JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Review

Cite This: J. Agric. Food Chem. 2017, 65, 9161-9179

pubs.acs.org/JAFC

Encapsulation of Bioactive Compound in Electrospun Fibers and Its Potential Application

Peng Wen,[†] Yan Wen,[†] Min-Hua Zong,[†] Robert J. Linhardt,[‡] and Hong Wu*[,†,§]

[†]School of Food Science and Engineering, South China University of Technology, Guangzhou 510640, China

[‡]Department of Chemical and Biological Engineering, Center for Biotechnology and Interdisciplinary Studies, Rensselaer Polytechnic Institute, Troy, New York 12180, United States

[§]Guangdong Province Key Laboratory for Green Processing of Natural Products and Product Safety, Guangzhou 510640, China

ABSTRACT: Electrospinning is a simple and versatile encapsulation technology. Since electrospinning does not involve severe conditions of temperature or pressure or the use of harsh chemicals, it has great potential for effectively entrapping and delivering bioactive compounds. Recently, electrospinning has been used in the food industry to encapsulate bioactive compounds into different biopolymers (carbohydrates and proteins), protecting them from adverse environmental conditions, maintaining the health-promoting properties, and achieving their controlled release. Electrospinning opens a new horizon in food technology with possible commercialization in the near future. This review summarizes the principles and the types of electrospinning processes. The electrospinning of biopolymers and their application in encapsulating of bioactive compounds are highlighted. The existing scope, limitations, and future prospects of electrospinning bioactive compounds are also presented.

KEYWORDS: *electrospinning, encapsulation, natural biopolymer, bioactive compounds, food applications*

INTRODUCTION

The incorporation of bioactive compounds as active agents in food packaging materials or as nutraceuticals in functional foods is becoming a growing area of research.[1,2] However, the application of bioactive compounds is often restricted by their unfavorable flavor, solubility, their poor stability during food processing (with respect to temperature, oxygen, light, etc.), uncontrolled release profile, and their low bioavailability in the upper gastrointestinal tract (GIT), which can significantly compromise their envisioned biological benefits.[1,3] Designing appropriate carriers is one approach to overcome these limitations.

An attractive method for entrapping bioactive compounds is encapsulation. This approach can protect these compounds from adverse environmental conditions or from the GIT (e.g., stomach acid), enhance the solubility or dispersibility of lipophilic compounds, achieve controlled release, and improve the bioavailability of bioactive molecules during digestion.[4−7] Various encapsulation methods including electrospinning, gelation, layer-by-layer deposition, extrusion, coprecipitation, coacervation, spray/freeze-drying, and emulsion formation have been reported for encapsulation of food ingredients.[8−10] These approaches have resulted in different nanostructures or microstructures having a variety of physicochemical and delivery properties. Among these approaches electrospinning represents a versatile method for the production of micro- and nanosized fibers and has been proposed as a feasible route for the encapsulation of various bioactive compounds.[11−13]

The electrospinning process uses high-voltage electric fields to produce electrically charged jets of bioactive compound-loaded solutions and results in ultrathin fibers on the evaporation of the solvent. Electrospinning is the most popular and preferred technique for fabrication of nanofibers, due to its simplicity, cost-effectiveness, flexibility, potential to scale up, and ability to spin a number of polymers.[14] The important advantage of electrospinning is that it provides the opportunity for direct encapsulation of hydrophobic and hydrophilic compounds and biomacromolecules, such as proteins, into the electrospun fibers. Moreover, because the electrospinning process takes place at ambient conditions, it is more suitable for encapsulating thermally labile active compounds as compared to other conventional encapsulation methods, like spray drying,[15] and is thus important for preserving the efficacy of the bioactive substances during the fiber forming process. For example, López-Rubio and co-workers found that spray drying significantly reduced the viability of bacteria or damaged the structure of target molecules,[16] while the viability of *Bifidobacterium* strains could be enhanced by encapsulation into electrospun poly(vinyl alcohol) (PVOH) nanofibers having an average diameter of 150 nm. Furthermore, electrospun nanofibers are able to significantly improve encapsulation efficiency (EE) and reduce the burst release via proper selection of a polymer−solvent system or electrospinning technique. Also, electrospun fibrous mats would facilitate the diffusion of encapsulated compounds into the surrounding medium in comparison to conventional films produced by a solution-casting technique, resulting in a more efficient release system.[14] In addition, the electrospun nanofibers obtained had many excellent properties, such as large surface area to volume ratio, high porosity, and excellent mechanical properties. The bioactive compounds encapsulated in an electrospun fiber also showed enhanced stability and functionality.[2,17] Fabra et al. observed that higher EE of α-

Received: June 27, 2017
Revised: September 24, 2017
Accepted: September 26, 2017
Published: September 26, 2017

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

tocopherol (α-TOC) in zein fibers was achieved than the entrapment of which in whey protein isolate (WPI) and soy protein isolate (SPI) capsules, demonstrating that higher EE values were obtained in fibers than in beads or capsules.[18] Owing to their submicrometer to nanoscale diameters and very large surface area, electrospun fibers were more responsive to changes in the surrounding atmosphere (e.g., relative humidity and temperature changes) than are film and sheet carriers, enabling the tunable release of the entrapped compounds.[19] These unique features suggest the application of electrospun nanofibers in various areas such as controlled release of compounds in drug delivery, scaffolds in tissue engineering, wound dressings in biomedical applications, and membranes for air and water filtration.[20] However, the potential of electrospinning in the field of food science is considerably less explored, and the operating conditions for high EE of bioactive compounds and preparation of composite structures with desirable characteristics require further exploration to broaden the application of electrospinning in the food industry.

Increasing attention has been focused on the electrospinning of natural polymers as their useful properties, including low toxicity, biocompatibility, and biodegradability, make these biopolymers highly desirable for food-related applications. The most widely studied natural biopolymers are polysaccharides and proteins. However, electrospinning of biopolymers has proven to be quite challenging because many materials tend to form gels through hydrogen bonding. Besides that, a minimum polymer concentration is required. Below this critical value, an insufficiently entangled network of polymer chains is thought to be responsible for the formation of beads or droplets instead of fibers.[21] As the polymer concentration is increased, a mixture of beads and fibers is obtained. Further increase in concentration results in formation of continuous fibers, and at even higher polymer concentrations uniform fibers are no longer produced due to the high solution viscosity. The critical overlap concentration has been discussed in previous literature.[22,23] An approach that has been popularly adapted to tackle these issues is to add a synthetic polymer, such as poly(ethylene oxide) (PEO) or poly(vinyl alcohol) (PVA), to disrupt gelation and promote molecular entanglement, inducing fiber formation. Previous studies have focused on the preparation of electrospun natural biopolymers, while the application of electrospinning in the encapsulation of bioactive compounds has been less intensively investigated. Particularly, emulsion electrospinning and coaxial electrospinning have been developed for encapsulation of sensitive compounds into core−sheath fibers. In this regard, this article covers the encapsulation of bioactive componds within certain electrospun natural biopolymer fibers. First, an introduction to the principle and types of electrospinning is presented. Then recent developments on the electrospinning of polymers and their potential application in the encapsulation of different bioactive compounds are summarized. This emerging field of nanotechnology provides a major impetus to food researchers in the development of novel functional foods and food packaging materials.

■ ELECTROSPINNING

The incorporation of bioactive compounds within polymeric electrospun fibers is a promising technique to enhance the performance of functional materials in the food industry. A clear understanding of the electrospinning mechanism is essential to optimize the production conditions and maximize throughput.

Principle of Electrospinning. Electrospinning is a simple and effective approach to produce submicrometer or nanoscale polymer fibers.[24] A typical electrospinning system consists of a high-voltage power supply, a syringe pump with a metal needle, and a grounded collector, either a plate or a rotating drum (Figure 1). During electrospinning, a polymer solution or melted polymer, having sufficient molecular entanglement, is extruded to form a droplet at the needle tip by a syringe pump. An electric field is applied between the needle tip and the grounded collector and distorts the hemispherical surface of a droplet into a conical shape through the action of electrostatic forces. When the applied electrical force overcomes the critical surface tension of the polymer liquid, an electrically charged jet of the polymer is ejected from the tip of the Taylor cone, stretched, and finally deposited on the collector as a randomly oriented nonwoven mat of fibers ranging from micrometers to nanometers in diameter.[25] The electrospinning process in terms of the spinnability, fiber morphology, and diameter distribution can be affected by characteristics of the solution (e.g., polymer, solvent, additives, electric conductivity, viscosity, surface tension, and concentration), the electrospinning process parameters (applied voltage, spinning distance, and feed rate), and ambient parameters (e.g., temperature, humidity, and air flow).[12,26]

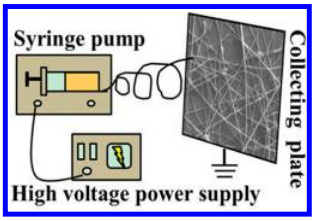

Figure 1. Schematic illustration of the basic setup for electrospinning.

Types of Electrospinning. Even though the electrospinning method is relatively convenient and versatile, difficulties may be encountered in aspects of the encapsulation of sensitive bioactive compounds into fibers. The major disadvantage of conventional electrospinning is that the blend formulations often give rise to burst release of some encapsulated compounds.[27] For example, an obvious burst release profile was found for doxorubicin hydrochloride due to the deposition of the drug on or near the surfaces of the fiber.[28] It was because the compounds cannot dissolve in the polymer solution and only dispersion can be obtained. After electrospinning of the dispersion, the compound was located on or near the fiber surfaces and their rapid diffusion into the release media would result in burst release. Hence, in the blend electrospinning, the solubility and compatibility of encapsulated compounds in the polymer/solvent system were the decisive factors for the preparation of the electrospun fiber with constant release of the compounds. Blend electrospinning also faces enormous challenges for the encapsulation of hydrophilic bioactive molecules into hydrophobic polymers or the hydrophobic bioactive molecules into hydrophilic polymers. The presence of organic solvents can result in the inactivation or denaturation of some hydrophilic bioactive substances as well. Two alternative electrospinning techniques, emulsion electrospinning and coaxial electrospinning, have been proposed to circumvent these limitations, preparing fibers having micro/nanosphere-embedded or core−sheath fibers. Emulsion and coaxial electrospinning can prevent an initial

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

burst release and facilitate a sustained release as well as protect entrapped bioactive substances from the harsh environment of the polymer−solvent phase.[29] The principle and technical details of these methods have been discussed in previous reviews.[30−32] Rather than covering all aspects of emulsion and coaxial electrospinning, we instead focus on the advantages and applications of these important techniques for encapsulation and controlled release of sensitive bioactive compounds.

