Trends in Food Science & Technology 70 (2017) 56–68

Contents lists available at ScienceDirect

Trends in Food Science & Technology

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

Review

Electrospinning: A novel nano-encapsulation approach for bioactive compounds

Peng Wen[a], Min-Hua Zong[a], Robert J. Linhardt[b], Kun Feng[a], Hong Wu[a,c,*]

[a] School of Food Science and Engineering, South China University of Technology, Guangzhou 510640, China
[b] Department of Chemical and Biological Engineering, Center for Biotechnology and Interdisciplinary Studies, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
[c] Guangdong Province Key Laboratory for Green Processing of Natural Products and Product Safety, Guangzhou 510640, China

ARTICLE INFO

Keywords:
Electrospinning
Nanofibers
Encapsulation
Bioactive compounds
Biopolymer
Application

ABSTRACT

Background: Bioactive compounds have gained increasing attention for their health benefits. However, the instability of bioactive compounds during food processing and storage, and low bioavailability or chemical instability when exposed to upper gastrointestinal tract conditions significantly compromised the envisioned benefits, thus limiting their applications. Electrospinning has been recognized as a promising method to encapsulate bioactive compounds since it does not involve any severe conditions of temperature, pressure, or harsh chemicals. Therefore, the nanofibers produced by electrospinning have attracted particular attention in food industry due to the potential as vehicle for the encapsulation and controlled delivery or release of bioactive compounds.

Scope and approach: Electrospinning is a novel delivery approach for bioactive compounds, it opens a new horizon in food technology with the possibility of commercialization in the near future. This paper presents a brief summary of electrospinning, and its application in encapsulation different types of bioactive compounds by biopolymer matrixes are also highlighted. Further, the existing limitations and scope for future research are discussed.

Key findings: Recently, considerable studies have been carried out in encapsulation of bioactive compounds using electrospinning. The obtained nanofilm could enhance stability, encapsulation efficiency and oral bioavailability of bioactive compounds, as well as achieve targeted delivery and controlled release, thus facilitating the development of functional foods.

1. Introduction

In recent years, driven by the increasing demands for health improvement or disease prevention through diet, bioactive compounds, such as polyphenols, vitamins, minerals, omega-3-fatty acids, bioactive proteins or peptides, probiotics etc, have been intensively investigated for their potential applications in the fields of pharmaceuticals, nutraceuticals and functional foods (Anu Bhushani & Anandharamakrishnan, 2014; Dias, Ferreira, & Barreiro, 2015). However, their poor stability during food processing or storage and their low bioavailability or chemical instability when exposed to the conditions of the upper gastrointestinal tract (GIT) significantly compromises their envisioned benefits, thus, limiting their applications. Hence, an effective delivery approach that can preserve biological activity, enhance bioavailability and achieve controlled release of bioactive compounds is desirable.

Encapsulation has been regarded as an attractive method to entrap bioactive compounds within a polymer material for the purpose of protecting and delivering bioactive compounds at the right time and to a targeted site (Ezhilarasi, Karthik, Chhanwal, & Anandharamakrishnan, 2013). Various techniques have been developed to encapsulate bioactive compounds each with their own merits and demerits. These approaches include spray drying (Đorđević, Balanč, Belščak-Cvitanović, Lević, Trifković, Kalušević, et al., 2015), freeze drying (Ray, Raychaudhuri, & Chakraborty, 2016), emulsification (Sanguansri & Augustin, 2006), inclusion complexation (Yang, Gu, Xu, Li, & Zhang, 2010), nano-precipitation (Gou, Men, Shi, Xiang, Zhang, Song, et al., 2011), liposome preparation (Coimbra, Isacchi, van Bloois, Torano, Ket, Wu, et al., 2011) and supercritical fluid (Gouin, 2004) etc. Among the methods for encapsulation, the solvent evaporation and spray-drying are the most commonly used techniques due to their simple procedures and the available industrial scale-up (Drosou, Krokida, & Biliaderis, 2016). However, the use of relatively high working temperature during the drying process may cause heat degradation and thus affecting stability and encapsulation efficiency of labile ingredients. For example, encapsulation by spray drying significantly reduced the viability of

* Corresponding author. School of Food Science and Engineering, South China University of Technology, Guangzhou 510640, China.
E-mail address: bbhwu@scut.edu.cn (H. Wu).

http://dx.doi.org/10.1016/j.tifs.2017.10.009
Received 1 May 2017; Received in revised form 4 July 2017; Accepted 17 October 2017
Available online 20 October 2017
0924-2244/

bacteria or damaged the structure of target molecules (López-Rubio, Sanchez, Wilkanowicz, Sanz, & Lagaron, 2012). The work of Fabra and coworkers demonstrated that the antioxidant capacity of α-tocopherol was decreased upon incorporation within pea protein and sodium caseinate using a casting method (Fabra, Jiménez, Talens, & Chiralt, 2014). Recently, electrospinning has been proposed as a feasible route to encapsulate bioactive compounds, including pharmaceuticals. It is a straightforward, facile and versatile method to produce fibers with high surface-to-volume ratio and porosity. Compared to the traditional encapsulation techniques, the key advantage of electrospinning process is the absence of heat, which is important for preserving the structure and achieving high encapsulation efficacy of the bioactive substances upon processing storage. Bioactive compounds, encapsulated into electrospun fibers, possess enhanced stability and functionality. For example, by virtue of their submicron to nanoscale diameters and high surface area, electrospun fibers were more responsive to changes in the surrounding atmosphere (e.g., relative humidity and temperature changes) compared to film and sheet carriers, and can enable the tunable release of entrapped compounds (Vega-Lugo & Lim, 2009). As a result, electrospun nanofibers have been well applied in multiple fields, including filtration, wound dressings, drug delivery, tissue engineering, military protective clothing etc. However, the potential application of electrospinning in the field of food science is relatively novel and less explored (Anu Bhushani & Anandharamakrishnan, 2014; Noruzi, 2016; Rezaei, Nasirpour, & Fathi, 2015; Wen, Feng, Yang, Huang, Zong, Lou, et al., 2017).

Encapsulation of bioactive compounds into fibers is often achieved by mixing the bioactive compounds with polymer solution followed by electrospinning. Regarding the encapsulation matrixes, food-grade polymers (proteins and polysaccharides) have attracted a considerable interest because they are nontoxic, biocompatible, biodegradable and sustainable. However, the electrospinning of some food-grade polymers has been restricted due to several factors (Ghorani & Tucker, 2015; Mendes, Stephansen, & Chronakis, 2017). Thus, the addition of biopolymers with food-grade polymers as delivery carriers in food systems is widely being investigated (Anu Bhushani & Anandharamakrishnan, 2014; Fathi, Martín, & McClements, 2014; Nieuwland, Geerdink, Brier, van den Eijnden, Henket, Langelaan, et al., 2013; Noruzi, 2016). Nevertheless, there is no review paper that describes the application of electrospun biopolymer nanofibers as a novel nano-encapsulation approach for bioactive compounds. Hence, in this article, a brief summary of electrospinning and its advantages are described. Recent studies in electrospinning of food-grade polymers with or without biopolymer for the purpose of encapsulation bioactive compounds are reviewed. In addition, the future scopes and existing limitations of this approach are also highlighted.

2. Electrospinning

The incorporation of bioactive compounds within electrospun fibers is an emerging technique to enhance the performance of functional materials in food industry. This approach has been revolutionizing the entire food system from production to processing and facilitating the development of innovative functional foods. A clear understanding of the electrospinning mechanism is essential to optimize the production conditions and maximize the throughput, and thus broadening the potential industrial applications in food science.

Electrospinning is an effective approach to produce sub-micron or nano-scale polymer fibers. It is performed by applying an electrical field to continuously draw the droplet of polymer solution or melt polymer into a fine fiber followed by its deposition on a grounded collector. A typical electrospinning system is schematically illustrated in Fig. 1. It consists of a high-voltage power supply, a syringe pump with a metal needle, and a grounded collector either can be a plate or a rotating drum. In electrospinning, a polymer solution or melt polymer with sufficient molecular entanglement is first extruded to form a droplet at the needle tip by a syringe pump. Then, an electric field is applied

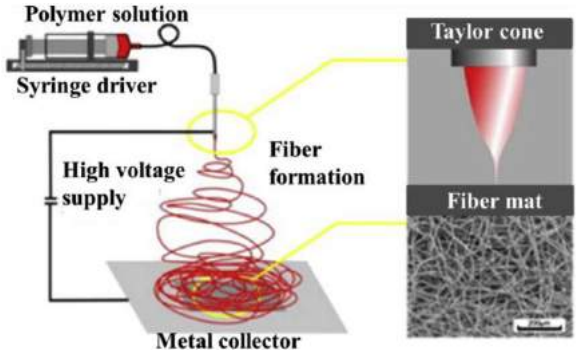

Fig. 1. Schematic illustration of the basic setup for electrospinning. (Nieuwland et al., 2013).

between the needle tip and the conductor, and the hemispherical surface of droplet is distorted into a conical shape through the action of two major electrostatic forces, including internal electrostatic repulsion and external coulombic force. With the increase of electric field strength, more electrical charges accumulate on the surface of suspended droplet, especially, when the electric field reaches a critical value under which the electrostatic repulsion counteracts the surface tension of polymer solution, the electrically charged jet of polymer is ejected from the tip of Taylor cone and directed towards the collector with opposite charges. As the jet is driven towards collector, the excess electrical charges cause the whipping or bending motion of jet, consequently, elongation of jet and rapid evaporation of solvent take place and polymer nanofibers are deposited on the grounded collector as randomly oriented, non-woven mat. The electrospinning process in terms of the spinability, fiber morphology and diameter distribution can be affected by characteristics of the solution (e.g., the type of polymer, solvent, additives, and concentration etc), the electrospinning process parameters (e.g., applied voltage, spinning distance, feed rate, and needle diameter) and ambient parameters (e.g., temperature, humidity and air flow) (Ghorani & Tucker, 2015; Mendes et al., 2017). Given the above parameters that contribute to fiber morphology, the electrospinning technique is highly tunable with the ability to modify fiber geometry, targeted collection, and fiber orientation through the modifications of setup (Fig. 2).

Electrospinning exhibits several advantages over other production methods, such as: 1) a relative ease of use, facile and being cost-effective method for production of nanofibers; 2) easy incorporation of bioactive compounds into nanofibers; 3) a decreased size requirement for bioactive compounds, allowing their incorporation into food systems without affecting the sensory qualities of products; and 4) the absence of heat during the electrospinning process, which can be of the key importance especially for sensitive compounds. In addition, nanofibers produced by electrospinning possess various structural and functional merits, such as submicron to nanoscale diameters, high surface to volume ratio, suitable porosity, tunable fiber diameters and high encapsulation efficiency for bioactive compounds. By virtue of these structural advantages, the bioactive compounds encapsulated in electrospun fibers exhibit enhanced stability and bioavailability, and can achieve targeted delivery and sustained release (Pérez-Masiá, Lagaron, & López-Rubio, 2014). Based on these advantages, electrospinning showed potential application in the field of food science (Fig. 3), such as the fabrication of functional materials for active packaging, the stabilization of nutraceuticals, improvement viability of probiotic substances, the preparation of edible films, and the construction of delivery systems for controlled release etc.

