, & Cummings, 2020). Furthermore, research involving various animal models has shown that nanoparticles tend to accumulate in various organs, interact with cellular macromolecules, and induce oxidative stress (Donaldson, Stone, Tran, Kreyling, & Borm, 2004). Most studies focusing on improving the

stability and bioavailability of cinnamon bioactives through nano/-microcarriers are conducted in simulated environments. However, the human body's physiological environment is much more complex, making it necessary for future studies to include animal or clinical experiments. Nevertheless, the lack of proper risk assessments for nanoparticles in the human body presents a significant challenge for such experimentation.

Another challenge lies in the absence of proper legislation governing the use of encapsulated products in various industries. While the European Food Safety Authority, World Health Organization, and Food and Agriculture Organization have assessed the risks and applications of nanotechnology in food, there is no clear regulation regarding the use of encapsulated compounds in different food categories or industries (Von Wright, 2007). Addressing this regulatory gap is essential for the safe and responsible application of encapsulated products.

Cost and scalability are also significant challenges for encapsulation applications. Further research should focus on developing cost-effective encapsulation techniques that utilize by-products and wastes from the food industry. Optimizing processing parameters, such as solvent usage, equipment usage, and drying methods, can help reduce costs without compromising the quality and stability of the encapsulated bioactives.

Consumer acceptance and perception of encapsulated products also play a critical role in the market penetration of encapsulated bioactives. Past research has shown that encapsulated cinnamon bioactives, with improved taste, texture, and appearance, received better sensory scores than unencapsulated products (Prastuty, Kaur, & Singh, 2021). Hence, increasing consumer awareness of the benefits of encapsulated bioactives can further enhance their acceptance in the market. The utilization of sustainable encapsulation materials such as polysaccharides and proteins are also gaining importance due to environmental concerns associated with petroleum-based polymers (Yang et al., 2022). However, there is also a rising concern that the production of biodegradable polymers is associated with adverse land use and greenhouse gas emissions. Research efforts should focus on exploring the life cycle evaluations of these encapsulating materials to develop biodegradable and renewable encapsulation materials to reduce environmental impact and enhance sustainability. Thus, although encapsulated cinnamon bioactives hold potential in various industries, addressing these challenges is essential for their safe and effective application. Through concerted efforts in safety assessment, stability improvement, cost reduction, regulatory guidance, sustainable materials, and innovative encapsulation techniques, the utilization of encapsulated cinnamon bioactives can be effectively optimized. Future research should also focus on conducting well-designed clinical studies and exploring combination approaches to unlock the full potential of encapsulated cinnamon bioactives for improved health and well-being.

8. Conclusion

This review comprehensively examines the impact of micro/nano-encapsulation techniques on cinnamon bioactives, including changes in antioxidant capacity, EE, stability, solubility, and bioactive compound retention. Utilizing carrier agents during encapsulation enhances the protection of cinnamon bioactive compounds. The choice of encapsulation technique and wall material, including type, hydrophilicity, and the ratio between active and wall material, significantly influences encapsulation characteristics, such as core retention, stability, solubility, and antioxidant power of the processed food antioxidants. The thermal stability of the polymer matrix also plays a vital role in preserving the bioactivities of the core material under adverse conditions. Therefore, optimization of physicochemical parameters related to the encapsulated material is crucial for each encapsulation technique, core, and wall material. This optimization leads to narrower size distributions, mitigates product loss, and enhances bioavailability. Each encapsulation method has its own set of advantages and disadvantages, primarily influenced by the thermosensitivity and solubility of the active compounds. During implementation, it is essential to consider whether post-encapsulation steps, such as separation, solvent removal, or purification, are necessary for obtaining the desired product(s). Looking ahead, the utilization of encapsulated micro/nanoparticles holds tremendous potential across various areas, including food packaging, nutrient delivery and fortification, flavor and texture enhancement, and controlled release of functional ingredients. These encapsulation techniques offer exciting opportunities for innovative product development and improved consumer experiences. To fully harness the benefits of encapsulated cinnamon bioactives, researchers and industries need to continue exploring and refining the encapsulation methods, conducting in-depth safety assessments, addressing regulatory considerations, and adopting sustainable and environmentally friendly materials. With concerted efforts and advancements in the field of encapsulation, cinnamon bioactives can be leveraged to create functional and healthier food products for consumers worldwide.

CRediT authorship contribution statement

M.S. Culas: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **D.G. Popovich:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Conceptualization. **A. Rashidinejad:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

Re the review manuscript entitled "*Recent advances in encapsulation techniques for cinnamon bioactive compounds: A review on stability, effectiveness, and potential applications*" by Culas M., Popovich D.G., and Rashidinejad A. to be considered for publication in *Food Bioscience*, and further to the information provided in the cover letter, on behalf of myself and other authors, I **declare that there is no conflict of interest for this work** and the manuscript, in its present or a substantially similar form, has not been published or is not being considered for publication elsewhere.

Data availability

Data will be made available on request.

Acknowledgements

The first author would like to acknowlege Massey University, Palmerston North, New Zealand for the scholarship funding received.

References

Abdel-Wahhab, M. A., El-Nekeety, A. A., Hassan, N. S., Gibriel, A. A., & Abdel-Wahhab, K. G. (2018). Encapsulation of cinnamon essential oil in whey protein enhances the protective effect against single or combined sub-chronic toxicity of fumonisin B1 and/or aflatoxin B1 in rats. *Environmental Science and Pollution Research, 25*, 29144–29161.

Ahmed, J. (2018). Advances in rheological measurements of food products. *Current Opinion in Food Science, 23*, 127–132.

Arias, J., Zapata, K., Rojano, B., & Arias, M. (2016). Effect of light wavelength on cell growth, content of phenolic compounds and antioxidant activity in cell suspension cultures of Thevetia peruviana. *Journal of Photochemistry and Photobiology B: Biology, 163*, 87–91.