Emulsion Electrospinning. The preparation core−sheath structure nanofibers by emulsion electrospinning has recently attracted increased attention.[33] A schematic illustration for emulsion electrospinning is depicted in Figure 2; either a water-in-oil (W/O) or an oil-in-water (O/W) emulsion can be electrospun as an emulsion. Since a hydrophilic polymer can easily dissolve in water thus causing the burst release of a hydrophilic compound in the release medium, usually water or a pH buffer solution for *in vitro* studies, W/O emulsion electrospinning is ideal for the delivery of hydrophilic bioactive compounds by hydrophobic polymers because a hydrophobic shell is needed to protect the compounds from burst release, as well as the ability to preserve the bioactivity of the compound that is sensitive to harsh solvents.

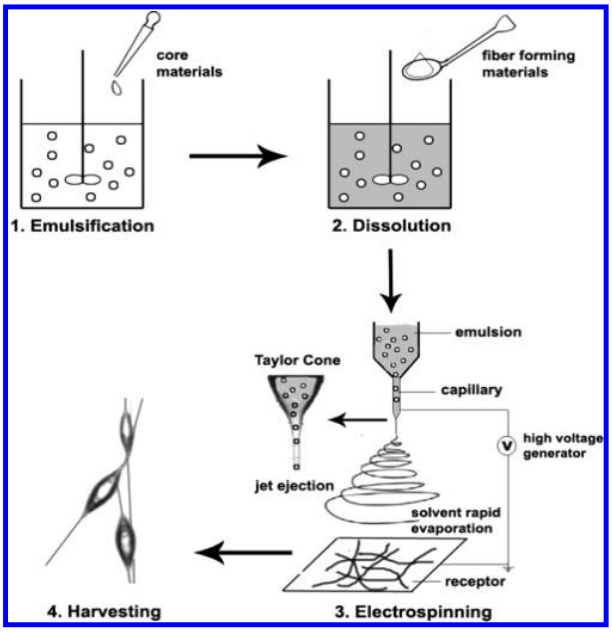

Figure 2. Schematic illustration of emulsion electrospinning. Reprinted with permission from ref 39. Copyright 2006 American Chemical Society.

W/O emulsion electrospinning relies on the dispersion of hydrophilic bioactive molecules into hydrophobic polymer solution.[34] It requires a relatively stable emulsion, wherein the oily phase consists of a polymer dissolved in an organic solvent and the water phase contains the bioactive compounds. During the electrospinning process, emulsion with the oil phase of polymer solution and the water phase of micrometer or submicrometer spheres could be elongated under the electric force. Core−sheath fibers can be formed as a result of relatively fast evaporation of solvent from the region close to the surface in comparison to the central part of the polymer jet. In such circumstances, the viscosity gradient of the core and shell segments changes dramatically and causes a slower rate of the evaporation process in the central part of the jet. The morphology of electrospun fibers obtained by emulsion electrospinning changes from a pearl-on-string like structure to a cocontinuous two-phase structure as the concentration of the aqueous phase is higher. The factors influencing the formation of the core−shell structured fibers prepared through emulsion electrospinning have been previously reviewed.[31] There are many advantages of W/O emulsion electrospinning. First, it provides an effective approach for incorporation of hydrophilic bioactive agents into hydrophobic polymers/organic solvents, overcoming the poor solubility of hydrophilic compounds in water-insoluble polymers. Second, W/O emulsions can be electrospun into core−shell structured fibers with bioactive compounds loaded in the core section. In that case solidified polymer acts as a hydrophobic barrier, which provides protection for a sensitive hydrophilic component from external conditions (solvent exposure, shear stresses), thus preserving the bioactivity. Third, the encapsulated bioactive agents need to pass through the core−shell fiber matrix before entering release medium during the release process, thus reducing their burst release. Fourth, emulsion electrospinning uses different solvents for the compound and polymer so that it does not require a common solvent, which is often difficult to find. Hence, W/O emulsion electrospinning enables the incorporation of a hydrophilic substance into hydrophobic polymers without compromising its bioactivity and avoiding burst release. For example, Li and co-workers encapsulated a

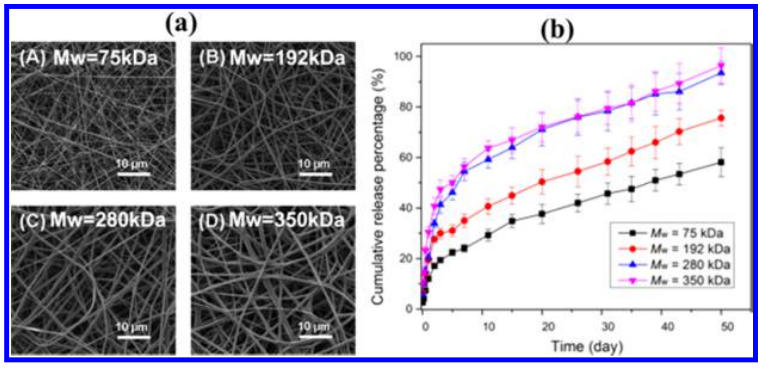

Figure 3. Scanning electron microscopy (SEM) images of BSA loaded electrospun nanofibers (a) and release profiles of BSA from electrospun nanofibers (b) with polystyrene of various molecular weights in PBS (pH = 7.0) at room temperature. Reprinted with permission from ref 36. Copyright 2015 John Wiley & Sons, Inc.

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

model protein, proteinase K, into poly(ethylene glycol)-poly(L-lactide) (PELA) fibers by emulsion electrospinning, and sustained release of proteinase K over 7 days from core−shell fibers without compromising its activity was achieved.[35] In another study, Wang and co-workers were able to eliminate an initial burst release of water-soluble protein and were able to obtain a relatively constant rate prolonged over 50 days. Interestingly, this study found that higher molecular weight of polystyrene produced larger fiber diameters and also provided a faster release of protein (Figure 3), which can possibly be attributed to the agglomeration of bovine serum albumin (BSA) on or adjacent to the surface of fiber and the looser fiber matrix.[36]

The incorporation of lipophilic molecules into hydrophilic nanofibers can be achieved by electrospinning of O/W emulsion, with the aim of improving the solubility of hydrophobic compounds. A highly volatile fragrance, (*R*)-(+)-limonene, was successfully encapsulated into PVA fibrous matrix by emulsion electrospinning.[37] Limonene displayed a sustained, slow release profile reaching only 30% after 15 days under ambient conditions, and higher temperatures accelerated its release. Nanofibers loaded with fish oil were also successfully produced by emulsion electrospinning using PVA polymer and WPI or fish protein hydrolysate (FPH) as emulsifiers. Although most of the fish oil was encapsulated inside both fibers as small droplets (with sizes similar to those in the initial emulsion), the fibers demonstrated a poor oxidative stability. This may be related to the presence of traces of metals (e.g., Fe) in the PVA used, which catalyzed lipid oxidation.[38]

Researchers have also reported a number of more complicated emulsion electrospinning approaches. For example, composite fibers were prepared by incorporating Ca-alginate microspheres that served as reservoirs for BSA into electrospun poly(L-lactic acid) (PLLA) fibers through emulsion electrospinnig.[39] An *in vitro* release test showed prolonged release profiles of BSA and lower burst release rates than those from naked Ca-alginate microspheres. In another study, de Freitas Zômpero et al. developed a hybrid encapsulation structure containing *β*-carotene-loaded nanoliposomes through electrospinning.[40] The electrospinning process did not affect the stability of *β*-carotene during encapsulation. Superior UV protection performance, of *β*-carotene loaded liposomes within electrospun fibers of PEO and PVOH polymers, was confirmed as 86.8% and 80.3% of the initial *β*-carotene remaining intact inside nanofibers after 6 h of UV light exposure, respectively. Gordon and co-workers successfully embedded amorphous celecoxib nanoparticles within PVA nanofibers. The rapid potential dissolution of the hydrophilic PVA nanofibers in an aqueous medium would enable immediate dispersion and dissolution of the lipophilic nanoparticles and, therefore, can potentially serve as a useful delivery system in applications including pharmaceuticals, food, and agriculture.[41] These studies demonstrate that emulsion electrospinning provides a platform for the encapsulation of sensitive bioactive compounds without compromising their activity, as well as the achievment of sustained release profile.

Coaxial Electrospinning. Coaxial electrospinning is significantly different from the emulsion electrospinning method since it generates core−sheath fibers by the utilization of two concentric needles and two solutions as illustrated in Figure 4. The shell solution, which consists of a spinnable polymeric material, is injected through the outer needle, whereas the core solution, consisting of encapsulated compounds, is injected

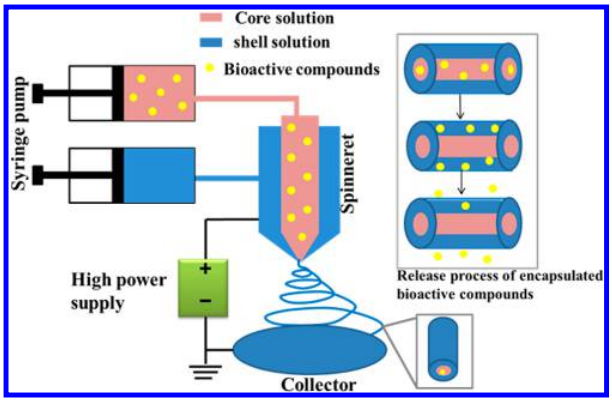

Figure 4. Schematic description of coaxial electrospinning.

through the inner needle. During coaxial electrospinning, parameters including miscibility of outer and inner solutions, evaporation and diffusion of solvent, and surface tension of liquid−liquid interfaces are crucial to the formation of fine core/shell fiber structure. The effects of various parameters on coaxial electrospinning have been evaluated.[31]

The primary motivation of coaxial electrospinning is to encapsulate bioactive compounds into the core to achieve high loading and maintain activity. Jiang and co-workers demonstrated the feasibility of coaxial electrospinning for encapsulation and controlled release of proteins. They found that the released lysozyme (a model protein) from coaxial electrospun core−shell fibers of poly(*ε*-caprolacton) (PCL) maintained its structure and bioactivity.[29] López-Rubio et al. encapsulated bifidobacteria into core−shell fibers with PVA as the shell material and bifidobacteria-containing milk constituting the core content. This encapsulation process had a beneficial effect on the storage stability of the microorganism.[42]

Coaxial electrospinning is also an attractive strategy for suppressing the initial burst release and thereby delivering compounds in a controlled manner.[43] Compounds that loaded into the polymer solution form the inner core whereas the outer shell serves as a diffusive barrier for the compounds. Yang et al. controlled the release of ferulic acid (FA) from zein film using a modified coaxial electrospinning technique.[44] The results showed that the release of FA from the coaxial fibers exhibited better sustained-release profiles with a smaller initial burst effect compared to FA released from monofilament electrospun fibers. Ji et al. compared blended and coaxial electrospun polycaprolactone (PCL)-based nanofibers for protein encapsulation, and coaxial electrospinning resulted in more sustained release and higher protein activity.[45]