3. Encapsulation of bioactive compounds by electrospinning

Bioactive compounds are molecules that provide several benefits to

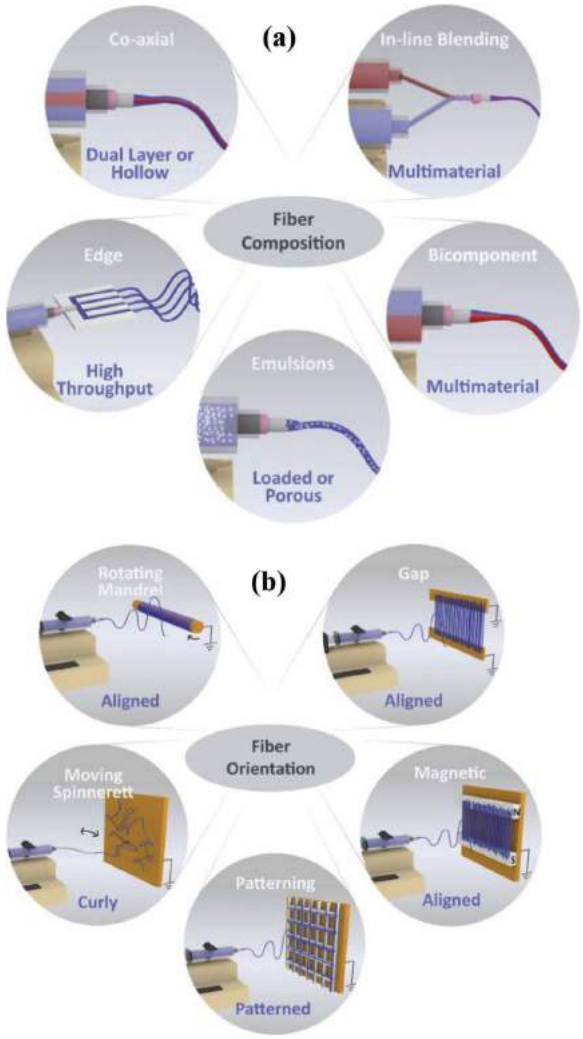

Fig. 2. (a) Schematics of electrospinning methods to alter fiber composition; (b) schematics of electrospinning methods to direct fiber orientation. (Kishan & Cosgriff-Hernandez).

human health by preventing or retarding the appearance of diseases through e.g., antioxidant, anti-inflammatory or anticancer activities etc. There are many kinds of bioactive compounds, including the hydrophobic small substances, hydrophilic small substances and macromolecular active substances (e.g., enzymes, active proteins, probiotics). However, in the food industry, their applications are limited since they are highly unstable in the presence of undesired oxygen, light, temperature or other extreme conditions. Encapsulation may represent a suitable solution to overcome this issue. Research have revealed the advantages and potential applications of electrospinning in the nano-encapsulation of bioactive compounds. For example, it can improve the stability and bioavailability of bioactive molecules and increase the viability of probiotics, which are of upmost importance for the development of novel functional food products. Another important advantage is the ability to mask undesirable odors and flavors to improve product acceptance. Additionally, the nanofibers obtained have also been used as carrier systems for the delivery and controlled or sustained release of nutraceuticals or pharmaceuticals in GIT (Mascheroni et al., 2013). Furthermore, electrospinning is a promising technique for fabrication of active packaging materials or production of nanostructured layers for food packaging (Fig. 4a), which have applications ranging from controlling microbial growth, inhibiting oxidative degradation reactions, to achieving targeted biocatalysis (see Section 3.2.1). Apart from these applications, a less explored potential application of electrospun fibers are as filtration membranes in food and beverage processing. Regarding the matrixes for encapsulation of bioactive compounds in food industry, food-grade polymers (proteins and polysaccharides) are of great interest because they are nontoxic, biocompatible and biodegradable, renewable, and sustainable. Hence, the current work aims to present a comprehensive review of electrospun carbohydrate- and protein-based polymers with or without biopolymers for the encapsulation of bioactive compounds. A number of bioactive compounds that have been used in food applications are discussed below.

3.1. Encapsulation of bioactive small molecules and potential applications

3.1.1. Hydrophobic compounds

The low water-solubility and poor stability of hydrophobic compounds limit the applications into commercial products, such as functional foods. In this section, the encapsulation of certain hydrophobic bioactive components within electrospun biopolymer fibers to improve the stability and bioavailability are briefly reviewed.

Lipid vitamins (e.g., vitamin A, D, E and K) are essential micronutrients and possess various biochemical functions in our body. However, they are susceptible to degradation during processing, storage and until the moment of their absorption in the GIT. Hence, they should be encapsulated effectively to improve their stability. α-Tocopherol (α-TOC), is the most biologically active form of Vitamin E (V_E). In a study performed by Fabra and coworkers, α-TOC was incorporated into three hydrocolloid matrixes (whey protein isolate (WPI), soybean protein isolate (SPI) and zein) by electrospinning

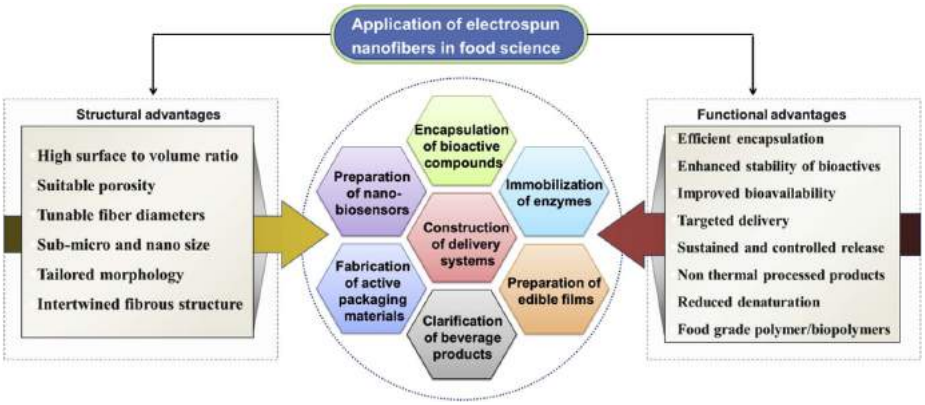

Fig. 3. A diagram of the advantages and applications of electrospun nanofibers in food science.

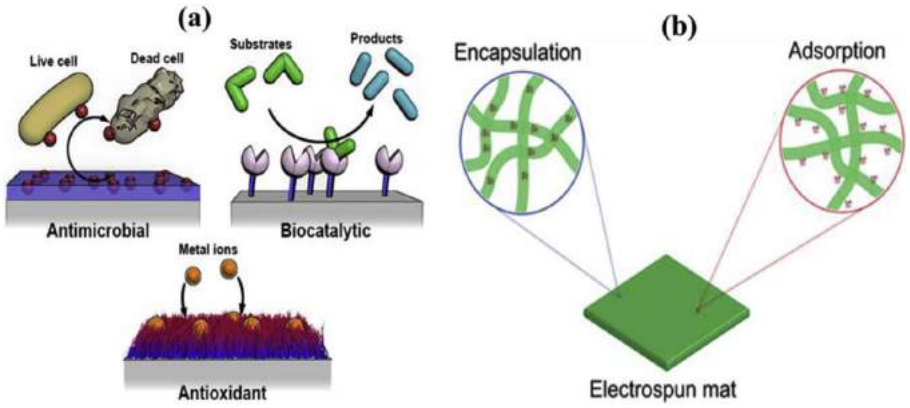

Fig. 4. (a) Schematics of major types of active food packaging (Bastarrachea, Wong, Roman, Lin, & Goddard, 2015); (b) A representation of electrospun fiber mat (in *green*) containing enzymes (in *red*) that encapsulated within the fiber (*left*) or adsorbed on the surface (*right*) (Tran & Balkus, 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fabra, López-Rubio, & Lagaron, 2016). It was found that higher encapsulation efficiency (EE) of *α*-TOC (100%) was obtained for the zein fibers compared to WPI and SPI capsules, indicating that EE are usually greater in fibers than in beads/capsules (Fig. 5). Similar results correlating morphology with EE were obtained for paraffin compounds (Pérez-Masiá, López-Rubio, Fabra, & Lagaron, 2014). One potential application of obtained material could be as a food contact layer, serving as package material for liquids products, such as juice, milk etc. In another work, Aytac & Uyar encapsulated *α*-TOC into *β*-cyclodextrin (*β*-CD) to form *α*-TOC/*β*-CD inclusion complex (IC) before electrospinning with polycaprolactone (PCL), and the results showed that the electrospun PCL/*α*-TOC/*β*-CD nanofiber exhibited higher antioxidant activity compared to PCL/*α*-TOC nanofiber (Aytac & Uyar, 2016), which was due to the presence of the IC. These results were consistent with the findings in other studies that IC can provide a better controlled release of compounds (Kayaci, Ertas, & Uyar, 2013; Kayaci, Sen, Durgun, & Uyar, 2014; Lemma et al., 2015). Mucoadhesive zein-chitosan composite nanofiber was also prepared to improve the delivery of *α*-TOC to the GIT. The resulting fibers exhibited good gastro-mucoadhesive property, and the release of *α*-TOC in simulated gastric fluid (SGF) were triggered by erosion and diffusion, demonstrating the potential applicability of zein-chitosan nanofibers as a gastro-mucoadhesive delivery vehicle for improving accessibility and bioavailability of hydrophobic compounds (Wongsasulak, Pathumban, & Yoovidhya, 2014). Vitamin A (V_A) and V_E were also successfully incorporated into biodegradable gelatin nanofibers using electrospinning. V_E can protect V_A from oxidation, resulting in less degradation during the release process. The electrospun gelatin/V_{A+E} fibers showed sustained release for more than 60 h and the dominant release mechanism was diffusion (Li et al., 2016).

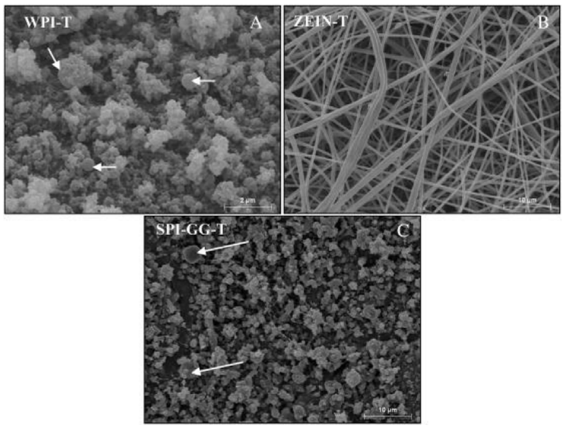

Fig. 5. Selected scanning electron microscopy microphotographs of WPI/*α*-TOC capsules (a), Zein/*α*-TOC fibers (b) and SPI-GG/*α*-TOC capsules (c) formed by means of the electrohydrodynamic process. (Fabra et al., 2016).

Omega-3 polyunsaturated fatty acids (PUFA), particularly eicosapentaenoic ($C_{20:5n-3}$, EPA) and docosahexaenoic ($C_{22:6n-3}$, DHA), have numerous beneficial health effects such as prevention of cardiovascular disease, improvement of anti-inflammatory response and development of brain and eye retina in infants. Efficient strategies for protecting these highly unsaturated fatty acids against oxidation and masking the unpleasant off-flavors are necessary. For this purpose, Moomand & Lim have successfully prepared zein fibers to encapsulate fish oil. The EE of zein fibers was higher than that from conventional methods, reaching as high as 91% for ethanol-based and 96% for isopropanol-based solvents. The oxidative stability of fish oil during storage (14 days) was also obviously enhanced in comparison to non-encapsulated fish oil (Moomand & Lim, 2014). Another study performed by both of them demonstrated that the release kinetics of omega-3-rich fish oil from zein fibers was controlled by matrix swelling, erosion and diffusion (Moomand & Lim, 2015). In a recent study, Yang and coworkers prepared core-shell electrospun fibers loaded with fish oil using coaxial electrospinning. Compared with single electrospinning, coaxial electrospinning signicantly improved the oxidative stability of encapsulated fish oil and the shelf life of encapsulated fish oil in the coaxial nanofibers was 65 days longer than that of single nanofibers, indicating that coaxial electrospinning is an effective strategy to encapsulate fish oil (Yang, Wen, Feng, Zong, Lou, & Wu, 2017).The above studies showed that electrospun nanofibers could be a useful carrier to deliver fish oil in the GIT for the functional foods and nutraceutical applications.

Curcumin is a fat-soluble polyphenol that possesses significant antioxidant and anticarcinogenic activities. Due to its poor bioavailability, new delivery carriers have been developed to achieve controlled release. For instance, uniform and homogeneous hybrid chitosan/phospholipid nanofibers were fabricated to deliver curcumin (Mendes, Gorzelanny, Halter, Schneider, & Chronakis, 2016). The release profile showed sustained release behavior of curcumin from fibers for over 7 days (around 75%) without significant burst effect. Similar release profile had been reported previously where curcumin was encapsulated within amaranth protein isolate (API)/pullulan nanofibers (Blanco-Padilla, López-Rubio, Loarca-Piña, Gómez-Mascaraque, & Mendoza, 2015). In another work, Dhandayuthapani and coworkers developed the smooth zein–curcumin fiber with a mean diameter of 310 nm, they found that curcumin maintained its free radical scavenging activity and showed sustained release behavior (Dhandayuthapani et al., 2012). As reported by Bui et al., the zein nanofibers containing 1.6 wt% curcumin can efficiently inhibit growth of *Staphylococcus aureus (S.aureus)* (83%), suggesting potential application in antibacterial nonwoven mat (Bui, Chung, & Park, 2014). In another study, curcumin-loaded zein membrane was utilized for Fe^{3+} sensing by naked-eye detection with an

optical detection limit of 0.4 mg/L (Saithongdee, Praphairaksit, & Imyim, 2014). Recently, Wang et al. prepared curcumin loaded zein electrospun fibers with good antimicrobial activity and antioxidant capacity. Release kinetics showed that the predominant release mechanism of curcumin was Fickian diffusion, exhibiting the potential as a promising material for antimicrobial applications (Wang et al., 2017). Gelatin nanofibres had also been applied for controlled release of curcumin with different surfactants (Tween 80, anionic sodium dodecyl sulfonate (SDS) and cationic cetyltrimethyl ammonium bromide (CTAB)). The addition of CTAB and Tween 80 did not significantly affect the diameter of nanofibers, while the addition of SDS afforded nanofibers with increased diameters. Furthermore, interaction between SDS and gelatin do not favor the release of curcumin, in contrast, CTAB and Tween 80 greatly improve the release of curcumin into polar solvents, resulting in a higher radical scavenging activity and a stronger antimicrobial activity. These results offer a new way to produce gelatin nanofibres with food grade surfactants for the control release of curcumin, which may find promising applications as a nutraceutical carrier in food industry (Deng, Kang, Liu, Feng, & Zhang, 2017). Curcumin has also been electrospun with cellulose acetate (CA) (Suwantong, Opanasopit, Ruktanonchai, & Supaphol, 2007) and silk fibroin (Elakkiya, Malarvizhi, Rajiv, & Natarajan, 2014).