Ascheri, D. P., Marquez, M. O., & Martucci, E. T. (2003). Microencapsulação de óleo essencial de laranja: seleção de material de parede. *Food Science and Technology, 23*, 1–6.

Ayala-Zavala, J. F., Soto-Valdez, H., Gonzalez-Leon, A., Alvarez-Parrilla, E., Martin-Belloso, O., & Gonzalez-Aguilar, G. A. (2008). Microencapsulation of cinnamon leaf (*Cinnamomum zeylanicum*) and garlic (*Allium sativum*) oils in β-cyclodextrin. *Journal of Inclusion Phenomena and Macrocyclic Chemistry, 60*, 359–368.

Barlow, S., Chesson, A., Collins, J. D., Flynn, A., Hardy, A., Jany, K. D., et al. (2009). The potential risks arising from nanoscience and nanotechnologies on food and feed safety. *EFSA Journal, 7*(3), 1–39.
Bennick, A. (2002). Interaction of plant polyphenols with salivary proteins. *Critical Reviews in Oral Biology & Medicine, 13*(2), 184–196.
Błaszczyk, N., Rosiak, A., & Kałużna-Czaplińska, J. (2021). The potential role of cinnamon in human health. *Forests, 12*(5), 648.
Bora, A. F. M., Ma, S., Li, X., & Liu, L. (2018). Application of microencapsulation for the safe delivery of green tea polyphenols in food systems: Review and recent advances. *Food Research International, 105*, 241–249.
Cadena, M. B., Preston, G. M., Van der Hoorn, R. A., Flanagan, N. A., Townley, H. E., & Thompson, I. P. (2018). Enhancing cinnamon essential oil activity by nanoparticle encapsulation to control seed pathogens. *Industrial Crops and Products, 124*, 755–764.
Campelo, P. H., de Abreu Figueiredo, J., Ferraz, V., Yoshida, M. I., de Barros Fernandes, R. V., Botrel, D. A., et al. (2017). Hygroscopic, thermal and chemical properties of cinnamon essential oil microparticle obtained by spray drying. *Emirates Journal of Food and Agriculture, 29*(11), 884–892.
Carvalho, I. T., Estevinho, B. N., & Santos, L. (2016). Application of microencapsulated essential oils in cosmetic and personal healthcare products–a review. *International Journal of Cosmetic Science, 38*(2), 109–119.
Chen, W., Cheng, F., Swing, C. J., Xia, S., & Zhang, X. (2019). Modulation effect of core-wall ratio on the stability and antibacterial activity of cinnamaldehyde liposomes. *Chemistry and Physics of Lipids, 223*, Article 104790.
Chen, Y., & Liu, Y. (2010). Cyclodextrin-based bioactive supramolecular assemblies. *Chemical Society Reviews, 39*(2), 495–505.
Choi, Y. S., Lee, J. S., & Lee, H. G. (2023). Nanoencapsulation of grapefruit seed extract and cinnamon oil for oral health: Preparation, *in vitro*, and clinical antimicrobial activities. *Journal of Agricultural and Food Chemistry, 71*(14), 5646–5654.
Chun, J. Y., Jo, Y. J., Bjrapha, P., Choi, M. J., & Min, S. G. (2015). Antimicrobial effect of α-or β-cyclodextrin complexes with trans-cinnamaldehyde against *Staphylococcus aureus* and *Escherichia coli*. *Drying Technology, 33*(3), 377–383.
Cid-Samamed, A., Rakmai, J., Mejuto, J. C., Simal-Gandara, J., & Astray, G. (2022). Cyclodextrins inclusion complex: Preparation methods, analytical techniques and food industry applications. *Food Chemistry, 384*, Article 132467.
Comunian, T. A., Chaves, I. E., Thomazini, M., Moraes, I. C. F., Ferro-Furtado, R., de Castro, I. A., et al. (2017). Development of functional yogurt containing free and encapsulated echium oil, phytosterol and sinapic acid. *Food Chemistry, 237*, 948–956.
Cui, H., Li, W., Li, C., Vittayapadung, S., & Lin, L. (2016). Liposome containing cinnamon oil with antibacterial activity against methicillin-resistant *Staphylococcus aureus* biofilm. *Biofouling, 32*(2), 215–225.
Das, G., Gonçalves, S., Heredia, J. B., Romano, A., Jiménez-Ortega, L. A., Gutiérrez-Grijalva, E. P., et al. (2022). Cardiovascular protective effect of cinnamon and its major bioactive constituents: An update. *Journal of Functional Foods, 97*, Article 105045.
Davaatseren, M., Jo, Y. J., Hong, G. P., Hur, H. J., Park, S., & Choi, M. J. (2017). Studies on the anti-oxidative function of trans-cinnamaldehyde-included β-cyclodextrin complex. *Molecules, 22*(12), 1868.
De Kruif, C. G., Weinbreck, F., & de Vries, R. (2004). Complex coacervation of proteins and anionic polysaccharides. *Current Opinion in Colloid & Interface Science, 9*(5), 340–349.