Complex coaxial electrospinning approaches have been reported to enhance the controlled release behavior of encapsulated bioactive compounds as well. For example, BSA entrapped in a W/O emulsion that served as the core solution has been encapsulated in the shell polymer through coaxial electrospinning. The results showed that emulsion-core electrospun membranes greatly suppressed the initial release of BSA, as compared to conventional coaxial electrospun sample, and the release profile of BSA could be tailored by changing the composition of poly(L-lactide-*co*-glycolide (PLGA) in the core emulsion.[46] Mickova et al. encapsulated protein-loaded liposome into core−shell fibers through coaxial electrospinning.[47] They found that while less than 10% of enzymatic activity of horseradish peroxidase (HRP) was

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

Table 1. Summary of Electrospun Carbohydrate-Based Biopolymers and Applications

polysaccharides	additive polymers	solvent	functionality and application	refs
cellulose and derivatives	gelatin	acetic acid	core–shell fibers with controlled release property in the gastrointestinal tract	75, 157
	PEO	chloroform and methanol	food packaging or wound dressing materials.	61
	PCL	*N*,*N*-dimethylformamide (DMF), chloroform, and acetone	biofilters and biosensor strips	158
	PVP	acetone, ethanol, and distilled water	scaffold for tissue engineering	159
	zein	acetone and DMF	improved thermal stability and hydrophilic property	160
	silk fibroin	trifluoroacetic acid (TFA)	heavy metal ion adsorption from wastewater	161
pectin	PEO	distilled water	biomedical applications, electrochemical devices, and drug delivery systems	162
	chitosan and PVA	acetic acid and distilled water	enhanced mechanical properties and biocompatible skin tissue scaffold	163
	alginate and PEO	NaOH solution	enhanced encapsulation of folic acid for functional food applications	98, 164
starch	PEO or PVA	distilled water	controlled drug delivery system	165
	polyacrylamide	formic acid	emzyme immobolization	166
	silk fibroin	formic acid	bone regeneration materials for cell viability, proliferation, and attachment	167
	poly(ethylene-*alt*-maleic anhydride	distilled water and DMSO	porous structure with improved thermal stability	168
	PVA	distilled water	electrochemical capacitor electrode	169
guar gum	PVA	distilled water	biocompatible and biodegradable curative membranes for biomedical applications	170
chitosan	PVA	acetic acid and distilled water	wound dressing with improved mechanical and antimicrobial properties	171
	PEO	acetic acid and distilled water	enhanced cell proliferation biomembranes; wound dressing material	172
	PVA and PVP	acetic acid and distilled water	wound dressings	173
	PLA	TFA, chloroform/ethanol, and water	potential application for tissue engineering; drug delivery; improvement of enzyme activity	89, 174
	PCL and PEO	dichloromethane (DCM) and methanol	biocomposite with for wound dressing applications	175
	PVA and silk fibroin	distilled water	biocompatible material for wound dressing	176
	PVA and alginate	acetic acid and distilled water	fiber with better biocompatibility and controlled degradation rate	177
	PVA and gelatin	acetic acid and distilled water	controlled dual drug delivery system	178
	gelatin	TFA and DCM	skin tissue engineering scaffold with good cell attachment and proliferation	179
	zein	ethanol and TFA	functional controlled delivery system	180
heparin	PCL	DCM and methanol	controlled delivery device to the site of vascular injury	181
	PLLA	DCM and methanol	scaffold as a differentiating device for human mesenchymal stem cells	182
hyaluronic acid	PEO	acetic acid and distilled water	core–shell fiber with good thermal stability for applications in tissue regeneration	183
	PCL	chloroform and folic acid	high encapsulation efficacy and control of the release of growth factors that can serve as skin tissue engineering scaffolds for wound healing	184
	PVP	ethanol and distilled water	core–sheath fibers for protection and stabilization of liposome thus to control the release of loaded drugs	185
	gelatin	NaOH, DMF, and acetic acid	biomedical materials	186
	silk fibroin	ethanol, formic acid, and distilled water	coaxial nanofibers with perfect antibacterial and antifungal activities for drug release application	187
chondroitin sulfate	PVA	distilled water	biocompatible and nontoxic materials for soft-tissue regeneration	188
	collagen and glycosaminoglycan	2,2,2-trifluoroethanol (TFE) and distilled water	biomaterials with enhanced cell proliferation	189
dextran	PCL and cellulose acetate	DMF, tetrahydrofuran (THF), and acetone	composite mats with good cell attachment and antibacterial property for wound dressing applications	190
pullulan	PVA	distilled water	fibers with improved mechanical and thermal properties; functional materials for delivery of bioactive compounds	93, 191
	cellulose acetate	DMF and DMSO	cell carrier for skin or bone tissue engineering applications	192
	amaranth protein	formic acid	encapsulation of bioactives for functional food or active packaging	13, 90–92
	whey protein concentrate	phosphate-buffered saline	encapsulation of *Bifidobacterium* strains for functional food applications	16
alginates	PVA	distilled water	antibacterial wound dressings and tissue engineering application	193
	chitosan	glycerol, acetic acid, and distilled water	tissue antiadhesion barrier	194

preserved during the single-nozzle electrospinning process, coaxial electrospinning preserved 62% of the enzyme activity of liposome-incorporated HRP. Zhang and co-workers reported that different release behaviors for basic fibroblast growth factor (bFGF) were obtained using emulsion or hydrogel as the core in the modified coaxial electrospun membranes.[48] The results showed that PLGA-heparin-based emulsion core was uniformly distributed, while the chitosan hydrogel core was aggregated in the electrospun fibers. The different distributions in electrospun fibers led to different release behaviors, as expected; the release amounts of bFGF from the emulsion-core and hydrogel-core coaxial electrospun samples were ~25% and ~64% in the first 7

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161–9179

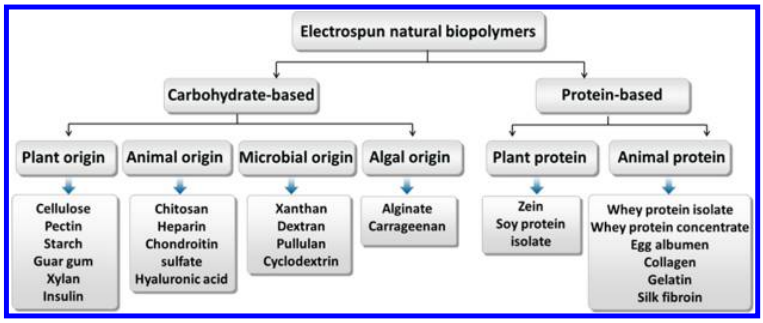

Figure 5. Schematics of biopolymeric scaffolds and source of materials.

days, respectively. In particular, bFGF of the modified coaxial electrospun samples afforded ∼90% cumulative release, much higher than the 60% cumulative release obtained using a conventional coaxial electrospun sample. These findings indicate that coaxial electrospinning can reduce burst effect and allow dual-compound loading to both core and shell layers, and coaxial electrospinning reveals better processing versatility compared with emulsion electrospinning or any other form of bioactive substance incorporation method.[49] However, the coaxial electrospinning requires a special apparatus and careful selection of operational parameters to ensure the desired results. The volatility of the solvent in the core polymer should be lower than that used for the sheath polymer for the successful formation of core−sheath structure fibers,

ELECTROSPINNING OF NATURAL BIOMATERIALS AND APPLICATIONS

In recent years, tremendous attention has been given to natural biopolymers due to their remarkable advantages including biocompatibility, biodegradability, renewability, and sustainability as carriers for encapsulation of bioactive compounds in the food industry.[50] In this section, the production of fibers from natural biopolymers and their potential applications in encapsulation of bioactive compounds are investigated.

Polysaccharide-Based Electrospun Nanofibers. *Electrospinning of Polysaccharide.* Although electrospinning of polysaccharides has been reported,[51] there are some limitations that hinder the electrospinning of polysaccharides. Polysaccharides have a tendency to form strong hydrogen bonds, leading to high solution viscosity or gel formation. Finally, biologically derived polysaccharides often require complicated and expensive purification steps prior to electrospinning. Rather than covering detailed information on the electrospinning of various polysaccharides, this section focuses on the efforts that have been made to fabricate electrospun polysaccharide-based fibers.

It is important to vary the concentration of polysaccharide and the composition of solvent to electrospin polysaccharides. For example, chitosan is difficult to electrospin into a fibrous structure because its polycationic character in aqueous acidic solution excessively increases the surface tension of solution.[52] Nevertheless, chitosan nanofibers of different diameters have been successfully electrospun using a wide variety of solvents, including trifluoroacetic acid (TFA), TFA/dichloromethane, concentrated acetic acid, etc.[53,54] It is also noteworthy that electrospinning of pure chitosan is restricted based on its concentration, molar mass, and degree of deacetylation (DD).[55] Similarly, the spinnability of cellulose is restricted due to the limited solubility and the strong intermolecular and intramolecular hydrogen bonds. Because of these demerits, the choice of a suitable solvent system is thus crucial, and a limited number of solvents have been applied in which pure cellulose nanofiber was successfully formed, such as NaOH/urea,[56] ionic liquids,[57,58] TFA/methylene chloride, etc.[59]

Another approach to improve the spinnability of polysaccharides is by blending them with other polymers, including PEO, PVA, polyvinylpyrrolidone (PVP), PLA, and some biopolymers like zein, gelatin, silk fibroin, etc. (see Table 1). These polymers have flexible linear chains that can play the role of providing the required linkage and facilitating a sufficient entanglement to induce the formation of fibers.[10] For example, defect-free nanofibers with diameters of 60−120 nm were obtained from a highly deacetylated chitosan blended with PEO.[60] Moderate temperatures (40−70 °C) favored the formation of uniform chitosan/PEO nanofibers with higher chitosan content, which were due to a faster solvent evaporation rate and increased chain entanglements. Additionally, higher chitosan content in the precursor blends led to a significant reduction in nanofiber diameters (from 123 to 63 nm for 50/50 and 90/10 chitosan/PEO blends, respectively, at room temperature). This is likely related to a reduction in viscosity and an increased conductivity when increasing the chitosan content from 50 to 90%.[60] In another study, a binary mixture of cellulose acetate (CA) and PEO was electrospun to create nanofibers with novel properties and structures.[61] In this study, fiber formation was influenced by the chain length of polymers, concentrations, and mixing ratios. Commercial cassava starch was also blended with PEO to improve its spinnability.[62]

Encapsulation of Bioactive Compounds by Electrospun Polysaccharide Fibers. Natural polysaccharides are promising vehicles for the encapsulation of bioactive compounds.[10] Fiber-based carbohydrate nanocomposites have been used in a wide variety of applications.[63] They exhibit high thermostability compared to lipid- or protein-based delivery systems. Moreover, polysaccharides can be modified to achieve the required properties or interact with bioactive compounds through their functional groups, which make polysaccharides versatile carriers to encapsulate compounds. A great number of polysaccharides, such as cellulose, chitosan, pullulan, dextran, starch, alginate, and pectin, have been employed as delivery materials for bioactive compounds (Figure 5). One potential of electrospun polysaccharide-based nanofibers in the food indutstry is to improve the stability and bioavailability of bioactive compounds, 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 the product acceptance. Nanofibers can also serve

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

as carrier systems for the target delivery and sustained release of nutraceuticals or pharmaceuticals in GIT owing to flexibility in changing the composition of fiber. Furthermore, they can be used for the fabrication of active packaging materials or nanostructured layers for packaging, which have applications like controlling microbial growth or inhibiting oxidative degradation reactions. Additionally, a less explored potential application of electrospun fibers is as filtration membranes and biosensors in food and beverage processing. Based on the above applications, a comprehensive review of electrospun polysaccharide-based polymers for the encapsulation of different bioactive compounds is described below.