Carotene, an antioxidant that has been widely used in food industry, is very sensitive to light and heat. Fernandez and coworkers have reported the encapsulation of carotene into zein nanofibers to increase its stability (Fernandez, Torres-Giner, & Lagaron, 2009). Results of confocal-raman spectroscopy and fluorescence microscopy showed that no remarkable chemical structure variation of carotene was observed in the nanofibers. UV–visible irradiation was used to investigate photo-oxidation of the encapsulated carotene, it found that carotene content did not change significantly after a 60 min of exposure to UV-visible radiation, while carotene content decreased dramatically in the case of control samples. In another study, dextran, whey protein concentrate (WPC) and chitosan were used as matrix materials to encapsulate lycopene by emulsion electrospinnig. WPC afforded the greatest EE (around 75%), and it was also able to protect lycopene against moisture and thermal degradation (Pérez-Masiá, Lagaron, & Lopez-Rubio, 2015).

Ferulic acid (FA), an antioxidant that can be capable of scavenging free radicals and a potent antimicrobial compound, is a preventive agent for colon cancer. However, the poor solubility of FA may impede its dissolution and absorption and thus resulting in poor bioavailability (Yu et al., 2010). A modified coaxial electrospinning process was developed to prepare medicated shellac nanofibers for the colon-targeted sustained release of FA (Wang, Yu, Li, Bligh, & Williams, 2015). *In vitro* dissolution tests revealed that less than 10% of the FA was released in a pH 2 solution, while the majority of the drug was freed over around 8 h in a neutral phosphate buffer through a complex erosion-controlled mechanism. The results suggest that the fibers comprise a useful strategy for the development of oral colon-targeted delivery system. Yan and coworkers prepared double-component nanofibers of FA-loaded CA and triple-component nanofibers of FA/polyvinyl pyrrolidone (PVP)-loaded CA through modified coaxial electrospinning processes (Yan, White, Yu, & Zhao, 2014). The results showed that the triple-component nanofibers exhibited better sustained-release profiles than the double-component nanofibers in terms of release completeness, tailing-off release time period, and release rates that could be modulated. In another study, Yang et al. prepared coaxial FA-loaded zein fibers by using acetic acid as sheath liquid and the co-dissolving solution of zein and FA as core fluid. *In vitro* dissolution tests showed that the release profile of FA from coaxial fibers exhibited better sustained-release profiles with a smaller initial burst effect and less tailing-off release compared with those from the single electrospinning fibers (Yang, Zha, Yu, & Liu, 2013), suggesting that coaxial electrospinning process is a useful tool for generating nanofibers with higher quality and improved functional performance.

Essential oils are volatile aromatic compounds that extracted from plant sources, and exhibit antibacterial, antiviral and antifungal properties. However, their applications in food industry are limited due to their poor solubility in water, high volatility and reactivity, readily being oxidized, and unpleasant aroma. Therefore, encapsulation appears to be a promising solution to solve these issues. Numerous studies have demonstrated electrospinning as effective platform to increase essential oil stability and bioactivity (Ribeiro-Santos, Andrade, Melo, & Sanches-Silva, 2017). Rose hip seed oil (REO) was encapsulated into a zein prolamine matrix using coaxial electrospinning. The EE of REO in zein prolamine matrix was 90.16%, and the resulting zein prolamine/REO electrospun films showed a significant effect on prolonging shelf-life of cumquats and bananas (Yao, Chang, Ahmad, & Li, 2016). In another study, the successful encapsulation of cinnamon essential oil into polyvinyl alcohol (PVA) and β-cyclodextrin matrix using a single needle was performed by Wen and coworkers. The resulting nanaofilm had better antimicrobial activity than the casting film, and it can effectively prolong the shelf-life of strawberry (Wen, Zhu, Wu, Zong, Jing, & Han, 2016). Actually, the complexation of bioactive compounds within cyclodextrins (CDs) before the electrospinning process has attracted a great deal of interest because it results in higher stability and allows a more sustained release (Kayaci et al., 2013). For example, Kayaci and coworkers applied the combination of IC and electrospinning techniques to improve the thermal stability and shelf life of the geraniol, a natural component of plant essential oils (Kayaci et al., 2014). The NMR study of PVA/γ-CD/geraniol showed that only 10% of geraniol was lost after 2 years storage at room temperature. This finding was in agreement with the other studies that demonstrated CD encapsulation could significantly improve the stability and shelf life of bioactive substances (Kayaci et al., 2013; Lemma et al., 2015). Wen and coworkers also observed that the inhibition zone of polylaceticacid/cinnamon essential oil-β-cyclodextrin inclusion complex (PLA/CEO-β-CD-IC) nanofilm was wider than in a PLA/CEO nanofilm. This might be attributed to the entrapment of CEO into the cavity of β-CD, which improves the solubility of CEO, leading to the efficient release of antimicrobials into the agar medium (Wen, Zhu, Feng, Liu, Lou, Li, et al., 2016). Besides that, Mascheroni and coworkers developed an edible polysaccharide nanofilm of pullulan-cyclodextrin for the efficient encapsulation and controlled release of perillaldehyde, the dominant constituent of perilla essential oil (Mascheroni et al., 2013). Release of perillaldehyde was negligible under ambient conditions (23 °C and 55% relative humidity) and even at high temperatures (up to 230 °C). In fact, the release was triggered at a higher relative humidity (threshold, $a_W \geq 0.9$) suggesting a potential application in active food packaging.

Allyl isothiocyanate (AITC) is a natural antimicrobial compound found in plants. The application of AITC is somehow restricted because of its highly volatile nature, unpleasant odor and hydrophobic nature. In a recent study, functional PVA-based nanofibers containing AITC and AITC/β-cyclodextrin inclusion complexation (β-CD-IC) were fabricated. ^{1}H-NMR analysis showed that a higher amount of AITC was encapsulated in the PVA/AITC/β-CD-IC nanofiber sample due to β-CD-IC, while the evaporation of AITC during electrospinning led to a reduced quantity of AITC in PVA/AITC nanofiber. Thus, PVA/AITC/β-CD-IC nanofiber showed better antibacterial activity against *E.coli* (94%) and *S.aureus* (100%) in comparison with PVA/AITC nanofibers that exhibited 32% and 54% activity, respectively (Aytac, Dogan, Tekinay, & Uyar, 2014). In a similar study, Vega-Lugo and coworkers incorporated AITC and AITC/β-CD-IC into SPI/polyoxyethylene (PEO) electrospun solutions and the resulting fibers exhibited humidity triggered release of the active compound, showing potential in active packaging (Vega-Lugo & Lim, 2009).

The encapsulation and the controlled release of other hydrophobic bioactive compounds have also been achieved using electrospun biopolymer fibers. For example, a controlled-release system for sea holly extract was fabricated by loading which into electrospun CA fibers (460 ± 84 nm) (Vongsetskul, Phurayar, Chutimasakul, Tuchinda,

Uamsiri, Kumkate, et al., 2016). The obtained fibers exhibited good antioxidant activity, and approximately 99% of the loaded extract was released from fibers in the acetate buffer at 37 °C through a diffusion mechanism, while only 35% of which could be released from the corresponding casting films. In another study, Chantarodsakun and coworkers reported the successful incorporation of [6]-gingerol into electrospun CA fibers for a potential application as a controlled release system. The release data showed that ~97% of [6]-gingerol could be released from fibers at 37 °C, whereas only 74% of which was released from the corresponding films (Chantarodsakun, Vongsetskul, Jangpatarapongsa, Tuchinda, Uamsiri, Bamrungcharoen, et al., 2014). Electrospun CA-based fiber film containing 50% neem seed oil exhibited antifungal effect on wounded-inoculated tomatoes when the utilized weight ratio of the film to tomato weight ratio was 125 mg/kg in a 100% relative humidity (Ai-Tang, Utarak, Yoovidhya, Intasanta, & Wongsasulak, 2013). In the study performed by Xu and Yang, SPI fibers was reported for encapsulation and controlled release three different compounds, metformin, 5-flouracil, and diclofenac. It showed that compounds with higher affinity of SPI possessed higher sorption loading capacity and a more sustained release rate (Xu & Yang, 2009).

As reported previously, the polymeric electrospun nanofibers incorporating cyclodextrin inclusion complex (CD-IC) with various active compounds have been fabricated to enhance their solubility and thermal stability, to achieve controlled release and to prolong shelf life for the applications in food packaging, functional foods and pharmaceutical fields (Aytac & Uyar, 2017; Aytac, Ipek, Durgun, Tekinay, & Uyar, 2017; Aytac, Keskin, Tekinay, & Uyar, 2017; Aytac, Kusku, Durgun, & Uyar, 2016b; Canbolat, Savas, & Gultekin, 2017; Costoya, Concheiro, & Alvarez-Lorenzo, 2017). However, some organic solvents have been used in some of these studies in order to dissolve the polymeric matrix for the preparation of electrospinning solution, and the weight loading of bioactive compounds was generally limited up to 5% (w/w) (with respect to polymer matrix) because the incorporation of higher amount of CD-IC affect the electrospinning to produce uniform nanofibers. Comparatively, polymer-free CD-IC electrospun nanofibers with bioactive molecules was a promising method to prepare bead-free fibers and to improve the loading capacity of guest molecules (Celebioglu & Uyar, 2011). For example, polymer-free nanofibers of cyclodextrin/linalool-inclusion complex (CD/linalool-IC-NFs) with a maximum loading of linalool up to 12% (w/w) were successfully obtained from three modified CD types, hydroxypropyl-beta-cyclodextrin (HPβCD), methylated-beta-cyclodextrin (MβCD) and hydroxypropyl-gamma-cyclodextrin (HPγCD) (Aytac, Yildiz, Kayaci-Senirmak, Tekinay, & Uyar, 2017). The resulting bead-free CD/linalool-IC-NFs can be dissolved completely in water within two seconds, especially, due to the higher solubility of HPγCD/linalool-IC than the HPβCD/linalool-IC and MβCD/linalool-IC, the HPγCD/linalool-IC-NF showed higher antibacterial efficiency than the HPβCD/linalool-IC-NF and MβCD/linalool-IC-NF. This result was correlated with the literature where essential oils complexed with HPβCD have shown much higher antibacterial efficiency than complexion with native CDs (α-CD, β-CD) (Liang, Yuan, Vriesekoop, & Lv, 2012). In another study, the uniform V_E/HPβCD-IC NF with a very high loading of V_E (up to ~11% w/w, with respect to fiber matrix) was also obtained, as well as the enhanced water-solubility, prolonged shelf life, and high photostability of V_E (Celebioglu & Uyar, 2017) (Fig. 6). Other polymer-free CD-IC nanofibers have been produced from IC of non-volatile compounds like triclosan (Celebioglu & Uyar, 2011; Celebioglu, Umu, Tekinay, & Uyar, 2014), sulfisoxazole (Yildiz, Celebioglu, & Uyar,) and volatile compounds such as geraniol (Aytac et al., 2016a,b,c), limonene (Aytac, Yildiz, Kayaci-Senirmak, San Keskin, Kusku, Durgun, et al., 2016), and vanillin(Celebioglu, Kayaci-Senirmak, Ipek, Durgun, & Uyar, 2016). The above-mentioned studies indicate that the electrospinning of polymer-free CD-IC nanofibers provides much higher loading capacity of guest molecules (up to ~10–15%, w/w), and much higher fiber throughput can be achieved for the electrospinning of polymer-free CD-IC systems when compare to polymeric systems. The results may open a new door to preserve bioactive compounds along with enhanced bioactivity, and to provide novel approaches for increased water-solubility formulations, which may be used as fast-dissolving supplement material in food and pharmaceutical products.

3.1.2. Hydrophilic compounds

Encapsulation of hydrophilic compounds may be required to prevent their chemical degradation, to inhibit adverse interactions with other components, to mask off-flavors, to ensure stability within the GIT, or to obtain a particular release profile. In this section, a brief introduction of encapsulation hydrophilic bioactive agents (such as anthocynanins, water-soluble vitamins, functional organic acids etc) with electrospun biopolymer nanofibers in the food industry is given.