De Souza, V. B., Thomazini, M., Barrientos, M. A. E., Nalin, C. M., Ferro-Furtado, R., Genovese, M. I., et al. (2018). Functional properties and encapsulation of a proanthocyanidin-rich cinnamon extract (*Cinnamomum zeylanicum*) by complex coacervation using gelatin and different polysaccharides. *Food Hydrocolloids, 77*, 297–306.
De Souza, V. B., Thomazini, M., Chaves, I. E., Ferro-Furtado, R., & Favaro-Trindade, C. S. (2020). Microencapsulation by complex coacervation as a tool to protect bioactive compounds and to reduce astringency and strong flavor of vegetable extracts. *Food Hydrocolloids, 98*, Article 105244.
Debnath, S., Kumar, R. S., & Babu, M. N. (2011). Ionotropic gelation–a novel method to prepare chitosan nanoparticles. *Research Journal of Pharmacy and Technology, 4*(4), 492–495.
Desai, K. G. H., & Jin Park, H. (2005). Recent developments in microencapsulation of food ingredients. *Drying Technology, 23*(7), 1361–1394.
Desai, K., & Park, H. (2005). Encapsulation of vitamin C in tripolyphosphate cross-linked chitosan microspheres by spray drying. *Journal of Microencapsulation, 22*(2), 179–192.
Donaldson, K., Stone, V., Tran, C. L., Kreyling, W., & Borm, P. J. (2004). Nanotoxicology. *Occupational and Environmental Medicine, 61*(9), 727–728.
El-Kader, A., & Abu Hashish, H. (2020). Encapsulation techniques of food bioproduct. *Egyptian Journal of Chemistry, 63*(5), 1881–1909.
Fachriyah, E., Eviana, I., Eldiana, O., Amaliyah, N., & Sektianingrum, A. (2017). Antidiabetic activity from gallic acid encapsulated nanochitosan. In *Proceedings of the 11th joint conference on chemistry in conjunction with the 4th regional biomaterials scientific meeting, Purwokerto, Indonesia*.
Farahmand, A., Emadzadeh, B., Ghorani, B., & Poncelet, D. (2022). Droplet-based millifluidic technique for encapsulation of cinnamon essential oil: Optimization of the process and physicochemical characterization. *Food Hydrocolloids, 129*, Article 107609.
Felix, P. H. C., Birchal, V. S., Botrel, D. A., Marques, G. R., & Borges, S. V. (2017). Physicochemical and thermal stability of microcapsules of cinnamon essential oil by spray drying. *Journal of Food Processing and Preservation, 41*(3), Article 12919.
Fernández-Pan, I., Carrión-Granda, X., & Maté, J. I. (2014). Antimicrobial efficiency of edible coatings on the preservation of chicken breast fillets. *Food Control, 36*(1), 69–75.
Ferraz, M. C., Procopio, F. R., de Figueiredo Furtado, G., & Hubinger, M. D. (2022). Co-encapsulation of paprika and cinnamon oleoresin by spray drying using whey protein isolate and maltodextrin as wall material: Development, characterization and storage stability. *Food Research International, 162*, Article 112164.
Ghaderi-Ghahfarokhi, M., Barzegar, M., Sahari, M. A., & Azizi, M. H. (2016). Nanoencapsulation approach to improve antimicrobial and antioxidant activity of thyme essential oil in beef burgers during refrigerated storage. *Food and Bioprocess Technology, 9*, 1187–1201.
Gong, C., Lee, M. C., Godec, M., Zhang, Z., & Abbaspourrad, A. (2020). Ultrasonic encapsulation of cinnamon flavor to impart heat stability for baking applications. *Food Hydrocolloids, 99*, Article 105316.
Gottardo, F. M., Biduski, B., Dos Santos, L. F., Dos Santos, J. S., Rodrigues, L. B., & Dos Santos, L. R. (2022). Microencapsulated oregano and cinnamon essential oils as a natural alternative to reduce *Listeria monocytogenes* in Italian salami. *Food Bioscience, 50*, Article 102146.
Gu, L., Kelm, M., Hammerstone, J., Zhang, Z., Beecher, G., Holden, J., & Prior, R. (2003). Liquid chromatographic/electrospray ionization mass spectrometric studies of proanthocyanidins in foods. *Journal of Mass Spectrometry, 38*(12), 1272–1280.
Gunes-Bayir, A., Bilgin, M. G., Guclu, D., Pogda, S., & Dadak, A. (2022). Preparation and evaluation of novel functional fermented dairy products containing propolis and cinnamon. *Journal of Food Science and Technology, 59*(6), 2392–2401.
Gupta, C., Garg, A. P., Uniyal, R. C., & Kumari, A. (2008). Comparative analysis of the antimicrobial activity of cinnamon oil and cinnamon extract on some food-borne microbes. *African Journal of Microbiology Research, 2*(9), 247–251.