Cellulose and Its Derivatives. Cellulose is the most abundant and a low-cost biodegradable byproduct in the food and agricultural industries. However, electrospinning of cellulose is limited due to its intrinsic chemistry. Previous studies showed that the electrospinnning of cellulose was achieved by the utilization of specific organic solvent, blending with other polymers, or the adoption of cellulose derivatives,[64] such as CA.

Electrospun cellulose-based fibers have been used to encapsulate bioactive compounds and enhance their stability. Cellulose has been electrospun with heparin to prepare anticoagulant nanofibers.[57] In another example, curcumin-loaded CA nanofibers were successfully prepared under a fixed electric field of 17.5 kV/15 cm.[65] The chemical integrity and antioxidant activity of the loaded curcumin were maintained after the electrospinning process, indicating the feasibility of electrospinning for the encapsulation of bioactive compounds. Yang et al. prepared tannic acid (TA)-Fe^{3+} loaded electrospun CA fibers with improved mechanical and antioxidant properties.[66]

Cellulose nanofibers have also been investigated for enzyme immobilization providing improved bioactivity. For instance, *Candida rugosa* lipase was immobilized on electrospun CA nanofibers. By optimizing the oxidation conditions, the obtained fibers showed significantly higher thermal stability and durability comparatively to the equivalent free enzyme.[67] Chen et al. immobilized lipase onto the regenerated cellulose fiber membrane for oil hydrolysis, and under the optimal operating conditions a bioreactor activity of 9.83×10^4 U/m^2 was obtained.[68] In another study, Huang and co-workers immobilized positively charged lysozyme−chitosan−organic rectorite composites on 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.[69] Naringinase-loaded electrospun CA nanofiber was also prepared by LBL, and the immobilized naringinase activity could be controlled by the LBL layers. The results showed that 22.7% of naringin and 60.7% of limonin in the grapefruit juice could be removed by obtained CA fibers, suggesting the potential application of these nanofiber composites to remove bitterness for fruit juice.[70]

Moreover, the electrospun fibers can be utilized for the delivery and controlled or sustained release of bioactive compounds. For example, CA fibers with diameter of 460 ± 84 nm have been used for the delivery of sea holly extract in a controlled-release application.[71] The fibers obtained exhibited good antioxidant activity, and approximately 99% of the loaded extract was released from fibers through a diffusion mechanism, while only 35% of the loaded extract was released from the corresponding cast films. Vitamin A and E (V_A and V_E) loaded electrospun nanofibers exhibited a gradual and monotonous increase in the cumulative release process over the test periods, 24 h for V_E-loaded samples and 6 h for V_A-loaded samples. In contrast, the corresponding casting films exhibited a burst release of the vitamins during the first 20 and 30 min, respectively.[72] In another study, Chantarodsakun and co-workers reported the successful incorporation of [6]-gingerol into electrospun CA fibers as a controlled release system. The data showed that ∼97% of [6]-gingerol could be released from fibers at 37 °C, whereas only 74% of it was released from the corresponding films.[73] Yan and co-workers prepared double-component nanofibers of FA-loaded CA and triple-component nanofibers of FA/PVP-loaded CA through modified coaxial electrospinning processes.[74] The results showed that the triple-component nanofibers exhibited better sustained-release profiles than the double-component nanofibers in terms of release completeness, the tailing-off release time period, and release rates. In another study, the release mechanism of the model protein gelatin from coaxial electrospun CA fibers was anomalous diffusion, exhibiting a near zero order release profile with a release half-life of ∼7.4 days.[75] The nanofilms obtained were found intact (without bursting) when immersed in PBS for 20 days. These findings suggest the potential application of electrospun CA fibers in the encapsulation and controlled release of functional compounds.

Apart from these applications, a less explored potential application is as filtration membranes in food and beverage processing. Ma and co-workers produced CA fibers to separate biomolecules such as bovine serum albumin and bilirubin[76] or to purify immunoglobulin G (IgG) since it had a strong binding capacity with IgG.[77] A recent study showed that a composite membrane using cellulosic nanofibers as the top layer could increase the filter efficiency by about 5 times compared to the same membranes without cellulosic nanofibers.[78] Electrospun cellulose acetate fibers have also been used as biosensors for the detection of very low concentrations of methyl viologen and cytochrome *c* in aqueous solutions,[79] as well as for applications in sensitive displays and optical devices.[80]

Chitosan. Chitosan, a chitin-derived polysaccharide, has received particular attention due to its biological properties including biocompatible, biodegradable, and antimicrobial properties. Several attempts have been made to fabricate electrospun chitosan nanofibers by changing the physical-chemical properties (e.g., M_w, DD, solvent), the electrospinning conditions (distance, voltage, flow rate), and blending with other polymers or proteins.

Electrospun chitosan fibers could serve as the delivery carriers for sustained release of bioactive compounds. For instance, uniform and homogeneous hybrid chitosan/phospholipid nanofibers were fabricated to deliver curcumin,[81] and the release of curcumin was in a sustained way for over 7 days (around 75%) without a significant burst effect. Vitamin B12 has also been delivered by chitosan/phospholipid nanofiber.[82] The release profile showed that a burst release occurred within 1 day and reached the maximum (nearly 100%) at day 2. 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 was triggered by erosion and diffusion, demonstrating the potential application of zein−chitosan nanofibers as a gastro-mucoadhesive delivery vehicle for improving accessibility and bioavailability of hydrophobic compounds.[83] A sustained and colon-specific delivery of protein was also achieved by coaxial

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

electrospinning of sodium alginate and chitosan.[84] It was found that around 75% of BSA was released in simulated colonic fluid for 16 h, and little change occurred in the secondary structure of encapsulated BSA indicated by FTIR and circular dichroism analysis. Core−shell nanofiber using chitosan in the core and PCL as the shell was constructed in an attempt to deliver FA and resveratrol.[20] The *in vitro* release studies showed that both resveratrol and FA were released in a sustained manner with approximately 48% and 55% being released in 120 h, respectively.

Enzymes can also be immobilized into chitosan fibers. Ge and co-workers immobilized glucose oxidase (GOD) in PVA/chitosan/tea extract nanofibers to make a novel food packaging system.[85] The GOD 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). Huang and co-workers 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.[86] Lysozyme (LZ) was also successfully incorporated into chitosan−ethylenediaminetetraacetic acid/PVA nanofiber without losing its activity.[87] However, burst release of LZ was observed as cumulative release reached ∼80% within 30 min, owing to the erosion of hydrophilic polymer and lysozyme diffusion. Another approach for incorporating lysozyme into nanofibers was described by Park and co-workers, who immobilized hen egg-white LZ on electrospun chitosan nanofibers through cross-linked enzyme aggregates (CLEAs).[88] 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. The LZ-CLEA immobilized chitosan nanofibers were reused for 10 cycles to investigate the antibacterial activity against *Staphylococcus aureus*, *Bacillus subtilis*, *Shigella flexneri*, and *Pseudomonas aeruginosa*, and the nanofibers were still effective against four pathogenic bacteria with an antibacterial ratio of >80% after 10 cycles. These results suggest that LZ-CLEA immobilized chitosan nanofibers could be used as a promising material for enhanced stability and remarkably high reusability of LZ in industrial applications.[88] Siqueira and co-workers recently reported an electrospun chitosan and PLA fiber mat employed as support for immobilization of *Pseudomonas cepacia* lipase. The results showed that the addition of chitosan, with more hydrophilic groups, reduced enzyme activity.[89] They concluded that the mechanism of interaction between fiber mat and enzyme was through a hydrophobic physical adsorption.

Pullulan. Pullulan is an extracellular microbial polysaccharide. It is water-soluble, biocompatible, and biodegradable. Hybrid pullulan based fibers with amaranth protein isolate (API) are commonly fabricated to encapsulate bioactive compounds with enhanced stability and bioactivity. For instance, encapsulation of nisin within API/pullulan nanofibers was developed to maintain its antimicrobial activity.[13] The average fiber diameters decreased with increasing nisin content. Fibers containing 20 mg/mL of nisin reached an encapsulation efficacy of 95% with good antimicrobial activity against *L. mesenteroides*, suggesting a potential application as edible films or packaging material in the food industry. Folic acid has also been encapsulated in API (*Amaranthus hypochondriacus* L.)/pullulan fibers with high EE (>95%).[90] In addition, the encapsulation of FA within fibers increased its thermal stability and protected it from degradation after ultraviolet (UV) light exposure. Another work showed that, by encapsulating them in API/pullulan nanofibers, the antioxidant properties of quercetin, FA, and curcumin were also maintained during *in vitro* digestion.[91,92] A blend of PVA and pullulan could also be used to load bioactive compounds. Qian et al. prepared rutin-loaded electrospun pullulan and PVA nanofibers to obtain UV-resistant properties.[93] The results showed that the addition of rutin could enhance the mechanical properties to some extent due to its stiff structure, and the incorporation of rutin was able to decrease the transmittance of UVA and UVB to be less than 5%. The value of the ultraviolet protection factor (UPF) was above 40 and above 50 when the contents of rutin were 4.46% and 5.67%, respectively. The fibers obtained have potential in anti-UV packaging and dressing materials.

Starch. Starch, one of the most abundant natural polysaccharides, is composed of mixtures of amylose and amylopectin. It is nonallergenic, GRAS, and inexpensive. There has been increasing interest in using starch-based delivery systems to encapsulate food ingredients.[7] Yet, the required viscoelasticity of electrospinning starch solution is needed, and efforts have been made to enable electrospinning and nanofiber formation, such as dissolving starch in organic acids or blending it with other polymers. Recently, starch−formate/glycerol (SFG) fibers loaded with *Lactobacillus paracasei* were successfully fabricated by coaxial electrospinning.[94] 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.