Gallic acid (GA), a natural antioxidant, was successfully incorporated into zein nanofibers at different loading ratios by Neo and coworkers with the aim of making functional edible nanofibers. The 1,1′-diphenyl-2-picrylhydrazyl (DPPH) assay indicated that encapsulated GA retained its original antioxidant properties. In another study, the nont-toxic GA loaded zein fibers with good antimicrobial properties was prepared, the release of GA from zein fibers was based on Fickian diffusion (Neo et al., 2013), suggesting the potential application as novel and safe food contact materials in food industry. Especially, a further study performed by Neo's group showed that the larger fiber diameters, enhanced hydrophobicity of obtained fibers and slower release profile of GA were occurred after the heat-curing process (Neo et al., 2014). This newly exhibited properties offer a potential to develop new protein-based nanostructured electrospun fibers for food packaging or food-contact materials with improved properties. Aytac et al. incorporated GA with hydroxypropyl-β-cyclodextrin (GA/HP-β-CD-IC) and then electrospun it with polylactic acid (PLA) to form PLA/GA/HP-β-CD-IC nanofibers. The release studies revealed that higher amount of GA was achieved from PLA/GA/HP-β-CD-IC nanofibers compared to PLA/GA nanofibers. The electrospinning process had no negative effect on the antioxidant activity of GA, suggesting that the obtained fibers might be applicable as an antioxidant food packaging material to increase the shelf life of food products and improve the overall food quality (Aytac, Kusku, Durgun, & Uyar, 2016a). (−)-Epigallocatechin gallate (EGCG), an antioxidant found in green tea, was encapsulated in water-insoluble zein nanofibers by Li and coworkers to enhance its stability in water (Li, Lim, & Kakuda, 2009). The results indicated that the release rate of EGCG in water depended on the ageing time and the relative humidity. Ageing in 0% humidity led to only 2% EGCG released in water, whereas ageing in 75% humidity led to a significant release in water.

Water-soluble vitamins are also incorporated into electrospun fibers. Folic acid (vitamin B) is susceptible to degradation when exposed to light and acidic conditions. The study of Alborzi et al. showed that the folic acid encapsulated in electrospun fibers could achieve almost 100% retention when stored in the dark at pH 3 after 41 days of storage, while the recovery of non-encapsulated folic acid after one day of storage at pH 3 was 8% and 0% in the absence and the presence of light, respectively. FTIR and NMR data demonstrated that the enhanced protection of folic acid by the electrospun fibers could be attributed to the physical entrapment, rather than folic acid -polymer interaction (Alborzi, Lim, & Kakuda, 2013). Food-grade amaranth (*Amaranthus hypochondriacus* L.) protein isolate-pullulan electrospun fibers was also used to encapsulate folic acid (Aceituno-Medina, Mendoza, Lagaron, & López-Rubio, 2015). Uniform and homogeneous hybrid chitosan/phospholipid nanofiber was fabricated to deliver Vitamin B12 (Goto, Masuda, & Aiba, 2015). The release profile showed that a burst release was occurred within 1 day and reached the maximum (nearly 100%) at day 2, which was similar to the previously published result (Madhaiyan, Sridhar, Sundarrajan, Venugopal, & Ramakrishna, 2013). Water-soluble derivative of V_E-loaded silk fibroin nanofibrous mats had

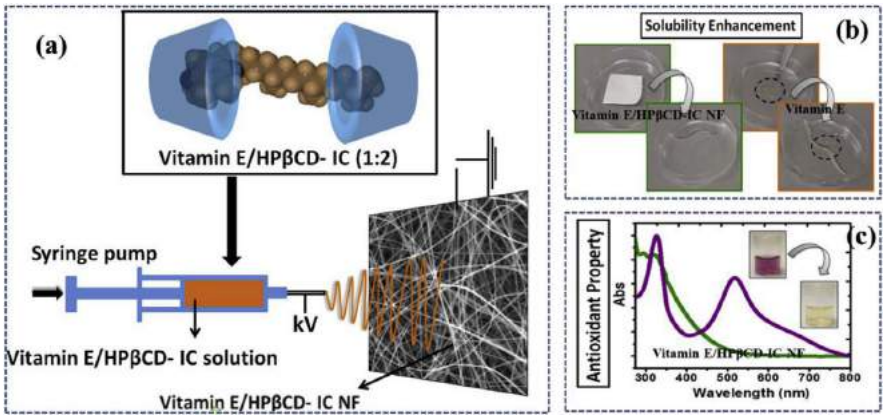

Fig. 6. (a) Schematic illustration of the V_E/HPβCD IC formation and electrospinning of V_E/HPβCD-IC NF; (b) Visual presentation of the water-solubility behavior of V_E/HPβCD-IC NF and V_E; (c) DPPH scavenging efficiency of freshly prepared V_E/HPβCD-IC NF after UV light exposure. (Celebioglu & Uyar, 2017).

been reported by Sheng and coworkers (Sheng et al., 2013). The vitamin exhibited a sustained release behaviour, moreover, the incorporation of vitamin could enhance the ability of silk fibroin nanofibers for protecting the cells against oxidation stress.

Anthocyanin is a water-soluble phytochemical that belongs to the flavonoids group. The anthocyanin rich plant extract shows a variety of applications in food science due to its multiple biological activities. Red raspberry extract (RRE), which is rich in anthocyanins, was incorporated into SPI before and after SPI denaturation by Wang and coworkers (Wang, Marcone, Barbut, & Lim, 2013). Although electron microscopy analysis indicated that both cases generated beaded nanofibers, functionalized nanofibers were obtained with good antimicrobial and antioxidant properties. It was noted that the incorporation of RRE into denatured SPI solution exerted the higher anthocyanin retention and greater antimicrobial activity. Proanthocyanidins (PA) was also encapsulated into zein fibers with an EE close to 100%. The encapsulated PA retained its antioxidant capacity in fibers, and the release of PA from fibers was based on Fickian diffusion, which was well described by a first-order model and a Hixson–Crowell model (Wang et al., 2016).

The encapsulation and the controlled release of other hydrophilic bioactive compounds have also been reported. Asiaticoside, the major component of *Centella asiatica* extracts that possesses wound healing ability, was electrospun with gelatin to improve its functionality (Panprung, Apichart, & Pitt, 2008). The author observed that higher amount of asiaticoside was in electrospun fiber compared to the casting film (~99 and ~87%, respectively). In addition, due to the greater surface area of the fiber over that of the film, greater release of asiaticoside was from the fiber mat over that from the film counterparts. Xiao and coworkers encapsulated carnosic acid into the kafirin protein-based nanofibers and the release of which followed a Fickian diffusion manner, suggesting potential nutraceutical delivery applications (Xiao et al., 2016). The study of de Oliveira Mori and coworkers confirmed the possibility of incorporating tannin into electrospun zein nanofibers with a ribbon-like shape and homogeneous morphology (de Oliveira Mori, dos Passos, Oliveira, Mattoso, Mori, Carvalho, et al., 2014). Yang et al. prepared tannic acid (TA)-Fe^{3+} loaded electrospun CA fibers with improved mechanical and antioxidant properties. The 2,2′-Azinobis-(3-ethylbenzthiazoline-6-sulphonate) (ABTS) results showed that TA retained its antioxidant activity in electrospun fibers, and a more sustained release behavior was observed for the CA mats with TA-Fe^{3+} (Yang, Sousa, Fan, Jin, Li, Tomasula, et al., 2017). The studies indicate that electrospinning is an excellent approach for encapsulation and controlled release of bioactive compounds.

3.2. Encapsulation of biological macromolecules and potential applications

3.2.1. Enzymes

Immobilized enzymes are widely used in food industry, in biosensors and in bioactive food packaging for food quality and safety. Immobilization confers enhanced enzyme stability to environmental changes, such as pH or temperature, and also serves as a medium for controlled release (Lopez-Rubio, Gavara, & Lagaron, 2006). Electrospinning, a simple and versatile method to fabricate nanofibrous supports, has attracted attention in the field of enzyme immobilization. Two major methods have been employed to assemble enzymes and polymeric fibers using electrospinning: (i) immobilization of the enzyme on the outer surface of the nanofibers and (ii) mixing enzyme with the polymer solution and subsequently spinning (Fig. 4b). The electrospun biopolymer nanofibers act as a support structure for enzyme immobilization, and can preserve activity and increase surface area and porosity, improving the efficiency of immobilized enzymes (Kim, Grate, & Wang, 2008). Apart from encapsulation, enzymes can be physically adsorbed or covalently attached to nanofibers.

Glucose oxidase (GOD) is an efficient scavenger. As a result, its incorporation into packaging materials can greatly prevent oxidation and spoilage of food materials and, thus, improve shelf life. Various studies have been carried out to immobilize GOD. Ge and coworkers immobilized GOD in PVA/chitosan/tea extract nanofibers to make a novel food packaging system (Ge, Zhao, Mo, Li, & Li, 2012). Immobilized enzyme still maintained 68% of its free enzyme activity and the electrospun membrane exhibited around 73% deoxidization efficiency in the test samples (haw jelly and cream cake). Although its effect on sugar-rich or semi-solid foods was low, it might have potential in food preservation applications. A new glucose amperometric biosensor was developed by immobilizing GOD on PVA/chitostan nanofibers (Su et al., 2013). Enzyme-loaded electrospun membrane can serve as a better sensing element due to the unique properties of nanofibers such as the special three-dimensional network structure, large pores, high porosity, and large surface to volume ratios.

Lipases are important enzymes for bioconversion reactions in the food industry, especially in the fats and oils, dairy and bakery industries. However, the high cost of lipase restricts its applications. Enzyme immobilization is an effective way to overcome these limitations. Researchers have used electrospun fibers as structural supports or as encapsulation matrices in the immobilization of lipases. Lipase encapsulated in the ultra-fine fibrous membranes PEO/casein or PVA/casein exhibited higher catalytic activity towards hydrolyzing olive oil than that in the cast films from the same solution, suggesting that electrospun fibrous membranes can serve as excellent enzyme-carrying substrate due to their higher surface area and porous structures (Xie & Hsieh, 2003). The release of free fatty acids reveals that enzyme-catalyzed hydrolysis of PVA/lipase membrane was higher than that of PEO/casein/lipase membrane. Although the activity of immobilized enzyme was much lower than the free enzyme, the lipase activity as a part of electrospun membrane was found to be 6-fold greater than that of the casting membrane. Huang and co-workers described lipase

immobilization using cellulose as supporting material. They immobilized lipase in a nanofibrous chitosan/PVA membrane using glutaraldehyde as a coupling agent. The lipase loading on this nanofibrous membrane was up to 64 mg/g, and the residual activities of the immobilized lipase were more than 50% after 30 days, suggesting excellent reusability and storage stability (Huang, Ge, & Xu, 2007). In another study, Huang and coworkers immobilized *Candida rugosa* lipase on electrospun CA nanofibers. By applying response surface methodology to optimize the oxidation conditions of the membrane, lipase can be directly tethered on the oxidized cellulose membrane with an activity retention as high as 30 U/g (Huang et al., 2011). Chen et al. immobilized lipase onto the regenerated cellulose ultrafine fibers for oil hydrolysis (Chen et al., 2011). This resulted in 1.07×10^4 U/g of lipase-immobilized membrane, while an activity of $9.83 \times 10^4 U/m^2$ was obtained under optimal operating conditions. Siqueira and coworkers recently reported an electrospun chitosan and PLA fibers employed as support for immobilization of *Pseudomonas cepacia* lipase. The results showed that the addition of chitosan, with more hydrophilic groups, reduced enzyme activity (Siqueira et al., 2015). They concluded that the mechanism of interaction between fiber mat and enzyme was through a hydrophobic physical adsorption, correspondingly, hydrophilic groups present on the surface of the support could result in surface hydration, inhibiting lipase adsorption (Huang et al., 2007).

In another study, Han and coworkers incorporated horseradish peroxidase (HRP) in chitosan hydrogel followed by suspension electrospinning to achieve controlled release (Han, Zhang, Zhao, Zhao, & Yuan, 2013). The EE for HRP was high (> 70%) and the burst release was < 20%, and the release rate of HRP from electrospun fibers with encapsulated hydrogel was larger than that from emulsion spun fibers because of the higher hydrophilicity of the hydrogel system. The above studies suggest a new strategy for encapsulating enzymes. The potential of electrospinning biopolymers for enzyme immobilization should aid in the effective utilization of immobilized enzymes and facilitate continuous reactions. However, the use of electrospinning for enzyme immobilization has not yet to be commercialized. Collaborations between researchers and manufacturers in the fabrication of industrial level electrospinning machines to prepare commercial nanofibers may lead to the applications of these technologies in the food sector.

3.2.2. Bioactivity proteins and peptides

The direct addition of active protein in practical food systems suffers from the disadvantage of inactivation caused by food components and environmental factors, thus limiting their successful incorporation into packaging materials, functional foods and edible films. The facile electrospinning process is expected to incorporate proteins into functional materials while preserve their bioactivity.