Han, H. S., Koo, S. Y., & Choi, K. Y. (2022). Emerging nanoformulation strategies for phytocompounds and applications from drug delivery to phototherapy to imaging. *Bioactive Materials, 14*, 182–205.
Hayward, N. J., McDougall, G. J., Farag, S., Allwood, J. W., Austin, C., Campbell, F., et al. (2019). Cinnamon shows antidiabetic properties that are species-specific: Effects on enzyme activity inhibition and starch digestion. *Plant Foods for Human Nutrition, 74*, 544–552.
Helal, A., Tagliazucchi, D., Verzelloni, E., & Conte, A. (2014). Bioaccessibility of polyphenols and cinnamaldehyde in cinnamon beverages subjected to *in vitro* gastro-pancreatic digestion. *Journal of Functional Foods, 7*, 506–516.
Hermanto, R., Khasanah, L., Atmaka, W., Manuhara, G., & Utami, R. (2016). Physical characteristics of cinnamon oil microcapsule. In *Proceedings of the 10th joint conference on chemistry in conjunction with the 4th regional biomaterials scientific meeting, Solo, Indonesia*.
Hill, L. E., Gomes, C., & Taylor, T. M. (2013). 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 & Technology, 51*(1), 86–93.
Hoang, N. H., Le Thanh, T., Sangpueak, R., Treekoon, J., Saengchan, C., Thepbandit, W., et al. (2022). Chitosan nanoparticles-based ionic gelation method: A promising candidate for plant disease management. *Polymers, 14*(4), 662.
Hofmann, T., Glabasnia, A., Schwarz, B., Wisman, K. N., Gangwer, K. A., & Hagerman, A. E. (2006). Protein binding and astringent taste of a polymeric procyanidin, 1, 2, 3, 4, 6-penta-O-galloyl-β-D-glucopyranose, castalagin, and grandinin. *Journal of Agricultural and Food Chemistry, 54*(25), 9503–9509.
Holkem, A. T., & Favaro-Trindade, C. S. (2020). Potential of solid lipid microparticles covered by the protein-polysaccharide complex for protection of probiotics and proanthocyanidin-rich cinnamon extract. *Food Research International, 136*, Article 109520.
Holkem, A. T., Favaro-Trindade, C. S., & Lacroix, M. (2020). Study of anticancer properties of proanthocyanidin-rich cinnamon extract in combination with *Bifidobacterium animalis* subsp. *lactis* BLC1 and resistance of these free and co-encapsulated materials under *in vitro* simulated gastrointestinal conditions. *Food Research International, 134*, Article 109274.
Honary, S., & Zahir, F. (2013). Effect of zeta potential on the properties of nano-drug delivery systems-a review (Part 2). *Tropical Journal of Pharmaceutical Research, 12*(2), 265–273.
Hou, K., Xu, Y., Cen, K., Gao, C., Feng, X., & Tang, X. (2021). Nanoemulsion of cinnamon essential oil Co-emulsified with hydroxypropyl-β-cyclodextrin and Tween-80: Antibacterial activity, stability and slow release performance. *Food Bioscience, 43*, Article 101232.
Huang, Y., Liu, H., Liu, S., & Li, S. (2020). Cinnamon cassia oil emulsions stabilized by chitin nanofibrils: Physicochemical properties and antibacterial activities. *Journal of Agricultural and Food Chemistry, 68*(49), 14620–14631.
Hu, Q., Li, X., Chen, F., Wan, R., Yu, C. W., Li, J., et al. (2020). Microencapsulation of an essential oil (cinnamon oil) by spray drying: Effects of wall materials and storage conditions on microcapsule properties. *Journal of Food Processing and Preservation, 44*(11), Article 14805.
Hyldgaard, M., Mygind, T., & Meyer, R. L. (2012). Essential oils in food preservation: Mode of action, synergies, and interactions with food matrix components. *Frontiers in Microbiology, 3*, 12.
Ifeduba, E. A., & Akoh, C. C. (2015). Microencapsulation of stearidonic acid soybean oil in complex coacervates modified for enhanced stability. *Food Hydrocolloids, 51*, 136–145.
de la Iglesia, R., Milagro, F. I., Campión, J., Boqué, N., & Martínez, J. A. (2010). Healthy properties of proanthocyanidins. *BioFactors, 36*(3), 159–168.
Inoue, K. I., & Takano, H. (2011). Aggravating impact of nanoparticles on immune-mediated pulmonary inflammation. *The Scientific World Journal, 11*, 382–390.
Jafari, S. M., He, Y., & Bhandari, B. (2007). Role of powder particle size on the encapsulation efficiency of oils during spray drying. *Drying Technology, 25*(6), 1081–1089.