Alginate. Alginate is an anionic linear polysaccharide that exists in brown seaweed. Due to the rigid and extended structure of alginate, the electrospinning of this biopolymer remains a challenge. Blending of alginate with other polymers such as PEO and adding a cosolvent like glycerol have been investigated to facilitate the electrospinning of alginate.[95] In a recent study, electrospun alginate-based nanofibers were fabricated to achieve a colon-specific delivery system of BSA. There was little change in the secondary structure of encapsulated BSA, and around 75% of BSA was released in the simulated colonic fluid.[96] The release kinetics revealed that the release of BSA in colon followed a complex mechanism, in which erosion was the dominant factor. This study showed that electrospun alginate/chitosan nanofilm is a promising colon-specific delivery system for bioactive protein. İspirli Doğaç and co-workers immobilized lipase onto electrospun alginate nanofibers.[97] Their results showed that nanofibers enhanced the stability of lipase, maintaining almost 65−70% of its activity, while the free lipase lost all of its activity after 40−60 min at high temperatures. PVA/alginate nanofibers maintained 60% of enzyme activity after 14 reuses compared to PEO/alginate nanofibers, which only afforded 7 reuses. The stability of FA is improved by alginate−pectin−PEO electrospun fibers. The results showed that FA encapsulated in electrospun fibers afforded nearly 100% retention when stored in the dark at pH 3 for 41 days, while the recovery of unencapsulated folic acid was 8% and 0% after 1 day of storage at pH 3 in the absence and the presence of light, respectively. FTIR and NMR data demonstrated that the enhanced protection on folic acid by the electrospun fibers was attributable to physical entrapment, rather than folic acid−polymer interaction.[98]

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

Table 2. Summary of Electrospun Natural Protein-Based Biopolymers and Applications

proteins	additive polymers	solvent	functionality and application	refs
zein	PLLA	1,1,1,3,3,3-hexafluoro-2-propanol (HFIP)	wound dressing with high cell proliferation and good hydrophilicity	137
	PVA	ethanol and water	wound healing	195
	PCL	TFE and DCM	wound healing application; bone tissue engineering scaffold	196
	polyurethane and cellulose acetate	DMF and methyl ethyl ketone/2-butanone	wound dressing	197
	cellulose acetate	acetone and DMF	tissue engineering scaffold	198
	WPI and SPI	ethanol/distilled water	bioactive packaging material for food system	199, 200
	bacterial cellulose	ethanol and distilled water	packaging film with enhanced water resistance	201
SPI	PVA	acetic acid/distilled water	eco-friendly filtration material; biodegradable material with adjustable mechanical property	202, 203
	PEO	1% NaOH solution or HFIP	tissue engineering scaffold	204, 205
	PLA	1% NaOH solution	active packaging material	19
WPI or WPC	PVA	distilled water	functional materials with enhanced encapsulation effiency	206
	PCL	THF/DMF or DCM/DMF	antimicrobial material for biomedical application	207
egg albumin	PVA	distilled water	antimicrobial material	208
casein	PCL	DCM and DMF	bone tissue engineering application	209
collagen or gelatin	PVA	acetic acid and distilled water	biomaterial with controlled release property; skin scaffold	210, 211
	PCL	chloroform, methanol, and acetic acid	tissue engineering material with good cell adhesion and biocompatibility	212
	hyaluronate	formic acid and HFIP	wound dressing for regeneration of scarless skin	213
silk fibroin	PCL	THF and DMF	artificial dermis scaffold	214
	carboxymethyl cellulose	LiBr aqueous solution	enhanced biomimetic potential for bone tissue engineering application	215
	collagen	acetic acid and distilled water	vascular tissue engineering	216

Cyclodextrins. In addition to the above polymeric systems, electrospinning has recently been used for the production of fibers from nonpolymeric systems such as cyclodextrins (CDs). CDs were used to encapsulate bioactive compounds to form an inclusion complex (IC). Actually, even in the absence of the electrospinning process the complexation of bioactive compounds within CDs has attracted a great deal of interest because it results in higher stability and allows sustained release.[99] Electrospun PVA nanofibers containing a curcumin−cyclodextrin complex showed improved thermal stability and sustained release properties when compared to PVA/curcumin fibers.[100] In particular, γ-CD was more effective than α-CD and β-CD in the stabilization and controlled release of flavor compounds such as menthol, vanillin, and eugenol.[50,99,101] These functional electrospun fibers may find practical application in the food industry especially in designing food packaging materials. Wen and co-workers successfully encapsulated cinnamon essential oil into PVA and β-cyclodextrin. The resulting nanofilm had better antimicrobial activity than the cast film and effectively prolonged the shelf life of strawberries.[102] Aytac and Uyar encapsulated α-TOC into β-cyclodextrin (β-CD) to form α-TOC/β-CD IC before electrospinning with polycaprolactone (PCL). Their results showed that the electrospun PCL/α-TOC/β-CD nanofiber exhibited higher antioxidant activity compared to PCL/α-TOC nanofiber due to the presence of the IC.[103] Mascheroni and co-workers developed an edible polysaccharide nanofilm of pullulan−cyclodextrin for the efficient encapsulation and controlled release of perillaldehyde.[104] 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 high relative humidity (RH) (threshold, $a_W \geq 0.9$), suggesting its application in active food packaging. Pullulan and β-cyclodextrin emulsions in water were also electrospun for the encapsulation of (*R*)-(+)-limonene. The release of limonene from the fibers was modulated by the RH changes and could be used as an active packaging device.[105] The results were consistent with the other studies that demonstrated that an IC provides better controlled release of compounds.[106−108]

Other CD derivatives such as hydroxypropyl-β-cyclodextrin, hydroxypropyl-γ-cyclodextrin, and methyl-β-cyclodextrin were also studied for their electrospinning behavior and their applicability as encapsulating materials.[109−111] Aytac and co-workers incorporated gallic acid (GA) with hydroxypropyl-β-cyclodextrin (GA/HP-β-CD-IC) and then electrospun it with PLA (PLA/GA/HP-β-CD-IC). Compared to PLA/GA fibers, the obtained PLA/GA/HP-β-CD-IC nanofibers with higher antioxidant activity exhibited controlled release profile for GA in three different mediums, suggesting a potential application of nanostructured electrospun fibers as food packaging materials to increase the shelf life of food products.[112] However, the previous studies were in laboratory scale; the proposed applications for electrospun fibers have to be effectively translated to be useful in food systems. Studies are required to prove the workability of the resultant products as active/smart food packaging materials without altering the physical, chemical, and sensory characteristics of food.

Protein-Based Electrospun Materials. *Electrospinning of Protein Fibers.* The electrospinning of proteins is notoriously difficult, mainly because of their complex secondary and tertiary structures.[113] Globular proteins have too little interaction with each other to entangle during the spinning process. Electrospinning of proteins is possible under conditions in which they are dissolved as a random coil conformation. Generally, there are several ways to fulfill this requirement, such as the appropriate choice of solvent, denaturation, heating, or blending with other polymers.

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

Research has demonstrated that fibers can be produced by breaking cysteine bridges and dissolving in fluorinated solvents. For example, collagen nanofibers have been spun from the NaAc/HAc solution at pH 3.0, maintaining 57% of their native structure.[114] Silk and fibrinogen were electrospun from HFP or 98% formic acid, and several globular proteins (hemoglobin and BSA) were spun from TFE.[115,116] It was also reported that when protein was denatured, the globular albumin molecule was transformed into a fibrillar form that was effective for nanofiber production.[115] Further, changing the pH of the solution expands the ability to incorporate bioactive compounds, and electrospinning of whey protein solutions at acidic pH would facilitate formulation flexibility. Similarly, electrospinning of gelatin solutions from water at room temperature has long been problematic;[117] nanofibers could be obtained at elevated temperatures, under which conditions gelatin behaves as a random-coil polymer.[118]

In another approach, some synthetic or natural polymers have been blended with proteins for the purpose of improving spinnability and the mechanical properties of fibers (e.g., thermal stability and degradability). Polymers utilized in this way including PEO, PVA, PVP, PCL, PGA, PLA, PLGA, PLLA, and natural biopolymers such as chitosan and hyaluronan (HA) (see Table 2). For example, Suganya and co-workers used PCL/collagen blend nanofibers for skin tissue regeneration and achieved augmented skin repair with the incorporation of an *Aloe vera* extract.[119] Core−sheath structured nanofibers of silk fibroin (SF) and PCL have also been constructed utilizing emulsion electrospinning. The main focus in generating SF/PCL fibers was to capitalize on the mechanical strength of the PCL and exploit the advantages of SF as a tissue engineering material. Natural biopolymers have also been reportedly blended with protein. Wongsasulak and co-workers investigated the electrospinning of egg albumen (EA) protein by blending it with CA. EA is a biopolymer that cannot be readily electrospun because of its high surface tension and conductivity. Adding CA and Tween 40 reduced the surface tension and facilitated the production of EA/CA nanofibers.[120] Since zein and gelatin can be spun from solvents acceptable in the food industry, it opens the possibility of using zein or gelatin as a carrier for proteins that cannot be spun by themselves in a way acceptable in the food industry.

Encapsulation of Bioactive Compounds by Electrospun Protein Nanofibers. For food applications, protein-based nanofibers are also preferably used for nutrient delivery because they offer advantages over other materials in terms of biodegradability and biocompatibility, *in vivo* safety status, and good functional properties.[121] For example, proteins exhibit high loading capacity of bioactive compounds due to their amphiphilic structure, multiple binding sites, and a variety of possible binding mechanisms including electrostatic attractions, hydrophobic interactions, hydrogen, and covalent bonding. All of these features motivate interest in developing electrospun protein-based nanomaterials. The main protein-based encapsulating materials for the purpose of delivery and controlled release applications are currently zein, whey protein concentrate (WPC), SPI, API, fish sarcoplasmic protein (FSP), and other proteins (Figure 5).

Zein. Zein, a hydrophobic protein (prolamin) extracted from corngrains, is known for its high thermal resistance and excellent oxygen barrier properties. Electrospinning of zein represents an excellent opportunity for preparing a promising delivery vehicle for encapsulation and stabilization and for the controlled release of various bioactive compounds, such as β-carotene, GA, curcumin, fish oil, (−)-epigallocatechin gallate (EGCG), FA, and tannin.

Electrospun zein fibers have been used to stabilize the light-sensitive bioactive antioxidant β-carotene.[122] The β-carotene antioxidant was stable and widely dispersed inside the zein fibers, and its UV−vis light stability could be significantly increased compared to nonencapsulated control.

GA could also be successfully incorporated into electrospun zein fibers at different loading ratios, and 1,1′-diphenyl-2-picrylhydrazyl (DPPH) assay showed that GA had retained its antioxidant activity after electrospinning.[123] GA exhibits a rapid release from zein fibers based on Fickian diffusion,[124] and the fibers obtained were not cytotoxic and exhibited antimicrobial properties, suggesting application as a novel and safe food contact material. Further studies performed by Neo and co-workers showed that the heat-curing process led to larger fiber diameters, enhanced fiber hydrophobicity, and a slower release profile for GA.[125] These new properties offer a potential for developing novel protein-based nanostructured electrospun fibers with improved properties for food packaging materials.