Nisin is a heat-stable peptide with a status of "General Recognized As Safe" (GRAS) by the Food Drug Administration. It is the only antimicrobial bacteriocin that exhibits antimicrobial activity against foodborne pathogenic microorganism. Nevertheless, its interaction with food components results in the loss of antimicrobial activity, limiting its use as a food ingredient. A novel nisin carrier was prepared by incorporating nisin into the amaranth protein-pullulan nanofibers to maintain its antimicrobial activity (Soto et al., 2016). The average fiber diameters, from 173 to 124 nm, decreased with increasing of nisin content. Fibers containing 20 mg/mL of nisin reached an encapsulation efficacy of 95% with good antimicrobial activity against *L. mesenteroides*. The electrospun mats obtained in this study were based on biodegradable food grade biopolymers, suggesting potential application as edible films or packaging material in food industry. A nisin-loaded (0–3%, wt/wt) gelatin electrospun fiber was also produced in 70% (v/v) acetic acid aqueous solution (Dheraprasart, Rengpipat, Supaphol, & Tattiyakul, 2009). It was found that around 1.0–1.22% of nisin was retained in the fibers, and the release of which could be facilitated by increasing temperature. After storage at 25 °C for 5 months, the antimicrobial fibers still showed inhibition against *Lactobacillus plantarum* TISTR 850. In another study, nisin was incorporated into poly (vinyl alcohol)/wheat gluten/zirconia (Nisin-PVA/WG/ZrO_2) nanofibrous membrane via electrospinning (Wang, She, Chu, Liu, Jiang, Sun, et al., 2015). The antimicrobial activity and release experimental results showed that the nisin-PVA/WG/ZrO_2 nanofilm displayed better antimicrobial activity against *S.aureus* and the nisin release from the nanofibers could be described by Fickian diffusion model, despite a very slight initial burst release phenomenon was presented during the first 7 h. Conventional (homogenous single or blended) electrospinning techniques were utilized and the sustained (multiple days) antimicrobial effect of the incorporated nisin was not achieved in the above nisin-containing fibers. Recently, the encapsulation of nisin into the core of a multi-layer fiber constructure with a hydrophobic PCL intermediate layer and a hygroscopic CA sheath, was prepared using triaxial electrospinning (Han, Sherman, Filocamo, & Steckl, 2017) (Fig. 7). Compared with other types of electrospun membranes, the obtained triaxial fiber membrane exhibited a more excellent and sustained antimicrobial activity of > 4 log kill for up to 5 days and then provide

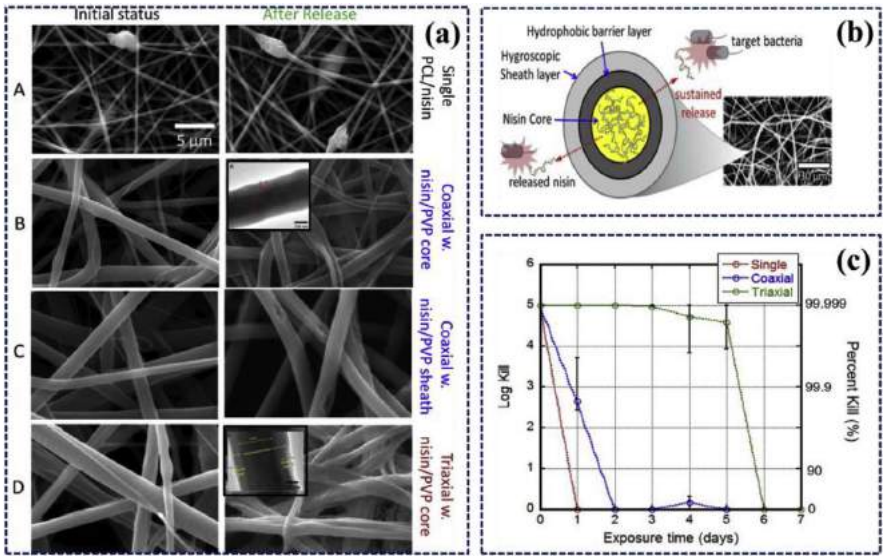

Fig. 7. (a) SEM and TEM microphotographs of nisin incorporated electrospun fibers; (b) Schematic illustration of nisin released from electrospun triaxial fiber membranes; (c) Quantitative analysis (AATCC100) of antimicrobial activity on electrospun membranes: bacteria log kill value vs. exposure days. (D. Han et al., 2017).

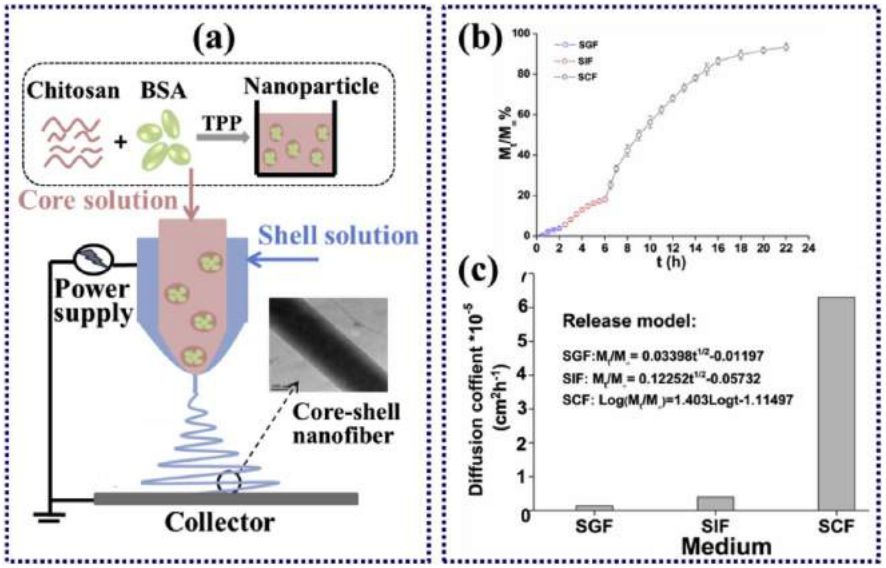

Fig. 8. (a) Schematics illustration of the core-shell structured electrospun nanofilm as a promising colon-specific delivery system for bioactive protein; (b) In vitro release profile of BSA from electrospun fiber mat; (c) The fitted curves and diffusion coefficients of BSA in different medium. (Wen, Wen, et al., 2017).

biostatic activity for 2 or more days, while the nisin-loaded single homogenous fibers showed relatively weak activity only for one day and coaxial fibers with nisin exhibited > 99% bacteria kill (2 log kill) after 1 day of exposure. This will be highly beneficial in many applications, such as protective textiles, food packaging and cancer therapy.

Lysozyme (LZ) is an effective protein against pathogenic microorganisms by damaging bacterial cell walls. The practical application of free LZ is limited because it is unstable and easily inactivated. Therefore, most researchers have focused in immobilized LZ. LZ was successfully loaded into chitosan–ethylenediaminetetraacetic acid (CS-EDTA)/PVA nanofiber without losing its activity (Charernsriwilaiwat, Opanasopit, Rojanarata, & Ngawhirunpat, 2012). The content of LZ in the nanofiber mats was 92–95% with the increase of LZ concentration from 10% to 30%. However, burst release of LZ was observed as cumulative release reached ~80% within 30 min, which was owing to the erosion of hydrophilic polymer and LZ diffusion. Another approach for incorporating LZ into nanofibers was described by Park and coworkers who immobilized hen egg-white LZ on electrospun CS nanofibers through cross-linked enzyme aggregates (CLEAs) (Park et al., 2013). The immobilized LZ-CLEA retained more than 75% of its initial activity after 80 days of storage at room temperature, while the free LZ lost all of its activity under the same conditions. After 10 cycles, the LZ-CLEA immobilized CS nanofibers can still effectively against four pathogenic bacteria with an antibacterial ratios of > 80% (Park et al., 2013). These results suggest that LZ-CLEA immobilized CS nanofibers could be used as a promising material for enhanced stability and remarkable high reusability of LZ in industrial applications. Huang and coworkers immobilized positively charged LZ-CS-organic rectorite composites on the negatively charged electrospun CA fibrous mats using a layer-by-layer (LBL) self-assembly technique, and the resulting film could extend the shelf life of fresh pork for about 3 days (Huang et al., 2012). This approach suggested that LZ immobilized onto a biopolymer might also be utilized to tailor the compositions and surface properties of other nanomaterials for various applications such as catalysis, wound dressing and antimicrobial packaging.

Lactoferrin, an 80 kDa iron binding glycoprotein, possesses diverse functions as a growth factor, antimicrobial and immune modulating agent. Padrão and coworkers fabricated a bovine lactoferrin (bLF)-based nanocomposite using fish gelatin as the structural matrix (Padrão et al., 2015). In this study, the incorporation of bLF into fibers was achieved either as a filler in electrospinning followed by glutaraldehyde vapour cross-linking, or through adsorption in a solution with 40 mg/mL bLF. The intact structure and the bactericidal efficiency of bLF against *E.coli* and *S.aureus* were all remained after the electrospinning and cross-linking procedure, and a higher killing capacity of bLF in electrospun samples was obtained compared to that of adsorbed bLF.

The maintenance of other proteins' stability and activity has been demonstrated in a number of studies. For example, insulin was efficiently encapsulated into water soluble fish sarcoplasmic protein (FSP) fibers without affecting the structure of the insulin (Stephansen, García-Díaz, Jessen, Chronakis, & Nielsen, 2015). The encapsulation of insulin into FSP fibers provided protection against chymotrypsin degradation, and resulted in an increase in insulin transport to ~12% without compromising the cellular viability. This increased transport was driven by interactions between the nanofibers and the Caco-2 cell monolayer that led to the opening of the tight junction proteins. In a recent study, a novel core-shell structured nanofilm for the delivery of bovine serum albumin (BSA) to the colon was developed by coaxial electrospinning (Wen, Wen, Huang, Zong, & Wu, 2017). Approximately 75% of BSA was released in simulated colonic fluid (SCF), and the release profile was better fitted with the Ritger-Peppas model (R^2 > 0.99, n = 1.043), indicating that the release mechanism was Super Case II transport, in which the erosion of polymer matrix was dominant. The diffusion coefficients (D) data of BSA from electrospun fiber mat in simulated gastric fluid (SGF), simulated intestinal fluid (SIF) and SCF also demonstrated that the degradation of matrix led to the release of BSA (Fig. 8). Furthermore, the FTIR and circular dichroism analysis indicated that the encapsulated BSA was still kept structural integrity. In another study, the release mechanism of the model protein gelatin from coaxially electrospun core-shell CA fibers was found to be anomalous diffusion, exhibiting a near zero order release pattern with release half-life of ~7.4 days (Sakuldao, Yoovidhya, & Wongsasulak, 2011). It was noted that, the structure of obtained nanofilms that immersed in PBS for 20 days were found intact, suggesting the potential for the controlled release of functional compounds to the GIT. Electrosupinning of food-grade globular proteins was also feasible using gelatin as a carrier polymer (Nieuwland et al., 2013). The capability of achieving controlled release of the fragile growth factors (GFs) with desirable bioactivity was also possible using biopolymer electrospinning (Tian et al., 2015). According to Zhang and coworkers, a wound dressing material comprise of poly-L-lactic acid (PLLA)/zein nanofiber that loaded with rana chensinensis skin peptides was also successfully produced by blend and coaxial electrospinning techniques (Zhang, Li, Li, Liu, & Hao, 2016).