Jafari, S. M., & McClements, D. J. (2017). Nanotechnology approaches for increasing nutrient bioavailability. *Advances in Food & Nutrition Research, 81*, 1–30.
Jeon, Y. O., Lee, J. S., & Lee, H. G. (2016). Improving solubility, stability, and cellular uptake of resveratrol by nanoencapsulation with chitosan and γ-poly (glutamic acid). *Colloids and Surfaces B: Biointerfaces, 147*, 224–233.
Jiao, L., Zhang, X., Huang, L., Gong, H., Cheng, B., Sun, Y., et al. (2013). Proanthocyanidins are the major anti-diabetic components of cinnamon water extract. *Food and Chemical Toxicology, 56*, 398–405.
Jiménez, M., Domínguez, J. A., Pascual-Pineda, L. A., Azuara, E., & Beristain, C. (2018). Elaboration and characterization of O/W cinnamon (*Cinnamomum zeylanicum*) and black pepper (*Piper nigrum*) emulsions. *Food Hydrocolloids, 77*, 902–910.
Johnson, N. R., & Wang, Y. (2014). Coacervate delivery systems for proteins and small molecule drugs. *Expert Opinion on Drug Delivery, 11*(12), 1829–1832.
Joukar, F., Hosseini, S. M. H., Moosavi-Nasab, M., Mesbahi, G. R., & Behzadnia, A. (2017). Effect of Farsi gum-based antimicrobial adhesive coatings on the refrigeration shelf life of rainbow trout fillets. *Lwt, 80*, 1–9.
Kalemba, D., & Kunicka, A. (2003). Antibacterial and antifungal properties of essential oils. *Current Medicinal Chemistry, 10*(10), 813–829.
Khasanah, L., Prasetyawan, P., Utami, R., Atmaka, W., Manuhara, G., & Sanjaya, A. (2017). Optimization and characterization of cinnamon leaves (*Cinnamomum burmannii*) oleoresin. In *In proceedings of the 10th joint conference on chemistry in conjunction with the 4th regional biomaterials scientific meeting, surakarta, Indonesia*.
Khazaei, K. M., Jafari, S., Ghorbani, M., & Kakhki, A. H. (2014). Application of maltodextrin and gum Arabic in microencapsulation of saffron petal's anthocyanins and evaluating their storage stability and color. *Carbohydrate Polymers, 105*, 57–62.
Kim, H. H. Y., & Baianu, I. C. (1991). Novel liposome microencapsulation techniques for food applications. *Trends in Food Science & Technology, 2*, 55–61.
Kim, I. H., Han, J., Na, J. H., Chang, P. S., Chung, M. S., Park, K. H., et al. (2013). Insect-resistant food packaging film development using cinnamon oil and microencapsulation technologies. *Journal of Food Science, 78*(2), 229–237.
Kometani, T., Fukuda, T., Kakuma, T., Kawaguchi, K., Tamura, W., Kumazawa, Y., et al. (2008). Effects of α-glucosylhesperidin, a bioactive food material, on collagen-induced arthritis in mice and rheumatoid arthritis in humans. *Immunopharmacology and Immunotoxicology, 30*(1), 117–134.
Krishnaswamy, K., Orsat, V., & Thangavel, K. (2012). Synthesis and characterization of nano-encapsulated catechin by molecular inclusion with beta-cyclodextrin. *Journal of Food Engineering, 111*(2), 255–264.
Kuehl, P. J., McDonald, J. D., Weber, D. T., Khlystov, A., Nystoriak, M. A., & Conklin, D. J. (2022). Composition of aerosols from thermal degradation of flavors used in ENDS and tobacco products. *Inhalation Toxicology, 34*(11), 319–328.
Kurniasari, L., & Kusumo, P. (2019). Kinetics of cinnamon oleoresin extraction using microwave-assisted extractor. In *In proceedings of the 12th joint conference on chemistry in conjunction with the 4th regional biomaterials scientific meeting, semarang, Indonesia*.
Kwak, H. S. (2014). Overview of nano-and microencapsulation for Foods. In *Nano-and microencapsulation for foods* (pp. 1–14). Oxford: John Wiley & sons.
Li, L., Zhang, W., Peng, J., Xue, B., Liu, Z., Luo, Z., & Zhao, X. (2020). A novel shell material—highland barley starch for microencapsulation of cinnamon essential oil with different preparation methods. *Materials, 13*(5), 1192.
Li, Q., Chen, J., Li, T., Liu, C., Wang, X., Dai, T., et al. (2015). Impact of *in vitro* simulated digestion on the potential health benefits of proanthocyanidins from *Choerospondias axillaris* peels. *Food Research International, 78*, 378–387.
Liu, Y., Wang, H., Fu, R., Zhang, L., Liu, M., Cao, W., et al. (2023). Preparation and characterization of cinnamon essential oil extracted by deep eutectic solvent and its microencapsulation. *Journal of Food Measurement and Characterization, 17*(1), 664–673.
Lu, W., Kelly, A. L., & Miao, S. (2016). Emulsion-based encapsulation and delivery systems for polyphenols. *Trends in Food Science & Technology, 47*, 1–9.
Madene, A., Jacquot, M., Scher, J., & Desobry, S. (2006). Flavour encapsulation and controlled release–a review. *International Journal of Food Science and Technology, 41*(1), 1–21.
Mahdavi, S. A., Jafari, S. M., Ghorbani, M., & Assadpoor, E. (2014). Spray-drying microencapsulation of anthocyanins by natural biopolymers: A review. *Drying Technology, 32*(5), 509–518.
Majeed, H., Bian, Y. Y., Ali, B., Jamil, A., Majeed, U., Khan, Q. F., et al. (2015). Essential oil encapsulations: Uses, procedures, and trends. *RSC Advances, 5*(72), 58449–58463.
Makimori, R., Endo, E., Makimori, J., Zanqueta, E., Ueda-Nakamura, T., Leimann, F., et al. (2020). Preparation, characterization and antidermatophytic activity of free- and microencapsulated cinnamon essential oil. *Journal de Mycologie Médicale, 30*(2), Article 100933.
Mao, L., Roos, Y. H., Biliaderis, C. G., & Miao, S. (2017). Food emulsions as delivery systems for flavor compounds: A review. *Critical Reviews in Food Science and Nutrition, 57*(15), 3173–3187.
Mathew, S., & Abraham, T. E. (2006). Studies on the antioxidant activities of cinnamon (*Cinnamomum verum*) bark extracts, through various *in vitro* models. *Food Chemistry, 94*(4), 520–528.
Mcclements, D. J. (2007). Critical review of techniques and methodologies for characterization of emulsion stability. *Critical Reviews in Food Science and Nutrition, 47*(7), 611–649.
McClements, D. J., & Li, Y. (2010). Structured emulsion-based delivery systems: Controlling the digestion and release of lipophilic food components. *Advances in Colloid and Interface Science, 159*(2), 213–228.