Brahatheeswaran and co-workers developed the smooth zein−curcumin fiber with a mean diameter of 310 nm and found that curcumin maintained its free radical scavenging activity and showed sustained release behavior.[126] Bui et al. reported that nanofibers containing 1.6 wt % curcumin could efficiently inhibit growth of *S. aureus* (83%), suggesting their potential application as an antibacterial nonwoven mat.[127] Curcumin-loaded zein membrane was utilized for Fe^{3+} sensing by naked-eye detection with an optical detection limit of 0.4 mg/L.[128] Recently, a study by Wang and co-workers demonstrated that the curcumin-loaded zein fibers possessed good antibacterial activity toward *S. aureus* and *Escherichia coli*, and the predominant release mechanism of curcumin from fibers was Fickian diffusion, suggesting their potential antimicrobial applications.[129]

Moomand and Lim encapsulated fish oil in zein fibers and showed that electrospun zein fibers provide a greater oxidative stability compared to nonencapsulated fish oil.[130] The same group demonstrated that the release kinetics of omega-3-rich fish oil from zein fibers was controlled by matrix swelling, erosion, and diffusion.[131] Yang and co-workers prepared core−shell electrospun fibers loaded with fish oil using coaxial electrospinning. Compared to monofilament electrospinning, coaxial electrospinning signicantly improved the oxidative stability of encapsulated fish oil and the shelf life of encapsulated fish oil. In coaxial nanofibers fish oil lasted 65 days longer than in monofilament nanofibers, indicating that coaxial electrospinning is an effective strategy to encapsulate fish oil.[132] These studies show that the electrospun zein matrix can be a useful carrier to deliver fish oil for functional foods.

Mucoadhesive nanofibers containing α-TOC have been electrospun from zein−chitosan composite solution. The resulting fibers exhibited good gastro-mucoadhesive property, and the release of α-TOC in simulated gastric fluid (SGF) with pepsin was triggered by erosion, while α-TOC release in SGF without pepsin was triggered by swelling and driven by diffusion. The gastro-mucoadhesive and release characteristics of fibers demonstrate the potential applicability of this composite fiber as a gastro-mucoadhesive delivery vehicle in GIT for improving accessibility and bioavailability of hydrophobic compounds.[83] In a study performed by Fabra and co-workers, a higher EE of α-TOC (100%) was obtained for the

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

zein fibers (100%) compared to WPI and SPI capsules, indicating that EE values are usually greater in fibers than in beads or capsules (Figure 6).[18] Similar results correlating

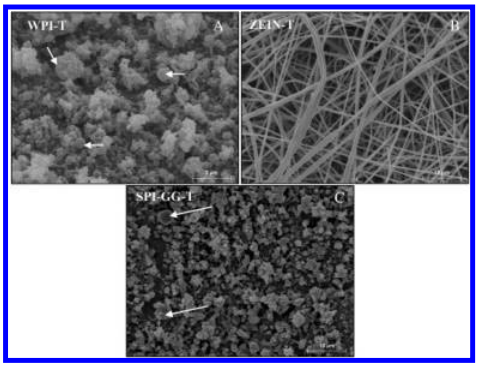

Figure 6. Selected scanning electron microscopy microphotographs of WPI/α-tocopherol capsules (a), zein/α-tocopherol fibers (b), and SPI-GG-α-tocopherol capsules (c) formed by means of the electrohydrodynamic process. Reprinted with permission from ref 18. Copyright 2016 Elsevier.

morphology with EE were obtained for paraffin compounds.[133] One potential application of the fibers obtained could be as a food contact layer for liquid products, such as juice or milk.

The encapsulation of other bioactive compounds was also achieved by zein. EGCG, an antioxidant found in green tea, was encapsulated in zein nanofibers by Li and co-workers to enhance its stability during simulated food processing conditions.[134] The results indicate that the stability of EGCG in water was enhanced, since aging in 0% humidity led to only 2% EGCG released in water, whereas aging in 75% humidity led to a significant release in water. Proanthocyanidin (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.[135] The release profile of FA from zein composite fibers was improved using fibers prepared through modified coaxial electrospinning. Results show that the FA from the coaxial fibers exhibits an improved sustained-release profile with a small initial burst effect and little tailing-off release when compared to monofilament fibers prepared using simple electrospinning,[44] suggesting that coaxial electrospinning is a useful tool for generating nanofibers with higher quality and improved functional performance. De Oliveira Mori and co-workers incorporated tannin into electrospun zein nanofibers affording a ribbon-like shape and homogeneous morphology.[136] Electrospinning has been employed to encapsulate anionic proteins. Zhang and co-workers prepared a wound dressing material composed of PLLA/zein nanofibers loaded with *Rana chensinensis* skin peptides using blending and coaxial electrospinning techniques.[137] Rose hip seed oil (REO) has been encapsulated into a zein prolamine matrix using coaxial electrospinning. The EE of REO in zein prolamine matrix was 90.2%, and the resulting zein prolamine/REO electrospun films showed a significantly prolonged shelf life for packaged cumquats and bananas.[138] These studies demonstrate that electrostatic encapsulation processes are very versatile for preparing a zein-based encapsulant polymeric matrix to protect bioactive compounds.

SPI. Soy protein, one of the least expensive vegetable products, has gained widespread interest as an electrospinning matrix. Unfortunately, electrospinning of pure soy protein is quite challenging and requires a carrier polymer to enhance molecular entanglement. Electrospun SPI/PEO fibers have been prepared and exhibit promising applications in the food industry. For instance, electrospun fibers from SPI/PEO blend and PLA were prepared for the controlled release of AITC.[19] The results indicated that the release of AITC from electrospun nanofibers could be controlled by varying the RH, with high RH triggering AITC release, suggesting potential applications in active packaging. In a study performed by Wang and co-workers, red raspberry extract (RRE), rich in anthocyanins, was incorporated in SPI before and after SPI denaturation.[139] Although electron microscopy analysis indicated that both cases generated beaded nanofibers, the functionalized nanofibers obtained had 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.

WPC. Recently, WPC has attracted considerable interest because it is an amphiphilic macromolecule that plays an essential role in stabilizing food formulations. López-Rubio and co-workers have shown the feasibility of electrospinning of WPC and pullulan for the encapsulation of *Bifidobacterium* strains. WPC demonstrates a greater protective ability as an encapsulation material than pullulan, and it effectively prolonged the survival of cells even at high RH.[16] Dextran, WPC, and chitosan were also used as matrix materials to encapsulate lycopene by emulsion electrospinning. WPC afforded high EE values of around 75%, and the resulting fibers were able to protect lycopene against moisture and thermal degradation.[140]

Gelatin. In a review, Sajkiewicz and Kolbuk have described that solvents and associated ambient parameters can influence the electrospinnability of gelatin.[141] The application of electrospun gelatin-based fibers in the encapsulation of bioactive compounds enhances stability and improves controlled release properties. For example, asiaticoside, the major component of *Centella asiatica* extracts that possesses wound healing ability, was electrospun with gelatin to improve its functionality.[142] The authors observed that higher amounts of asiaticoside were present in the electrospun fiber than were found in a cast film (i.e., ∼99 and ∼87%, respectively). In addition, the greater surface area of the fiber over that of the film results in more release of asiaticoside from the fiber mat compared to the film. Vitamin A (V_A) and vitamin E (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.[143] Padrão and co-workers fabricated a bovine lactoferrin (bLF)-loaded fish gelatin in an electrospun membrane.[144] The intact structure and the bactericidal efficiency of bLF against *E. coli* and *S. aureus* were retained after the electrospinning and cross-linking, and a higher killing capacity of bLF in electrospun samples was observed when compared to adsorbed bLF.

Recently, rather than using organic solvents that are unsuitable for food applications, there have been some reports on fabricating pure gelatin nanofibers using food-approved solvent for the purpose of encapsulating bioactives. Hani et al.

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

encapsulated *Moringa oleifera* bioactive extract in gelatin nanofibers spun from 30% acetic acid solution to improve stability and maintain the antioxidant activity of this bioactive extract.[145] Laha et al. fabricated cross-linked gelatin nanofibers from 20% acetic acid solution, and controlled release experiments suggested good compatibility of hydrophobic molecules in the fibers.[146] Gelatin nanofibers had also been applied for controlled release of curcumin with acetic acid and surfactants (Tween 80, anionic sodium dodecyl sulfonate (SDS), and cationic cetyltrimethylammonium bromide (CTAB)). The addition of CTAB and Tween 80 did not significantly affect the diameter of gelatin nanofibers, while the addition of SDS afforded nanofibers with increased diameters. Interaction between SDS and gelatin does not favor the release of the encapsulated 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 nanofibers with food grade surfactants for the controlled release of curcumin, which may find promising applications as a nutraceutical carrier in the food industry.[147]

API. Amaranth protein isolate is a safe ingredient for human consumption and functions as a bioactive encapsulation matrix for functional foods.[148] Two bioactive compounds, quercetin and FA, were encapsulated within API/pullulan fibers.[91] Due to the protection of API/pullulan electrospun structures, sustained release of quercetin and FA was achieved during *in vitro* digestion, and this was also responsible for the improved antioxidant capacity of the bioactives in comparison to the free compounds. These electrospun structures exhibit promising application in functional foods. Electrospun fibers from API/pullulan dispersions were also developed for protection and controlled release of curcumin. The antioxidant activity of curcumin was maintained after an *in vitro* digestion process and was superior for encapsulated curcumin when compared to free curcumin. In addition, the controlled and sustained release of curcumin was observed both in buffer solution (pH 7.4) and during an *in vitro* digestion process. Different release behavior was observed depending on the fiber composition, as a higher proportion of API decreased curcumin diffusion, thus, resulting in a more controlled release. This versatile delivery vehicle composed of API and pullulan electrospun fibers is suitable as a carrier for the encapsulation and for the protection of bioactive compounds for food-related applications.[92] The ability of API/pullulan fiber structures for the encapsulation and photoprotection of FA for food fortification has also been studied.[90]

FSP. The numerous health benefits and bioactive properties has made FSP appealing for use in an oral delivery formulation.[149] Insulin was efficiently encapsulated into water-soluble FSP fibers without affecting its conformation structure, and it provided protection against chymotrypsin degradation.[150] Stephansen and co-workers found that the interactions between insulin-loaded protein fibers and surfactants had a significant influence on insulin release, due to fiber porosity and surface properties. Anionic surfactants increased the insulin release in a concentration-dependent manner, whereas the neutral surfactant had no significant effect on the release and almost no insulin was released from the FSP-insulin fibers upon incubation with the cationic surfactant. Additionally, the FSP-insulin fibers appear dense after incubation with this cationic surfactant, whereas the fibers were highly porous after incubation with anionic or neutral surfactants.[151]

Other Proteins. Xiao and co-workers encapsulated carnosic acid into the kafirin protein-based nanofibers, and release followed Fickian diffusion, suggesting its potential application in nutraceutical delivery.[152] Casein has been electrospun with PVA or PEO to encapsulate lipase.[153] Both fibers exhibit higher catalytic activity, hydrolyzing olive oil, than cast films prepared from the same solution, suggesting that electrospun fibrous membranes can serve as an excellent enzyme-carrying substrate. Curcumin has also been electrospun with silk fibroin.[154] This vitamin exhibited a sustained release behavior; moreover, the incorporation of this vitamin could enhance the ability of SF nanofibrous mats in protecting the cells against oxidative stress.