3.2.3. Probiotics

The encapsulation of probiotics, enhancing their stability during food processing and storage and passing through upper GI tract, is also an area of great interest for both academia and the food industries. Probiotics are living microorganisms (in most cases, bacteria) that are used in supplements and foods, especially for dairy products. They provide health benefits such as the reduction of gastrointestinal infections and serum cholesterol, improvement in lactose metabolism and immune system defense (Jankovic, Sybesma, Phothirath, Ananta, & Mercenier, 2010). However, considerable loss of probiotic viability inevitably occurs during processing and oral administration, especially in the upper GIT. Growing attention has been made to achieve efficient oral administration of probiotic bacteria as nutraceuticals in recent years (Zheng, Gao, Ren, Lou, Xie, Yu, et al., 2017). The most common techniques to encapsulate probiotics are extrusion, emulsification and spray drying. However, the main demerits of above methods are the use of high temperature or organic solvents, for instance, the viability of bacteria was significantly reduced by spray drying (López-Rubio et al., 2012). Electrospinning technique has been established as a promising encapsulation approach. López-Rubio and coworkers demonstrated the feasibility of using electrospinning for encapsulating *Bifidobacterium* strains in food hydrocolloids for functional food applications. The viability of *Bifidobacterium* strains (specifically *Bifidobacterium animalis* subsp. *lactis Bb12*) was enhanced by encapsulation it into PVA electrospun nanofibers (average diameter 150 nm). The encapsulation process did not affect the viability of the cells and the viability of encapsulated bacteria was significantly higher than that of non-encapsulated bacteria after 40 days of storage at room temperature (20 °C) and 130 days at refrigerated temperature (4 °C), respectively (López-Rubio, Sanchez, Sanz, & Lagaron, 2009). In another work, the viability studies showed good survivability of *Lactobacillus acidophilus* (78.6–90%) after electrospinning and retained viability for over 21 day storage at 4 °C (Fung, Yuen, & Liong, 2011). Living cells of *L.gasseri*-inanimate were also successfully incorporated into PVA nanofibers (Amna, Hassan, Pandeya, Khil, & Hwang, 2013). A negligible decrease in the viability of encapsulated *L.gasseri* was observed upon electrospinning and *L. gasseri* showed good viability at −70 °C for long-term preservation. However, the encapsulation of probiotics in the above studies was accomplished using synthetic polymers. Proteins and polysaccharides have attracted a considerable interest because these natural biopolymers are considered as amphiphilic macromolecules that play an essential role in stabilizing food formulations. For example, López-Rubio and coworkers have demonstrated the feasibility of electrospinning of WPC and pullulan for encapsulation *Bifidobacterium* strains in food hydrocolloids. WPC demonstrated greater protective ability as an encapsulation material than pullulan, as it effectively prolonged the survival of cells even at high relative humidities (López-Rubio et al., 2012). Recently, starch-formate/glycerol (SFG) fibers loaded with *Lactobacillus paracasei* was successfully fabricated by coaxial electrospinning (Lancuški, Abu Ammar, Avrahami, Vilensky, Vasilyev, & Zussman, 2017). The entrapped microorganism was stable with retained bacterial viability when stored at 4 °C and room temperature for up to 21 days. The SFG fibers exhibit a potential alternative route for cell encapsulation and extended storage of biotherapeutic products. The advantage of using natural biopolymers, which are permitted in the food industry, may allow the development of commercially available probiotics-loaded electrospun edible films for functional foods. Since it had reported that some biopolymers (such as pectin–-whey protein, milk and pea protein and pectin etc) can improve stability and viability of various probiotics by other encapsulation methods, the potential application of encapsulation probiotics by these biopolymers can be achieved through optimizing the electrospinning parameters. Further, researches may be warranted to prepare nanofibers with increased EE, probiotic stability and controlled release properties. This might be accomplished by the utilization of coaxial or emulsion electrospinning techniques. In summary, electrospinning allows the design of novel delivery system for probiotics and can increase the performance of functional foods.

4. Current limitations and future trends

Although electrospinning has made significant progress in the laboratory scale in the past two decades, obstacles still exist that limit the application of electrospinning in the food industry. The main limitation of electrospinning is low throughput, which restricts its large-scale commercial exploitation. Thus, addressing this constraint by modifying the structural aspects of electrospinning setup (e.g., multi-needle arrangement) is a vital area of research. Secondly, the established general parameters for successful encapsulation and controlled release of bioactive agents is challenging because of the myriad of polymers, solvents, experimental conditions, and compounds to choose from. Hence, it is critical to determine specific applications for bioactive compounds-loaded nanofibers. Additionally, the probable or proposed applications of electrospun fibers have to be efficiently translated to their use in food systems. Studies are required to prove the workability of the resultant products as active/smart food packaging materials without altering the physical and chemical characteristics of food. Finally, with respect to food safety, one reason why nanofibers have not been widely adopted in the food industry can be attributed to the prevalence of studies on synthetic polymers rather than on biopolymers. Questions on consuming nano-scale food materials still remain and need to be further analyzed, as do their effects on human health and the environment. Legislation by government agencies on the application of nanomaterials in the food industry is needed to ensure the safe of nano-food products.

Electrospinning has demonstrated great potential for developing innovative products with specific new properties, nevertheless, its application in agriculture and food science is still in the early stages of development. One of the main areas where electrospun nanofibers can be developed further in the future is novel functional foods and food packaging materials because antimicrobials, antioxidants, and other bioactive materials can be easily incorporated into electrospun nanofibers. The utilization and modifications of coaxial or emulsion electrospinning to generate core-shell structured nanofibers may be required to achieve sustained release or construct a suitable delivery device if the fragile compounds are not suitable for blend electrospinning. This approach can also facilitate the designs of multiaxial nanofibers that exhibit three (or more) distinct layers in individual fibers, thus the bioactive compounds may be loaded into any or all of the layers to produce systems with highly specific applications. Moreover, combining electrospinning with other technologies, such as liposomes, nanoparticles, from the micro/nano encapsulation field can also broaden the possibilities for new products with improved functionalities. In addition, due to the extensive environmental pollution caused by chemical pesticides and synthetic polymers, the need for replacing them with natural bio-antimicrobials and biopolymers should be considered. Furthermore, mathematical modeling of the release profile of bioactive compounds would be an interesting topic to study. Such modeling can help predict release amounts and select suitable materials for obtaining desirable release kinetics. Electrospun nanofibers also achieved remarkable effects in water purification and desalination mainly because of high surface area, porous structure, and high functionality (Ahmed, Lalia, & Hashaikeh, 2015), hence, the application of electrospun nanofibers in the desalination of salt water to irrigate crops or refine waters contaminated by fertilizer will be of great importance. Currently, the fabrication of electrospun fibers at industrial scale is feasible (mainly for medical purpose), however, advanced researches are still needed to enable the industrial application in food science, as well as the collaborations between researchers and manufacturers.

5. Conclusions

Electrospinning is a simple, flexible, and cost-effective technology to produce nanofibers. It is attractive since it is a facile process that does not involve any severe conditions in comparison with other encapsulation methods, and is therefore suitable for encapsulation of bioactive compounds. The nanofibers produced by electrospinning have merits such as submicron to nano-scale diameter, high surface to volume ratio, suitable porosity, tunable fiber diameters and tailored morphology. By virtue of these structural advantages, the encapsulation of bioactive compounds in electrospun fibers are shown to exhibit high EE and possess enhanced stability and bioavailability, as well as can achieve targeted delivery and sustained release. Recent progress in encapsulation of different types of bioactive compounds (including hydrophobic and hydrophilic small molecules, enzymes, bioactive proteins and probiotics) by electrospun natural biopolymers (carbohydrates and proteins) was highlighted, as well as their potential applications. Currently, the fabrication of electrospun fibers at industrial scale is feasible (mainly for medical purpose), however, its application in agriculture and food science is still in the early stages of development. Advanced researches are still needed to enable the applications workable for functional foods or active/smart food packaging materials. The utilization and modifications of coaxial or emulsion electrospinning with other technologies, such as liposomes, nanoparticles etc., can be investigated to broaden the possibilities for new products with improved functionalities. Moreover, collaborations between researchers and manufacturers are required to fabricate industrial level of electrospinning machines, and thus improving throughput. In addition, legislation by government agencies on the application of nanofibers in the food industry is needed to ensure the safe of nano-food products.

Acknowledgements

We acknowledge the National Natural Science Foundation of China (No. 31671852), the Natural Science Foundation of Guangdong Province (No. 2015A030313217), and the National Natural Science Foundation of China (NSFC)-Guangdong Joint Foundation Key Project (No. U1501214) for financial supports.

References

Aceituno-Medina, M., Mendoza, S., Lagaron, J. M., & López-Rubio, A. (2015). Photoprotection of folic acid upon encapsulation in food-grade amaranth (Amaranthus hypochondriacus L.) protein isolate – pullulan electrospun fibers. *LWT - Food Science and Technology, 62*(2), 970–975.

Ahmed, F. E., Lalia, B. S., & Hashaikeh, R. (2015). A review on electrospinning for membrane fabrication: Challenges and applications. *Desalination, 356*, 15–30.

Ai-Tang, R., Utarak, H., Yoovidhya, T., Intasanta, V., & Wongsasulak, S. (2013). Fabrication and antifungal activity of cellulose acetate-based fibers encapsulating natural neem seed oil. In N. Sombatsompop, D. Bhattacharyya, & K. H. Y. Cheung (Eds.). *Multi-functional materials and structures* (pp. 166–169). Stafa-Zurich: Trans Tech Publications Ltd.

Alborzi, S., Lim, L. T., & Kakuda, Y. (2013). Encapsulation of folic acid and its stability in sodium alginate-pectin-poly(ethylene oxide) electrospun fibres. *Journal of Microencapsulation, 30*(1), 64–71.

Amna, T., Hassan, M. S., Pandeya, D. R., Khil, M. S., & Hwang, I. H. (2013). Classy nonwovens based on animate L. gasseri-inanimate poly(vinyl alcohol): Upstream application in food engineering. *Applied Microbiology and Biotechnology, 97*(10), 4523–4531.

Anu Bhushani, J., & Anandharamakrishnan, C. (2014). Electrospinning and electrospraying techniques: Potential food based applications. *Trends in Food Science & Technology, 38*(1), 21–33.

Aytac, Z., & Uyar, T. (2016). Antioxidant activity and photostability of α-tocopherol/β-cyclodextrin inclusion complex encapsulated electrospun polycaprolactone nanofibers. *European Polymer Journal, 79*, 140–149.

Aytac, Z., & Uyar, T. (2017). Core-shell nanofibers of curcumin/cyclodextrin inclusion complex and polylactic acid: Enhanced water solubility and slow release of curcumin. *International Journal of Pharmaceutics, 518*(1–2), 177–184.

Aytac, Z., Dogan, S. Y., Tekinay, T., & Uyar, T. (2014). Release and antibacterial activity of allyl isothiocyanate/β-cyclodextrin complex encapsulated in electrospun nanofibers. *Colloids and Surfaces B: Biointerfaces, 120*, 125–131.

Aytac, Z., Ipek, S., Durgun, E., Tekinay, T., & Uyar, T. (2017). Antibacterial electrospun zein nanofibrous web encapsulating thymol/cyclodextrin-inclusion complex for food packaging. *Food Chemistry, 233*, 117–124.

Aytac, Z., Keskin, N. O. S., Tekinay, T., & Uyar, T. (2017). Antioxidant α-tocopherol/γ-cyclodextrin–inclusion complex encapsulated poly(lactic acid) electrospun nanofibrous web for food packaging. *Journal of Applied Polymer Science, 134*(21) n/a-n/a.

Aytac, Z., Kusku, S. I., Durgun, E., & Uyar, T. (2016a). Encapsulation of gallic acid/cyclodextrin inclusion complex in electrospun polylactic acid nanofibers: Release behavior and antioxidant activity of gallic acid. *Materials Science and Engineering: C, 63*, 231–239.

Aytac, Z., Kusku, S. I., Durgun, E., & Uyar, T. (2016b). Quercetin/β-cyclodextrin inclusion complex embedded nanofibres: Slow release and high solubility. *Food Chemistry, 197*, 864–871.

Aytac, Z., Yildiz, Z. I., Kayaci-Senirmak, F., Keskin, N. O. S., Tekinay, T., & Uyar, T. (2016c). Electrospinnin gg of polymer-free cyclodextrin/geraniol-inclusion complex nanofibers: Enhanced shelf-life of geraniol with antibacterial and antioxidant properties. *RSC Advances, 6*(52), 46089–46099.

Aytac, Z., Yildiz, Z. I., Kayaci-Senirmak, F., San Keskin, N. O., Kusku, S. I., et al. (2016d). Fast-dissolving, prolonged release, and antibacterial cyclodextrin/limonene-inclusion complex nanofibrous webs via polymer-free electrospinning. *Journal of Agricultural and Food Chemistry, 64*(39), 7325–7334.

Aytac, Z., Yildiz, Z. I., Kayaci-Senirmak, F., Tekinay, T., & Uyar, T. (2017). Electrospinning of cyclodextrin/linalool-inclusion complex nanofibers: Fast-dissolving nanofibrous web with prolonged release and antibacterial activity. *Food Chemistry, 231*, 192–201.

Bastarrachea, L., Wong, D., Roman, M., Lin, Z., & Goddard, J. (2015). Active packaging coatings. *Coatings, 5*(4), 771.

Blanco-Padilla, A., López-Rubio, A., Loarca-Piña, G., Gómez-Mascaraque, L. G., & Mendoza, S. (2015). Characterization, release and antioxidant activity of curcumin-loaded amaranth-pullulan electrospun fibers. *LWT - Food Science and Technology, 63*(2), 1137–1144.

Bui, H. T., Chung, O. L., & Park, J. S. (2014). Fabrication of electrospun antibacterial curcumin-loaded zein nanofibers. *Polymer-Korea, 38*(6), 744–751.

Canbolat, M. F., Savas, H. B., & Gultekin, F. (2017). Improved catalytic activity by catalase immobilization using γ-cyclodextrin and electrospun PCL nanofibers. *Journal of Applied Polymer Science, 134*(4) n/a-n/a.