Meghani, N., Patel, P., Kansara, K., Ranjan, S., Dasgupta, N., Ramalingam, C., et al. (2018). Formulation of vitamin D encapsulated cinnamon oil nanoemulsion: Its potential anti-cancerous activity in human alveolar carcinoma cells. *Colloids and Surfaces B: Biointerfaces, 166*, 349–357.
Meligy, A. M., Abd El-Hamid, M. I., Yonis, A. E., Elhaddad, G. Y., Abdel-Raheem, S. M., El-Ghareeb, W. R., et al. (2023). Liposomal encapsulated oregano, cinnamon, and clove oils enhanced the performance, bacterial metabolites antioxidant potential, and intestinal microbiota of broiler chickens. *Poultry Science, 102*(6), Article 102683.
Merino, N., Berdejo, D., Bento, R., Salman, H., Lanz, M., Maggi, F., et al. (2019). Antimicrobial efficacy of *Thymbra capitata* (L.) Cav. essential oil loaded in self-assembled zein nanoparticles in combination with heat. *Industrial Crops and Products, 133*, 98–104.
Mishra, N., & Srivastava, R. (2022). Storage of particulate solids. In M. E. Fayed, & L. Otten (Eds.), *Handbook of powder science and technology* (pp. 365–463). New York: Van Nostrand Reinhold.
Mohammadi, A., Hashemi, M., & Hosseini, S. M. (2015). Chitosan nanoparticles loaded with *Cinnamomum zeylanicum* essential oil enhance the shelf life of cucumber during cold storage. *Postharvest Biology and Technology, 110*, 203–213.
Mohammadi, A., Hosseini, S. M., & Hashemi, M. (2020). Emerging chitosan nanoparticles loading-system boosted the antibacterial activity of *Cinnamomum zeylanicum* essential oil. *Industrial Crops and Products, 155*, Article 112824.
Momtaz, S., Hassani, S., Khan, F., Ziaee, M., & Abdollahi, M. (2018). Cinnamon, a promising prospect towards Alzheimer's disease. *Pharmacological Research, 130*, 241–258.
Muhammad, D. R. A., & Dewettinck, K. (2017). Cinnamon and its derivatives as potential ingredient in functional food—a review. *International Journal of Food Properties, 20*(2), 2237–2263.
Muhammad, D. R. A., Doost, A. S., Gupta, V., bin Sintang, M. D., Van de Walle, D., Van der Meeren, P., et al. (2020). Stability and functionality of xanthan gum–shellac nanoparticles for the encapsulation of cinnamon bark extract. *Food Hydrocolloids, 100*, Article 105377.
Muhoza, B., Qi, B., Harindintwali, J. D., Koko, M. Y. F., Zhang, S., & Li, Y. (2023). Encapsulation of cinnamaldehyde: An insight on delivery systems and food applications. *Critical Reviews in Food Science and Nutrition, 63*(15), 2521–2543.
Muhoza, B., Xia, S., Cai, J., Zhang, X., Duhoranimana, E., & Su, J. (2019). Gelatin and pectin complex coacervates as carriers for cinnamaldehyde: Effect of pectin esterification degree on coacervate formation, and enhanced thermal stability. *Food Hydrocolloids, 87*, 712–722.
Muhoza, B., Xia, S., Wang, X., Zhang, X., Li, Y., & Zhang, S. (2022). Microencapsulation of essential oils by complex coacervation method: Preparation, thermal stability, release properties and applications. *Critical Reviews in Food Science and Nutrition, 62*(5), 1363–1382.
Munhuweyi, K., Caleb, O. J., Van Reenen, A. J., & Opara, U. L. (2018). Physical and antifungal properties of β-cyclodextrin microcapsules and nanofibre films containing cinnamon and oregano essential oils. *Lwt, 87*, 413–422.
Najahi-Missaoui, W., Arnold, R. D., & Cummings, B. S. (2020). Safe nanoparticles: Are we there yet? *International Journal of Molecular Sciences, 22*(1), 385.
Nedovic, V., Kalusevic, A., Manojlovic, V., Levic, S., & Bugarski, B. (2011). An overview of encapsulation technologies for food applications. *Procedia Food Science, 1*, 1806–1815.
Nguyen, M. H., Tran, T. N. M., & Vu, N. B. D. (2022). Antifungal activity of essential oil-encapsulated lipid nanoemulsions formulations against leaf spot disease on tomato caused by *Alternaria alternata*. *Archives of Phytopathology and Plant Protection, 55*(2), 235–257.
Nouri, A. (2019). Chitosan nano-encapsulation improves the effects of mint, thyme, and cinnamon essential oils in broiler chickens. *British Poultry Science, 60*(5), 530–538.
Ostroschi, L. C., De Souza, V. B., Echalar-Barrientos, M. A., Tulini, F. L., Comunian, T. A., Thomazini, M., et al. (2018). Production of spray-dried proanthocyanidin-rich cinnamon (*Cinnamomum zeylanicum*) extract as a potential functional ingredient: Improvement of stability, sensory aspects and technological properties. *Food Hydrocolloids, 79*, 343–351.
Osznianski, J., Sapis, J. C., & Jean, J. (1985). Changes in grape seed phenols as affected by enzymic and chemical oxidation *in vitro*. *Journal of Food Science, 50*(5), 1505–1506.
Panceri, C. P., Gomes, T. M., De Gois, J. S., Borges, D. L., & Bordignon-Luiz, M. T. (2013). Effect of dehydration process on mineral content, phenolic compounds and antioxidant activity of *Cabernet sauvignon* and Merlot grapes. *Food Research International, 54*(2), 1343–1350.
Pattison, T. L., & Von Holy, A. (2001). Effect of selected natural antimicrobials on Baker's yeast activity. *Letters in Applied Microbiology, 33*(3), 211–215.
Piechowiak, T., Grzelak-Błaszczyk, K., Sójka, M., Skóra, B., & Balawejder, M. (2022). Quality and antioxidant activity of highbush blueberry fruit coated with starch-based and gelatine-based film enriched with cinnamon oil. *Food Control, 138*, Article 109015.
Piechowiak, T., & Skóra, B. (2023). Edible coating enriched with cinnamon oil reduces the oxidative stress and improves the quality of strawberry fruit stored at room temperature. *Journal of the Science of Food and Agriculture, 103*(5), 2389–2400.
Pourashouri, P., Shabanpour, B., Razavi, S. H., Jafari, S. M., Shabani, A., & Aubourg, S. P. (2014). Oxidative stability of spray-dried microencapsulated fish oils with different wall materials. *Journal of Aquatic Food Product Technology, 23*(6), 567–578.
Pramote, K., Nucha, S., Suched, S., Parinda, P., Prasong, S., & Shuji, A. (2012). Subcritical water extraction of flavoring and phenolic compounds from cinnamon bark (*Cinnamomum zeylanicum*). *Journal of Oleo Science, 61*(6), 349–355.
Praseptiangga, D., Invicta, S. E., & Khasanah, L. U. (2019). Sensory and physicochemical characteristics of dark chocolate bar with addition of cinnamon (*Cinnamomum burmannii*) bark oleoresin microcapsule. *Journal of Food Science and Technology, 56*, 4323–4332.