As demonstrated by the above findings, proteins exhibit great potential for encapsulating bioactive compounds with controlled release profile. Clear advantages of food protein matrices include their high nutritional value, abundant renewable sources, and acceptability as naturally occurring food components degradable by digestive enzymes. Nevertheless, fundamental understanding of protein−protein and protein−nutraceutical interactions at the molecular level and their impact on functional properties of proteins is still required to ensure design of ideal nutraceutical carriers for use in the food industry.

FUTURE TRENDS

Electrospinning has become a well-established encapsulation approach over the past few years, and its application has resulted in the development of innovative products. The market of electrospinning equipment, both for laboratory research and for industrial production, is expected to grow significantly due to the many advantages of nanofibers and their applications. Nevertheless, the application of electrospinning in agriculture and food science is still in the early stages of development, and several obstacles remain that prevent the application of electrospinning in the food industry.

One major limitation of electrospinning is the relatively low productivity, which restricts its large-scale commercial exploitation. Thus, addressing this constraint by modifying the structural aspects of the electrospinning setup (e.g., multineedle arrangement or multiaxial technologies) offers the possibility for scale-up. Besides, it remains a challenge to ensure uniform nanofibers to be fabricated repeatedly and massively with the desired morphological, mechanical, and chemical properties, especially in industrial scale. From laboratory prototypes to commercial applications, more research and collaborations are necessary to lower cost and improve efficiency for the industrialization of electrospinning.

Second, the electrospinning process can be difficult to completely control. Challenges in the electrospinning of proteins and polysaccharides are associated with the selection of appropriate solvents or polymer additives for facilitating fiber formation and the necessity of postprocessing procedures for improving the mechanical resistance and controlling the degradation rate of the scaffolds. In addition, a number of other issues need to be addressed, such as proper amount of compound loading content and encapsulation efficiency, removal of residual organic solvent, bioactivity retention of the incorporated compounds, effect of the initial burst drug release, assurance of a required release profile, etc. Several reports showed greater extent of drug loading with certain polymers for extended release; however, uneven distribution of the drug in nanofibers often results in initial burst effect, which still needs a lot of fine-tuning. Apart from this, the loading of a

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

bioactive compound in polymer solution may adversely affect its viscosity and surface tension, rendering it unsuitable for electrospinning. Laboratory scale machines are generally dealing with small volumes in milliliters; however, when it comes to liters in industrial scale, there is a lack of accurate control over process parameters and solution properties. Scale-up of electrospun nanofiber with accuracy and reproducibility is again questionable. It is desirable that all these challenges be solved before nanofibers are obtained.

Furthermore, a more sophisticated preparation method, such as the utilization of coaxial or emulsion electrospinning with liposomes or nanoparticles, expected to generate core−shell structured nanofibers, is required to fabricate suitable delivery devices and also broaden the possibilities for new products with improved functionalities.[155,156] There are clear advantages of nanofibrous carriers such as site-specific delivery and multiple drug encapsulation, but additional work has to be performed to tailor the delivery rate in order to increase efficacy.

Last but not least, it is then foreseeable that bioactive compound loaded electrospun materials can play an important role in food technology, and the safety of obtained materials and the bioactivity and bioavailability of loaded compounds should be of concern. For example, since solvent residues could be trapped inside the produced nanofibers, an accurate control over solvent residuals becomes crucial in food-related applications. Most importantly, proposed applications for electrospun fibers have to be effectively translated to be useful in food systems. Studies are required to prove the workability of the resultant products as active/smart food packaging materials without altering the physical, chemical, and sensory characteristics of food. For the assessment of bioavailability of food ingredients, simulated GIT may need to be employed. Indeed, there has been very little work on *in vivo* and clinical tests, and efficient biological models (e.g., cell-based systems) mimicking the uptake of the released components require development. The impact of biopolymer−bioactive compound interactions in the targeted area on the adsorption should be studied for targeted delivery (e.g., protection against the gastric environment, release under intestinal conditions). Also, toxicity experiments, residual solvent analysis, and their biological fate during digestion and absorption need be considered by future researchers. Additionally, questions of consuming nanoscale food materials still remain and require further analysis, and legislation by government agencies on the application of nanomaterials in the food industry is required to ensure the safety of nanofood products.

AUTHOR INFORMATION

Corresponding Author

*Tel: +86-20-22236669. E-mail: bbhwu@scut.edu.cn.

ORCID

Robert J. Linhardt: 0000-0003-2219-5833

Hong Wu: 0000-0002-4711-9979

Funding

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 support.

Notes

The authors declare no competing financial interest.

REFERENCES

(1) Dias, M. I.; Ferreira, I. C. F. R.; Barreiro, M. F. Microencapsulation of bioactives for food applications. *Food Funct.* **2015**, *6* (4), 1035−1052.

(2) Anu Bhushani, J.; Anandharamakrishnan, C. Electrospinning and electrospraying techniques: Potential food based applications. *Trends Food Sci. Technol.* **2014**, *38* (1), 21−33.

(3) Wan, Z. L.; Guo, J.; Yang, X. Q. Plant protein-based delivery systems for bioactive ingredients in foods. *Food Funct.* **2015**, *6* (9), 2876−2889.

(4) Fang, Z.; Bhandari, B. Encapsulation of polyphenols − a review. *Trends Food Sci. Technol.* **2010**, *21* (10), 510−523.

(5) Wang, S.; Chen, Y.; Liang, H.; Chen, Y.; Shi, M.; Wu, J.; Liu, X.; Li, Z.; Liu, B.; Yuan, Q.; Li, Y. Intestine-specific delivery of hydrophobic bioactives from oxidized starch microspheres with an enhanced stability. *J. Agric. Food Chem.* **2015**, *63* (39), 8669−8675.

(6) Gomez-Estaca, J.; Balaguer, M. P.; Gavara, R.; Hernandez-Munoz, P. Formation of zein nanoparticles by electrohydrodynamic atomization: eEffect of the main processing variables and suitability for encapsulating the food coloring and active ingredient curcumin. *Food Hydrocolloids* **2012**, *28* (1), 82−91.

(7) Zhu, F. Encapsulation and delivery of food ingredients using starch based systems. *Food Chem.* **2017**, *229*, 542−552.

(8) Ezhilarasi, P. N.; Karthik, P.; Chhanwal, N.; Anandharamakrishnan, C. Nanoencapsulation Techniques for Food Bioactive Components: A Review. *Food Bioprocess Technol.* **2013**, *6* (3), 628−647.

(9) Joye, I. J.; McClements, D. J. Biopolymer-based delivery systems: challenges and opportunities. *Curr. Top. Med. Chem.* **2016**, *16* (9), 1026−1039.

(10) Fathi, M.; Martín, Á.; McClements, D. J. Nanoencapsulation of food ingredients using carbohydrate based delivery systems. *Trends Food Sci. Technol.* **2014**, *39* (1), 18−39.

(11) Jiang, H.; Wang, L.; Zhu, K. Coaxial electrospinning for encapsulation and controlled release of fragile water-soluble bioactive agents. *J. Controlled Release* **2014**, *193*, 296−303.

(12) Ghorani, B.; Tucker, N. Fundamentals of electrospinning as a novel delivery vehicle for bioactive compounds in food nanotechnology. *Food Hydrocolloids* **2015**, *51*, 227−240.

(13) Soto, K. M.; Hernández-Iturriaga, M.; Loarca-Piña, G.; Luna-Bárcenas, G.; Gómez-Aldapa, C. A.; Mendoza, S. Stable nisin food-grade electrospun fibers. *J. Food Sci. Technol.* **2016**, *53* (10), 3787−3794.

(14) Zamani, M.; Prabhakaran, M. P.; Ramakrishna, S. Advances in drug delivery via electrospun and electrosprayed nanomaterials. *Int. J. Nanomed.* **2013**, *8*, 2997−3017.

(15) Drosou, C. G.; Krokida, M. K.; Biliaderis, C. G. Encapsulation of bioactive compounds through electrospinning/electrospraying and spray drying: A comparative assessment of food-related applications. *Drying Technol.* **2017**, *35* (2), 139−162.

(16) López-Rubio, A.; Sanchez, E.; Wilkanowicz, S.; Sanz, Y.; Lagaron, J. M. Electrospinning as a useful technique for the encapsulation of living bifidobacteria in food hydrocolloids. *Food Hydrocolloids* **2012**, *28* (1), 159−167.

(17) Agarwal, S.; Greiner, A.; Wendorff, J. H. Functional materials by electrospinning of polymers. *Prog. Polym. Sci.* **2013**, *38* (6), 963−991.

(18) Fabra, M. J.; López-Rubio, A.; Lagaron, J. M. Use of the electrohydrodynamic process to develop active/bioactive bilayer films for food packaging applications. *Food Hydrocolloids* **2016**, *55*, 11−18.

(19) Vega-Lugo, A. C.; Lim, L. T. Controlled release of allyl isothiocyanate using soy protein and poly(lactic acid) electrospun fibers. *Food Res. Int.* **2009**, *42* (8), 933−940.

(20) Poornima, B.; Korrapati, P. S. Fabrication of chitosan-polycaprolactone composite nanofibrous scaffold for simultaneous delivery of ferulic acid and resveratrol. *Carbohydr. Polym.* **2017**, *157*, 1741−1749.