Celebioglu, A., Umu, O. C. O., Tekinay, T., & Uyar, T. (2014). Antibacterial electrospun nanofibers from triclosan/cyclodextrin inclusion complexes. *Colloids and Surfaces B: Biointerfaces, 116*, 612–619.

Celebioglu, A., Kayaci-Senirmak, F., Ipek, S., Durgun, E., & Uyar, T. (2016). Polymer-free nanofibers from vanillin/cyclodextrin inclusion complexes: High thermal stability, enhanced solubility and antioxidant property. *Food & Function, 7*(7), 3141–3153.

Celebioglu, A., & Uyar, T. (2011). Electrospinning of polymer-free nanofibers from cyclodextrin inclusion complexes. *Langmuir, 27*(10), 6218–6226.

Celebioglu, A., & Uyar, T. (2017). Antioxidant vitamin e/cyclodextrin inclusion complex electrospun Nanofibers: Enhanced water solubility, prolonged shelf life, and photostability of vitamin E. *Journal of Agricultural and Food Chemistry, 65*(26), 5404–5412.

Chantarodsakun, T., Vongsetskul, T., Jangpatarapongsa, K., Tuchinda, P., Uamsiri, S., Bamrungcharoen, C., et al. (2014). [6]-Gingerol-loaded cellulose acetate electrospun fibers as a topical carrier for controlled release. *Polymer Bulletin, 71*(12), 3163–3176.

Charernsriwilaiwat, N., Opanasopit, P., Rojanarata, T., & Ngawhirunpat, T. (2012). Lysozyme-loaded, electrospun chitosan-based nanofiber mats for wound healing. *International Journal of Pharmaceutics, 427*(2), 379–384.

Chen, P. C., Huang, X. J., Huang, F., Ou, Y., Chen, M. R., & Xu, Z. K. (2011). Immobilization of lipase onto cellulose ultrafine fiber membrane for oil hydrolysis in high performance bioreactor. *Cellulose, 18*(6), 1563–1571.

Coimbra, M., Isacchi, B., van Bloois, L., Torano, J. S., Ket, A., Wu, X., et al. (2011). Improving solubility and chemical stability of natural compounds for medicinal use by incorporation into liposomes. *International Journal of Pharmaceutics, 416*(2), 433–442.

Costoya, A., Concheiro, A., & Alvarez-Lorenzo, C. (2017). Electrospun fibers of cyclodextrins and poly(cyclodextrins). *Molecules, 22*(2), 230.

Deng, L., Kang, X., Liu, Y., Feng, F., & Zhang, H. (2017). Effects of surfactants on the formation of gelatin nanofibres for controlled release of curcumin. *Food Chemistry, 231*, 70–77.

de Oliveira Mori, C. L. S., dos Passos, N. A., Oliveira, J. E., Mattoso, L. H. C., Mori, F. A., Carvalho, A. G., et al. (2014). Electrospinning of zein/tannin bio-nanofibers. *Industrial Crops and Products, 52*, 298–304.

Dhandayuthapani, B., Anila, M., Ravindran Girija, A., Yutaka, N., Venugopal, K., Yasuhiko, Y., et al. (2012). Hybrid fluorescent curcumin loaded zein electrospun nanofibrous scaffold for biomedical applications. *Biomedical Materials, 7*(4), 045001.

Dheraprasart, C., Rengpipat, S., Supaphol, P., & Tattiyakul, J. (2009). Morphology, release characteristics, and antimicrobial effect of nisin-loaded electrospun gelatin fiber mat. *Journal of Food Protection, 72*(11), 2293–2300.

Dias, M. I., Ferreira, I. C. F. R., & Barreiro, M. F. (2015). Microencapsulation of bioactives for food applications. *Food & Function, 6*(4), 1035–1052.

Đorđević, V., Balanč, B., Belščak-Cvitanović, A., Lević, S., Trifković, K., Kalušević, A., et al. (2015). Trends in encapsulation technologies for delivery of food bioactive compounds. *Food Engineering Reviews, 7*(4), 452–490.

Drosou, C. G., Krokida, M. K., & Biliaderis, C. G. (2016). Encapsulation of bioactive compounds through electrospinning/electrospraying and spray drying: A comparative assessment of food-related applications. *Drying Technology, 35*(2), 139–162.

Elakkiya, T., Malarvizhi, G., Rajiv, S., & Natarajan, T. S. (2014). Curcumin loaded electrospun Bombyx mori silk nanofibers for drug delivery. *Polymer International, 63*(1), 100–105.

Ezhilarasi, P. N., Karthik, P., Chhanwal, N., & Anandharamakrishnan, C. (2013). Nanoencapsulation techniques for food bioactive components: A review. *Food and Bioprocess Technology, 6*(3), 628–647.

Fabra, M. J., Jiménez, A., Talens, P., & Chiralt, A. (2014). Influence of homogenization conditions on physical properties and antioxidant activity of fully biodegradable pea protein–alpha-tocopherol films. *Food and Bioprocess Technology, 7*(12), 3569–3578.
Fabra, M. J., López-Rubio, A., & Lagaron, J. M. (2016). Use of the electrohydrodynamic process to develop active/bioactive bilayer films for food packaging applications. *Food Hydrocolloids, 55*, 11–18.
Fathi, M., Martín, Á., & McClements, D. J. (2014). Nanoencapsulation of food ingredients using carbohydrate based delivery systems. *Trends in Food Science & Technology, 39*(1), 18–39.
Fernandez, A., Torres-Giner, S., & Lagaron, J. M. (2009). Novel route to stabilization of bioactive antioxidants by encapsulation in electrospun fibers of zein prolamine. *Food Hydrocolloids, 23*(5), 1427–1432.
Fung, W. Y., Yuen, K. H., & Liong, M. T. (2011). Agrowaste-based nanofibers as a probiotic Encapsulant: Fabrication and characterization. *Journal of Agricultural and Food Chemistry, 59*(15), 8140–8147.
Ge, L., Zhao, Y. S., Mo, T., Li, J. R., & Li, P. (2012). Immobilization of glucose oxidase in electrospun nanofibrous membranes for food preservation. *Food Control, 26*(1), 188–193.
Ghorani, B., & Tucker, N. (2015). Fundamentals of electrospinning as a novel delivery vehicle for bioactive compounds in food nanotechnology. *Food Hydrocolloids, 51*, 227–240.
Goto, Y., Masuda, A., & Aiba, T. (2015). In vivo application of chitosan to improve bioavailability of cyanocobalamin, a form of vitamin B12, following intraintestinal administration in rats. *International Journal of Pharmaceutics, 483*(1–2), 250–255.
Gouin, S. (2004). Microencapsulation. *Trends in Food Science & Technology, 15*(7), 330–347.
Gou, M., Men, K., Shi, H., Xiang, M., Zhang, J., Song, J., et al. (2011). Curcumin-loaded biodegradable polymeric micelles for colon cancer therapy in vitro and in vivo. *Nanoscale, 3*(4), 1558–1567.
Han, F., Zhang, H., Zhao, J., Zhao, Y., & Yuan, X. (2013). In situ encapsulation of chitosan hydrogel in ultrafine fibers by electrospinning as system for the controlled release of bioactive proteins. *Journal of Controlled Release, 172*(1), e101–e102.
Han, D., Sherman, S., Filocamo, S., & Steckl, A. J. (2017). Long-term antimicrobial effect of nisin released from electrospun triaxial fiber membranes. *Acta Biomaterialia, 53*, 242–249.
Huang, X. J., Chen, P. C., Huang, F., Ou, Y., Chen, M. R., & Xu, Z. K. (2011). Immobilization of Candida rugosa lipase on electrospun cellulose nanofiber membrane. *Journal of Molecular Catalysis B: Enzymatic, 70*(3–4), 95–100.
Huang, X. J., Ge, D., & Xu, Z. K. (2007). Preparation and characterization of stable chitosan nanofibrous membrane for lipase immobilization. *European Polymer Journal, 43*(9), 3710–3718.
Huang, W., Xu, H., Xue, Y., Huang, R., Deng, H., & Pan, S. (2012). Layer-by-layer immobilization of lysozyme–chitosan–organic rectorite composites on electrospun nanofibrous mats for pork preservation. *Food Research International, 48*(2), 784–791.
Jankovic, I., Sybesma, W., Phothirath, P., Ananta, E., & Mercenier, A. (2010). Application of probiotics in food products—challenges and new approaches. *Current Opinion in Biotechnology, 21*(2), 175–181.
Kayaci, F., Ertas, Y., & Uyar, T. (2013). Enhanced thermal stability of eugenol by cyclodextrin inclusion complex encapsulated in electrospun polymeric nanofibers. *Journal of Agricultural and Food Chemistry, 61*(34), 8156–8165.
Kayaci, F., Sen, H. S., Durgun, E., & Uyar, T. (2014). Functional electrospun polymeric nanofibers incorporating geraniol–cyclodextrin inclusion complexes: High thermal stability and enhanced durability of geraniol. *Food Research International, 62*, 424–431.
Kim, J., Grate, J. W., & Wang, P. (2008). Nanobiocatalysis and its potential applications. *Trends in Biotechnology, 26*(11), 639–646.
Kishan, A. P., & Cosgriff-Hernandez, E. M.. Recent advancements in electrospinning design for tissue engineering applications: A review. Journal of Biomedical Materials Research Part A, (n/a-n/a).
Lancuški, A., Abu Ammar, A., Avrahami, R., Vilensky, R., Vasilyev, G., & Zussman, E. (2017). Design of starch-formate compound fibers as encapsulation platform for biotherapeutics. *Carbohydrate Polymers, 158*, 68–76.
Lemma, S. M., Scampicchio, M., Mahon, P. J., Sbarski, I., Wang, J., & Kingshott, P. (2015). Controlled release of retinyl acetate from β-cyclodextrin functionalized poly(vinyl alcohol) electrospun nanofibers. *Journal of Agricultural and Food Chemistry, 63*(13), 3481–3488.
Liang, H., Yuan, Q., Vriesekoop, F., & Lv, F. (2012). Effects of cyclodextrins on the antimicrobial activity of plant-derived essential oil compounds. *Food Chemistry, 135*(3), 1020–1027.
Li, Y., Lim, L. T., & Kakuda, Y. (2009). Electrospun zein fibers as carriers to stabilize (−)-Epigallocatechin gallate. *Journal of Food Science, 74*(3), C233–C240.
Li, H., Wang, M., Williams, G. R., Wu, J., Sun, X., Lv, Y., et al. (2016). Electrospun gelatin nanofibers loaded with vitamins A and E as antibacterial wound dressing materials. *RSC Advances, 6*(55), 50267–50277.
Lopez-Rubio, A., Gavara, R., & Lagaron, J. M. (2006). Bioactive packaging: Turning foods into healthier foods through biomaterials. *Trends in Food Science and Technology, 17*(10), 567–575.
López-Rubio, A., Sanchez, E., Sanz, Y., & Lagaron, J. M. (2009). Encapsulation of living bifidobacteria in ultrathin PVOH electrospun fibers. *Biomacromolecules, 10*(10), 2823–2829.
López-Rubio, A., Sanchez, E., Wilkanowicz, S., Sanz, Y., & Lagaron, J. M. (2012). Electrospinning as a useful technique for the encapsulation of living bifidobacteria in food hydrocolloids. *Food Hydrocolloids, 28*(1), 159–167.
Madhaiyan, K., Sridhar, R., Sundarrajan, S., Venugopal, J. R., & Ramakrishna, S. (2013). Vitamin B12 loaded polycaprolactone nanofibers: A novel transdermal route for the water soluble energy supplement delivery. *International Journal of Pharmaceutics, 444*(1–2), 70–76.
Mascheroni, E., Fuenmayor, C. A., Cosio, M. S., Di Silvestro, G., Piergiovanni, L., Mannino, S., et al. (2013). Encapsulation of volatiles in nanofibrous polysaccharide membranes for humidity-triggered release. *Carbohydrate Polymers, 98*(1), 17–25.
Mendes, A. C., Gorzelanny, C., Halter, N., Schneider, S. W., & Chronakis, I. S. (2016). Hybrid electrospun chitosan-phospholipids nanofibers for transdermal drug delivery. *International Journal of Pharmaceutics, 510*(1), 48–56.
Mendes, A. C., Stephansen, K., & Chronakis, I. S. (2017). Electrospinning of food proteins and polysaccharides. *Food Hydrocolloids, 68*, 53–68.
Moomand, K., & Lim, L. T. (2014). Oxidative stability of encapsulated fish oil in electrospun zein fibres. *Food Research International, 62*, 523–532.
Moomand, K., & Lim, L. T. (2015). Properties of encapsulated fish oil in electrospun zein fibres under simulated in vitro conditions. *Food and Bioprocess Technology, 8*(2), 431–444.
Neo, Y. P., Perera, C. O., Nieuwoudt, M. K., Zujovic, Z., Jin, J., Ray, S., et al. (2014). Influence of heat curing on structure and physicochemical properties of phenolic acid loaded proteinaceous electrospun fibers. *Journal of Agricultural and Food Chemistry, 62*(22), 5163–5172.
Neo, Y. P., Swift, S., Ray, S., Gizdavic-Nikolaidis, M., Jin, J., & Perera, C. O. (2013). Evaluation of gallic acid loaded zein sub-micron electrospun fibre mats as novel active packaging materials. *Food Chemistry, 141*(3), 3192–3200.
Nieuwland, M., Geerdink, P., Brier, P., van den Eijnden, P., Henket, J. T. M. M., Langelaan, M. L. P., et al. (2013). Food-grade electrospinning of proteins. *Innovative Food Science & Emerging Technologies, 20*, 269–275.
Noruzi, M. (2016). Electrospun nanofibres in agriculture and the food industry: A review. *Journal of the Science of Food and Agriculture, 96*(14), 4663–4678.
Padrão, J., Machado, R., Casal, M., Lanceros-Méndez, S., Rodrigues, L. R., Dourado, F., et al. (2015). Antibacterial performance of bovine lactoferrin-fish gelatine electrospun membranes. *International Journal of Biological Macromolecules, 81*, 608–614.
Panprung, S., Apichart, S., & Pitt, S. (2008). Electrospun gelatin fiber mats containing a herbal— Centella asiatica —extract and release characteristic of asiaticoside. *Nanotechnology, 19*(1), 015102.
Park, J. M., Kim, M., Park, H.-S., Jang, A., Min, J., & Kim, Y. H. (2013). Immobilization of lysozyme-CLEA onto electrospun chitosan nanofiber for effective antibacterial applications. *International Journal of Biological Macromolecules, 54*, 37–43.
Pérez-Masiá, R., Lagaron, J. M., & López-Rubio, A. (2014). Development and optimization of novel encapsulation structures of interest in functional foods through electrospraying. *Food and Bioprocess Technology, 7*(11), 3236–3245.
Pérez-Masiá, R., Lagaron, J. M., & Lopez-Rubio, A. (2015). Morphology and stability of edible lycopene-containing micro- and nanocapsules produced through electrospraying and spray drying. *Food and Bioprocess Technology, 8*(2), 459–470.
Pérez-Masiá, R., López-Rubio, A., Fabra, M. J., & Lagaron, J. M. (2014). Use of electrohydrodynamic processing to develop nanostructured materials for the preservation of the cold chain. *Innovative Food Science & Emerging Technologies, 26*, 415–423.
Ray, S., Raychaudhuri, U., & Chakraborty, R. (2016). An overview of encapsulation of active compounds used in food products by drying technology. *Food Bioscience, 13*, 76–83.
Rezaei, A., Nasirpour, A., & Fathi, M. (2015). Application of cellulosic nanofibers in food science using electrospinning and its potential risk. *Comprehensive Reviews in Food Science and Food Safety, 14*(3), 269–284.
Ribeiro-Santos, R., Andrade, M., Melo, N. R. d., & Sanches-Silva, A. (2017). Use of essential oils in active food packaging: Recent advances and future trends. *Trends in Food Science & Technology, 61*, 132–140.
Saithongdee, A., Praphairaksit, N., & Imyim, A. (2014). Electrospun curcumin-loaded zein membrane for iron(III) ions sensing. *Sensors and Actuators B: Chemical, 202*, 935–940.
Sakuldao, S., Yoovidhya, T., & Wongsasulak, S. (2011). Coaxial electrospinning and sustained release properties of gelatin-cellulose acetate core-shell ultrafine fibres. *ScienceAsia, 37*(4), 335–343.
Sanguansri, P., & Augustin, M. A. (2006). Nanoscale materials development – a food industry perspective. *Trends in Food Science & Technology, 17*(10), 547–556.
Sheng, X., Fan, L., He, C., Zhang, K., Mo, X., & Wang, H. (2013). Vitamin E-loaded silk fibroin nanofibrous mats fabricated by green process for skin care application. *International Journal of Biological Macromolecules, 56*, 49–56.
Siqueira, N. M., Garcia, K. C., Bussamara, R., Both, F. S., Vainstein, M. H., & Soares, R. M. D. (2015). Poly (lactic acid)/chitosan fiber mats: Investigation of effects of the support on lipase immobilization. *International Journal of Biological Macromolecules, 72*, 998–1004.
Soto, K. M., Hernández-Iturriaga, M., Loarca-Piña, G., Luna-Bárcenas, G., Gómez-Aldapa, C. A., & Mendoza, S. (2016). Stable nisin food-grade electrospun fibers. *Journal of Food Science and Technology, 53*(10), 3787–3794.
Stephansen, K., García-Díaz, M., Jessen, F., Chronakis, I. S., & Nielsen, H. M. (2015). Bioactive protein-based nanofibers interact with intestinal biological components resulting in transepithelial permeation of a therapeutic protein. *International Journal of Pharmaceutics, 495*(1), 58–66.
Suwantong, O., Opanasopit, P., Ruktanonchai, U., & Supaphol, P. (2007). Electrospun cellulose acetate fiber mats containing curcumin and release characteristic of the herbal substance. *Polymer, 48*(26), 7546–7557.
Su, X. F., Wei, J. F., Ren, X. L., Li, L. L., Meng, X. W., Ren, J., et al. (2013). A new amperometric glucose biosensor based on one-step electrospun poly(vinyl alcohol)/chitosan nanofibers. *Journal of Biomedical Nanotechnology, 9*(10), 1776–1783.
Tian, L. L., Prabhakaran, M. P., Hu, J., Chen, M. L., Besenbacher, F., & Ramakrishna, S. (2015). Coaxial electrospun poly(lactic acid)/silk fibroin nanofibers incorporated with nerve growth factor support the differentiation of neuronal stem cells. *RSC Advances, 5*(62), 49838–49848.
Tran, D. N., & Balkus, K. J. (2012). Enzyme immobilization via electrospinning. *Topics in Catalysis, 55*(16), 1057–1069.