Prastuty, Kaur, G., & Singh, A. (2021). Shelf life extension of muffins coated with cinnamon and clove oil nanoemulsions. *Journal of Food Science and Technology*, 1–11.
Prata, A. S., & Grosso, C. R. (2015). Influence of the oil phase on the microencapsulation by complex coacervation. *Journal of the American Oil Chemists' Society, 92*, 1063–1072.
Pratiwi, I. Y., Darmadji, P., & Hastuti, P. (2016). Effect of storage temperature on the stability of microencapsulated essential oil from cinnamon. In *Proceedings of the 1st international conference on science and technology 2015, Yogyakarta, Indonesia*.
Procopio, F. R., Oriani, V. B., Paulino, B. N., do Prado-Silva, L., Pastore, G. M., Sant'Ana, A. S., et al. (2018). Solid lipid microparticles loaded with cinnamon oleoresin: Characterization, stability and antimicrobial activity. *Food Research International, 113*, 351–361.
Rao, M. A., & Rao, M. A. (2014). Flow and functional models for rheological properties of fluid foods. In *Rheology of fluid, semisolid, and solid foods: Principles and applications* (pp. 27–61). New York: Springer.
Rashidinejad, A., & Singh, H. (2021). Application of nano/microencapsulated ingredients in milk and dairy products. In *Application of nano/microencapsulated ingredients in food products* (pp. 43–103). London: Elsevier.
Rauf, A., Imran, M., Abu-Izneid, T., Patel, S., Pan, X., Naz, S., et al. (2019). Proanthocyanidins: A comprehensive review. *Biomedicine & Pharmacotherapy, 116*, Article 108999.
Razavi, M. S., Golmohammadi, A., Nematollahzadeh, A., Fiori, F., Rovera, C., & Farris, S. (2020). Preparation of cinnamon essential oil emulsion by bacterial cellulose nanocrystals and fish gelatin. *Food Hydrocolloids, 109*, Article 106111.
Ríos-Pérez, M. F., Quintero-Lira, A., Piloni-Martini, J., Soto-Simental, S., López-Palestina, C. U., Urrutia-Hernández, T. A., et al. (2023). Antioxidant capacity and physicochemical characterization of microencapsulated aqueous extracts of cinnamon (*Cinnamon zeylanicum*) by spray-dryer. *Biointerface Research in Applied Chemistry, 13*(6).
Saifullah, M., Shishir, M. R. I., Ferdowsi, R., Rahman, M. R. T., & Van Vuong, Q. (2019). Micro and nano encapsulation, retention and controlled release of flavor and aroma compounds: A critical review. *Trends in Food Science & Technology, 86*, 230–251.
Sanguansri, P., & Augustin, M. A. (2006). Nanoscale materials development–a food industry perspective. *Trends in Food Science & Technology, 17*(10), 547–556.
Santiago-Adame, R., Medina-Torres, L., Gallegos-Infante, J., Calderas, F., González-Laredo, R., Rocha-Guzmán, N., et al. (2015). Spray drying-microencapsulation of cinnamon infusions (*Cinnamomum zeylanicum*) with maltodextrin. *LWT-Food Science & Technology, 64*(2), 571–577.
Santos, D. I., Saraiva, J. M. A., Vicente, A. A., & Moldão-Martins, M. (2019). Methods for determining bioavailability and bioaccessibility of bioactive compounds and nutrients. In *Innovative thermal and non-thermal processing, bioaccessibility and bioavailability of nutrients and bioactive compounds* (pp. 23–54). Duxford: Elsevier.
Satya, N. S., Prakash, S., & Meena, V. (2012). Purification of cinnamaldehyde from cinnamon species by column chromatography. *International Research Journal of Biological Sciences, 1*, 49–51.
Schink, A., Naumoska, K., Kitanovski, Z., Kampf, C. J., Fröhlich-Nowoisky, J., Thines, E., et al. (2018). Anti-inflammatory effects of cinnamon extract and identification of active compounds influencing the TLR2 and TLR4 signaling pathways. *Food & Function, 9*(11), 5950–5964.
Shahidi Noghabi, M., & Molaveisi, M. (2020a). The effect of wall formulation on storage stability and physicochemical properties of cinnamon essential oil microencapsulated by spray drying. *Chemical Papers, 74*(10), 3455–3465.
Shahidi Noghabi, M., & Molaveisi, M. (2020b). Microencapsulation optimization of cinnamon essential oil in the matrices of gum Arabic, maltodextrin, and inulin by spray-drying using mixture design. *Journal of Food Process Engineering, 43*(2), Article e13341.
Shan, B., Cai, Y. Z., Sun, M., & Corke, H. (2005). Antioxidant capacity of 26 spice extracts and characterization of their phenolic constituents. *Journal of Agricultural and Food Chemistry, 53*(20), 7749–7759.
Sharma, D., Dhanjal, D. S., & Mittal, B. (2017). Development of edible biofilm containing cinnamon to control food-borne pathogen. *Journal of Applied Pharmaceutical Science, 7*(1), 160–164.
Simionato, I., Domingues, F. C., Nerin, C., & Silva, F. (2019). Encapsulation of cinnamon oil in cyclodextrin nanosponges and their potential use for antimicrobial food packaging. *Food and Chemical Toxicology, 132*, Article 110647.
Singh, G., Maurya, S., DeLampasona, M., & Catalan, C. A. (2007). A comparison of chemical, antioxidant and antimicrobial studies of cinnamon leaf and bark volatile oils, oleoresins and their constituents. *Food and Chemical Toxicology, 45*(9), 1650–1661.
Tao, W., Zhang, Y., Shen, X., Cao, Y., Shi, J., Ye, X., et al. (2019). Rethinking the mechanism of the health benefits of proanthocyanidins: Absorption, metabolism, and interaction with gut microbiota. *Comprehensive Reviews in Food Science and Food Safety, 18*(4), 971–985.
Thomas, J., & Kuruvilla, K. (2012). Cinnamon. In *Handbook of herbs and spices* (pp. 182–196). Cambridge: Elsevier.
Timilsena, Y. P., Akanbi, T. O., Khalid, N., Adhikari, B., & Barrow, C. J. (2019). Complex coacervation: Principles, mechanisms and applications in microencapsulation. *International Journal of Biological Macromolecules, 121*, 1276–1286.
Trinh, T. H., Shaari, K. Z. K., Basit, A., & Azeem, B. (2014). Effect of particle size and coating thickness on the release of urea using multi-diffusion model. *International Journal of Chemical Engineering and Applications, 5*(1), 58.
Tung, W. C., Rizzo, B., Dabbagh, Y., Saraswat, S., Romanczyk, M., Codorniu-Hernández, E., et al. (2020). Polyphenols bind to low density lipoprotein at biologically relevant concentrations that are protective for heart disease. *Archives of Biochemistry and Biophysics, 694*, Article 108589.
Tu, Q. B., Wang, P. Y., Sheng, S., Xu, Y., Wang, J. Z., You, S., et al. (2020). Microencapsulation and antimicrobial activity of plant essential oil against *Ralstonia solanacearum*. *Waste and Biomass Valorization, 11*, 5273–5282.
Vaidya, S., Bhosale, R., & Singhal, R. S. (2006). Microencapsulation of cinnamon oleoresin by spray drying using different wall materials. *Drying Technology, 24*(8), 983–992.
Valencia-Sullca, C., Jiménez, M., Jiménez, A., Atarés, L., Vargas, M., & Chiralt, A. (2016). Influence of liposome encapsulated essential oils on properties of chitosan films. *Polymer International, 65*(8), 979–987.
Vangalapati, M., Sree Satya, N., Surya Prakash, D. V., & Sumanjali, A. (2012). A review on pharmacological activities and clinical effects of cinnamon species. *Research Journal of Pharmaceutical, Biological and Chemical Sciences, 3*(1), 653–663.
Viuda-Martos, M., Ruiz-Navajas, Y., Fernández-López, J., & Pérez-Álvarez, J. A. (2010). Spices as functional foods. *Critical Reviews in Food Science and Nutrition, 51*(1), 13–28.
Von Wright, A. (2007). Regulation of functional dairy products. In *Functional dairy products* (pp. 265–276). Cambridge: Elsevier.
Wang, X., Cheng, F., Wang, X., Feng, T., Xia, S., & Zhang, X. (2021). Chitosan decoration improves the rapid and long-term antibacterial activities of cinnamaldehyde-loaded liposomes. *International Journal of Biological Macromolecules, 168*, 59–66.
Wang, J., Li, Y., Gao, Y., Xie, Z., Zhou, M., He, Y., et al. (2018). Cinnamon oil-loaded composite emulsion hydrogels with antibacterial activity prepared using concentrated emulsion templates. *Industrial Crops and Products, 112*, 281–289.
Wijesekera, R. (1978). Historical overview of the cinnamon industry. *CRC Critical Reviews in Food Science & Nutrition, 10*(1), 1–30.
Xing, Y., Xu, Q., Lin, H., Li, X., Zhang, D., Yang, S. X., et al. (2016). Preparation, properties and *in vivo* antimicrobial activity in yacon roots of microencapsulation containing cinnamon oil. *Materials Technology, 31*(1), 40–46.
Xing, Y. G., Xu, Q. L., Sun, Y. J., Li, X. H., & Li, W. L. (2011). Antibacterial property of active packaging of microencapsulated cinnamon oil combined with ZnO-coated PVC film. *Advanced Materials Research, 239*, 3119–3122.
Xu, E., Wu, Z., Jin, Z., & Campanella, O. H. (2018). Bioextrusion of broken rice in the presence of divalent metal salts: Effects on starch microstructure and phenolics compounds. *ACS Sustainable Chemistry & Engineering, 6*(1), 1162–1171.
Yang, K., Liu, A., Hu, A., Li, J., Zen, Z., Liu, Y., et al. (2021). Preparation and characterization of cinnamon essential oil nanocapsules and comparison of volatile components and antibacterial ability of cinnamon essential oil before and after encapsulation. *Food Control, 123*, Article 107783.
Yang, W., Ding, H., Puglia, D., Kenny, J. M., Liu, T., Guo, J., & Lemstra, P. J. (2022). Bio-renewable polymers based on lignin-derived phenol monomers: Synthesis, applications, and perspectives. *SusMat, 2*(5), 535–568.
Yin, C., Huang, C., Wang, J., Liu, Y., Lu, P., & Huang, L. (2019). Effect of chitosan-and alginate-based coatings enriched with cinnamon essential oil microcapsules to improve the postharvest quality of mangoes. *Materials, 12*(13), 2039.
Yu, X., Yang, Y., Liu, Q., Jin, Z., & Jiao, A. (2023). A hydroxypropyl methylcellulose/hydroxypropyl starch nanocomposite film reinforced with chitosan nanoparticles encapsulating cinnamon essential oil: Preparation and characterization. *International Journal of Biological Macromolecules, 242*, Article 124605.
Zainol, N., Ming, T., & Darwis, Y. (2015). Development and characterization of cinnamon leaf oil nanocream for topical application. *Indian Journal of Pharmaceutical Sciences, 77*(4), 422.
Zakharova, L., Mirgorodskaya, A., Gaynanova, G., Kashapov, R., Pashirova, T., Vasilieva, E., et al. (2016). Supramolecular strategy of the encapsulation of low-molecular-weight food ingredients. In *Encapsulations* (pp. 295–362). London: Elsevier.
Zhang, H., Jung, J., & Zhao, Y. (2017). Preparation and characterization of cellulose nanocrystals films incorporated with essential oil loaded β-chitosan beads. *Food Hydrocolloids, 69*, 164–172.
Zhang, Y., Liu, X., Wang, Y., Jiang, P., & Quek, S. (2016). Antibacterial activity and mechanism of cinnamon essential oil against *Escherichia coli* and *Staphylococcus aureus*. *Food Control, 59*, 282–289.
Zuidam, N. J., & Shimoni, E. (2010). Overview of microencapsulates for use in food products or processes and methods to make them. In *Encapsulation technologies for active food ingredients and food processing* (pp. 3–29). London: Elsevier.