Vega-Lugo, A. C., & Lim, L. T. (2009). Controlled release of allyl isothiocyanate using soy protein and poly(lactic acid) electrospun fibers. *Food Research International, 42*(8), 933–940.

Vongsetskul, T., Phurayar, P., Chutimasakul, T., Tuchinda, P., Uamsiri, S., Kumkate, S., et al. (2016). Acanthus ebracteatus Vahl. extract-loaded cellulose acetate ultrafine fibers as a topical carrier for controlled-release applications. *Polymer Bulletin, 73*(12), 3319–3331.

Wang, H., Hao, L., Niu, B., Jiang, S., Cheng, J., & Jiang, S. (2016). Kinetics and antioxidant capacity of proanthocyanidins encapsulated in zein electrospun fibers by cyclic voltammetry. *Journal of Agricultural and Food Chemistry, 64*(15), 3083–3090.

Wang, H., Hao, L., Wang, P., Chen, M., Jiang, S., & Jiang, S. (2017). Release kinetics and antibacterial activity of curcumin loaded zein fibers. *Food Hydrocolloids, 63*, 437–446.

Wang, S., Marcone, M. F., Barbut, S., & Lim, L. T. (2013). Electrospun soy protein isolate-based fiber fortified with anthocyanin-rich red raspberry (Rubus strigosus) extracts. *Food Research International, 52*(2), 467–472.

Wang, H., She, Y., Chu, C., Liu, H., Jiang, S., Sun, M., et al. (2015). Preparation, antimicrobial and release behaviors of nisin-poly (vinyl alcohol)/wheat gluten/ZrO2 nanofibrous membranes. *Journal of Materials Science, 50*(14), 5068–5078.

Wang, X., Yu, D. G., Li, X. Y., Bligh, S. W. A., & Williams, G. R. (2015). Electrospun medicated shellac nanofibers for colon-targeted drug delivery. *International Journal of Pharmaceutics, 490*(1–2), 384–390.

Wen, P., Feng, K., Yang, H., Huang, X., Zong, M. H., Lou, W. Y., et al. (2017). Electrospun core-shell structured nanofilm as a novel colon-specific delivery system for protein. *Carbohydrate Polymers, 169*, 157–166.

Wen, P., Wen, Y., Huang, X., Zong, M. H., & Wu, H. (2017). Preparation and characterization of protein-loaded electrospun fiber mat and its release kinetics. *Journal of Agricultural and Food Chemistry, 65*(23), 4786–4796.

Wen, P., Zhu, D. H., Feng, K., Liu, F. J., Lou, W. Y., Li, N., et al. (2016). Fabrication of electrospun polylactic acid nanofilm incorporating cinnamon essential oil/β-cyclodextrin inclusion complex for antimicrobial packaging. *Food Chemistry, 196*, 996–1004.

Wen, P., Zhu, D. H., Wu, H., Zong, M. H., Jing, Y. R., & Han, S. Y. (2016). Encapsulation of cinnamon essential oil in electrospun nanofibrous film for active food packaging. *Food Control, 59*, 366–376.

Wongsasulak, S., Pathumban, S., & Yoovidhya, T. (2014). Effect of entrapped α-tocopherol on mucoadhesivity and evaluation of the release, degradation, and swelling characteristics of zein–chitosan composite electrospun fibers. *Journal of Food Engineering, 120*, 110–117.

Xiao, J., Shi, C., Zheng, H., Shi, Z., Jiang, D., Li, Y., et al. (2016). Kafirin protein based electrospun fibers with tunable mechanical property, wettability, and release profile. *Journal of Agricultural and Food Chemistry, 64*(16), 3226–3233.

Xie, J., & Hsieh, Y. L. (2003). Ultra-high surface fibrous membranes from electrospinning of natural proteins: Casein and lipase enzyme. *Journal of Materials Science, 38*(10), 2125–2133.

Xu, W., & Yang, Y. (2009). Drug sorption onto and release from soy protein fibers. *Journal of Materials Science: Materials in Medicine, 20*(12), 2477–2486.

Yang, Y., Gu, Z., Xu, H., Li, F., & Zhang, G. (2010). Interaction between amylose and β-cyclodextrin investigated by complexing with conjugated linoleic acid. *Journal of Agricultural and Food Chemistry, 58*(9), 5620–5624.

Yang, W., Sousa, A. M. M., Fan, X., Jin, T., Li, X., Tomasula, P. M., et al. (2017). Electrospun ultra-fine cellulose acetate fibrous mats containing tannic acid-Fe^{3+} complexes. *Carbohydrate Polymers, 157*, 1173–1179.

Yang, H., Wen, P., Feng, K., Zong, M. H., Lou, W. Y., & Wu, H. (2017). Encapsulation of fish oil in a coaxial electrospun nanofibrous mat and its properties. *RSC Advances, 7*(24), 14939–14946.

Yang, J. M., Zha, L. S., Yu, D. G., & Liu, J. (2013). Coaxial electrospinning with acetic acid for preparing ferulic acid/zein composite fibers with improved drug release profiles. *Colloids and Surfaces B: Biointerfaces, 102*, 737–743.

Yan, J., White, K., Yu, D. G., & Zhao, X. Y. (2014). Sustained-release multiple-component cellulose acetate nanofibers fabricated using a modified coaxial electrospinning process. *Journal of Materials Science, 49*(2), 538–547.

Yao, Z. C., Chang, M. W., Ahmad, Z., & Li, J. S. (2016). Encapsulation of rose hip seed oil into fibrous zein films for ambient and on demand food preservation via coaxial electrospinning. *Journal of Food Engineering, 191*, 115–123.

Yildiz, Z. I., Celebioglu, A., & Uyar, T.. Polymer-free electrospun nanofibers from sulfobutyl ether7-beta-cyclodextrin (SBE7-β-CD) inclusion complex with sulfisoxazole: Fast-dissolving and enhanced water-solubility of sulfisoxazole. International Journal of Pharmaceutics.

Yu, D. G., Yang, J. M., Branford-White, C., Lu, P., Zhang, L., & Zhu, L. M. (2010). Third generation solid dispersions of ferulic acid in electrospun composite nanofibers. *International Journal of Pharmaceutics, 400*(1–2), 158–164.

Zhang, M., Li, X., Li, S., Liu, Y., & Hao, L. (2016). Electrospun poly(l-lactide)/zein nanofiber mats loaded with Rana chensinensis skin peptides for wound dressing. *Journal of Materials Science: Materials in Medicine, 27*(9), 136.

Zheng, H., Gao, M., Ren, Y., Lou, R., Xie, H., Yu, W., et al. (2017). An improved pH-responsive carrier based on EDTA-Ca-alginate for oral delivery of Lactobacillus rhamnosus ATCC 53103. *Carbohydrate Polymers, 155*, 329–335.