(21) Shenoy, S. L.; Bates, W. D.; Frisch, H. L.; Wnek, G. E. Role of chain entanglements on fiber formation during electrospinning of

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

polymer solutions: good solvent, non-specific polymer−polymer interaction limit. *Polymer* **2005**, *46* (10), 3372−3384.
(22) Subramanian, C.; Weiss, R. A.; Shaw, M. T. Electrospinning and characterization of highly sulfonated polystyrene fibers. *Polymer* **2010**, *51* (9), 1983−1989.
(23) Dilamian, M.; Montazer, M.; Masoumi, J. Antimicrobial electrospun membranes of chitosan/poly(ethylene oxide) incorporating poly(hexamethylene biguanide) hydrochloride. *Carbohydr. Polym.* **2013**, *94* (1), 364−371.
(24) Konwarh, R.; Karak, N.; Misra, M. Electrospun cellulose acetate nanofibers: The present status and gamut of biotechnological applications. *Biotechnol. Adv.* **2013**, *31* (4), 421−437.
(25) Reneker, D. H.; Yarin, A. L.; Fong, H.; Koombhongse, S. Bending instability of electrically charged liquid jets of polymer solutions in electrospinning. *J. Appl. Phys.* **2000**, *87* (9), 4531−4547.
(26) Mendes, A. C.; Stephansen, K.; Chronakis, I. S. Electrospinning of food proteins and polysaccharides. *Food Hydrocolloids* **2017**, *68*, 53−68.
(27) Yang, Y.; Li, X.; Cui, W.; Zhou, S.; Tan, R.; Wang, C. Structural stability and release profiles of proteins from core-shell poly (DL-lactide) ultrafine fibers prepared by emulsion electrospinning. *J. Biomed. Mater. Res., Part A* **2008**, *86A* (2), 374−385.
(28) Zeng, J.; Yang, L.; Liang, Q.; Zhang, X.; Guan, H.; Xu, X.; Chen, X.; Jing, X. Influence of the drug compatibility with polymer solution on the release kinetics of electrospun fiber formulation. *J. Controlled Release* **2005**, *105* (1), 43−51.
(29) Jiang, H.; Hu, Y.; Li, Y.; Zhao, P.; Zhu, K.; Chen, W. A facile technique to prepare biodegradable coaxial electrospun nanofibers for controlled release of bioactive agents. *J. Controlled Release* **2005**, *108* (2−3), 237−243.
(30) Amler, E.; Mickova, A.; Buzgo, M. Electrospun core/shell nanofibers: A promising system for cartilage and tissue engineering? *Nanomedicine* **2013**, *8* (4), 509−512.
(31) Zhang, H.; Zhao, C.; Zhao, Y.; Tang, G.; Yuan, X. Electrospinning of ultrafine core/shell fibers for biomedical applications. *Sci. China Chem.* **2010**, *53* (6), 1246−1254.
(32) McClellan, P.; Landis, W. J. Recent applications of coaxial and emulsion electrospinning methods in the field of tissue engineering. *BioRes. Open Access* **2016**, *5* (1), 212−227.
(33) Dvores, M. P.; Marom, G.; Magdassi, S. Formation of organic nanoparticles by electrospinning of volatile microemulsions. *Langmuir* **2012**, *28* (17), 6978−6984.
(34) Yarin, A. L. Coaxial electrospinning and emulsion electrospinning of core−shell fibers. *Polym. Adv. Technol.* **2011**, *22* (3), 310−317.
(35) Li, X.; Zhang, H.; Li, H.; Yuan, X. Encapsulation of proteinase K in PELA ultrafine fibers by emulsion electrospinning: preparation and in vitro evaluation. *Colloid Polym. Sci.* **2010**, *288* (10), 1113−1119.
(36) Wang, X.; Yuan, Y.; Huang, X.; Yue, T. Controlled release of protein from core−shell nanofibers prepared by emulsion electrospinning based on green chemical. *J. Appl. Polym. Sci.* **2015**, *132* (16), 41811−41819.
(37) Camerlo, A.; Vebert-Nardin, C.; Rossi, R. M.; Popa, A. M. Fragrance encapsulation in polymeric matrices by emulsion electrospinning. *Eur. Polym. J.* **2013**, *49* (12), 3806−3813.
(38) García-Moreno, P. J.; Stephansen, K.; van der Kruijs, J.; Guadix, A.; Guadix, E. M.; Chronakis, I. S.; Jacobsen, C. Encapsulation of fish oil in nanofibers by emulsion electrospinning: Physical characterization and oxidative stability. *J. Food Eng.* **2016**, *183*, 39−49.
(39) Qi, H.; Hu, P.; Xu, J.; Wang, A. Encapsulation of drug reservoirs in fibers by emulsion electrospinning: morphology characterization and preliminary release assessment. *Biomacromolecules* **2006**, *7* (8), 2327−2330.
(40) de Freitas Zômpero, R. H.; López-Rubio, A.; de Pinho, S. C.; Lagaron, J. M.; de la Torre, L. G. Hybrid encapsulation structures based on β-carotene-loaded nanoliposomes within electrospun fibers. *Colloids Surf., B* **2015**, *134*, 475−482.
(41) Gordon, V.; Marom, G.; Magdassi, S. Formation of hydrophilic nanofibers from nanoemulsions through electrospinning. *Int. J. Pharm.* **2015**, *478* (1), 172−179.
(42) López-Rubio, A.; Sanchez, E.; Sanz, Y.; Lagaron, J. M. Encapsulation of living bifidobacteria in ultrathin PVOH electrospun fibers. *Biomacromolecules* **2009**, *10* (10), 2823−2829.
(43) He, M.; Xue, J.; Geng, H.; Gu, H.; Chen, D.; Shi, R.; Zhang, L. Fibrous guided tissue regeneration membrane loaded with anti-inflammatory agent prepared by coaxial electrospinning for the purpose of controlled release. *Appl. Surf. Sci.* **2015**, *335*, 121−129.
(44) Yang, J. M.; Zha, L. S.; Yu, D. G.; Liu, J. Coaxial electrospinning with acetic acid for preparing ferulic acid/zein composite fibers with improved drug release profiles. *Colloids Surf., B* **2013**, *102*, 737−743.
(45) Ji, W.; Yang, F.; van den Beucken, J. J. J. P.; Bian, Z.; Fan, M.; Chen, Z.; Jansen, J. A. Fibrous scaffolds loaded with protein prepared by blend or coaxial electrospinning. *Acta Biomater.* **2010**, *6* (11), 4199−4207.
(46) Zhang, H.; Zhao, Y.; Han, F.; Wang, M.; Yuan, X. Controlled release of bovine serum albumin from electrospun fibrous membranes via an improved emulsion-core technique. *J. Controlled Release* **2011**, *152* (Suppl. 1), 181−182.
(47) Mickova, A.; Buzgo, M.; Benada, O.; Rampichova, M.; Fisar, Z.; Filova, E.; Tesarova, M.; Lukas, D.; Amler, E. Core/shell nanofibers with embedded liposomes as a drug delivery system. *Biomacromolecules* **2012**, *13* (4), 952−962.
(48) Zhang, H.; Liang, J.; Ding, Y.; Li, P. The controlled release of growth factor via modified coaxial electrospun fibres with emulsion or hydrogel as the core. *Mater. Lett.* **2016**, *181*, 119−122.
(49) Zhang, H.; Jia, X.; Han, F.; Zhao, J.; Zhao, Y.; Fan, Y.; Yuan, X. Dual-delivery of VEGF and PDGF by double-layered electrospun membranes for blood vessel regeneration. *Biomaterials* **2013**, *34* (9), 2202−2212.
(50) Kayaci, F.; Uyar, T. Encapsulation of vanillin/cyclodextrin inclusion complex in electrospun polyvinyl alcohol (PVA) nanowebs: prolonged shelf-life and high temperature stability of vanillin. *Food Chem.* **2012**, *133* (3), 641−649.
(51) Kriegel, C.; Arrechi, A.; Kit, K.; McClements, D. J.; Weiss, J. Fabrication, functionalization, and application of electrospun biopolymer nanofibers. *Crit. Rev. Food Sci. Nutr.* **2008**, *48* (8), 775−797.
(52) Min, B. M.; Lee, S. W.; Lim, J. N.; You, Y.; Lee, T. S.; Kang, P. H.; Park, W. H. Chitin and chitosan nanofibers: Electrospinning of chitin and deacetylation of chitin nanofibers. *Polymer* **2004**, *45* (21), 7137−7142.
(53) Haider, S.; Al-Zeghayer, Y.; Ahmed Ali, F.; Haider, A.; Mahmood, A.; Al-Masry, W.; Imran, M.; Aijaz, M. Highly aligned narrow diameter chitosan electrospun nanofibers. *J. Polym. Res.* **2013**, *20* (4), 1−11.
(54) Ignatova, M.; Manolova, N.; Rashkov, I. Electrospun Antibacterial Chitosan-Based Fibers. *Macromol. Biosci.* **2013**, *13* (7), 860−872.
(55) De Vrieze, S.; Westbroek, P.; Van Camp, T.; Van Langenhove, L. Electrospinning of chitosan nanofibrous structures: feasibility study. *J. Mater. Sci.* **2007**, *42* (19), 8029−8034.
(56) Qi, H.; Sui, X.; Yuan, J.; Wei, Y.; Zhang, L. Electrospinning of Cellulose-Based Fibers From NaOH/Urea Aqueous System. *Macromol. Mater. Eng.* **2010**, *295* (8), 695−700.
(57) Viswanathan, G.; Murugesan, S.; Pushparaj, V.; Nalamasu, O.; Ajayan, P. M.; Linhardt, R. J. Preparation of biopolymer fibers by electrospinning from room temperature ionic liquids. *Biomacromolecules* **2006**, *7* (2), 415−418.
(58) Meli, L.; Miao, J.; Dordick, J. S.; Linhardt, R. J. Electrospinning from room temperature ionic liquids for biopolymer fiber formation. *Green Chem.* **2010**, *12* (11), 1883−1892.
(59) Jahanbaani, A. R.; Behzad, T.; Borhani, S.; Darvanjooghi, M. H. K. Electrospinning of cellulose nanofibers mat for laminated epoxy composite production. *Fibers Polym.* **2016**, *17* (9), 1438−1448.
(60) Pakravan, M.; Heuzey, M. C.; Ajji, A. A fundamental study of chitosan/PEO electrospinning. *Polymer* **2011**, *52* (21), 4813−4824.

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

(61) Korehei, R.; Kadla, J. F. Encapsulation of T4 bacteriophage in electrospun poly(ethylene oxide)/cellulose diacetate fibers. *Carbohydr. Polym.* **2014**, *100*, 150−157.
(62) Sunthornvarabhas, J.; Thumanu, K.; Limpirat, W.; Kim, H. J.; Piyachomkwan, K.; Sriroth, K. Assessment of material blending distribution for electrospun nanofiber membrane by Fourier transform infrared (FT-IR) microspectroscopy and image cluster analysis. *Infrared Phys. Technol.* **2014**, *66*, 141−145.
(63) Zheng, Y.; Monty, J.; Linhardt, R. J. Polysaccharide-based nanocomposites and their applications. *Carbohydr. Res.* **2015**, *405*, 23−32.
(64) Frey, M. W. Electrospinning cellulose and cellulose derivatives. *Polym. Rev.* **2008**, *48* (2), 378−391.
(65) Suwantong, O.; Opanasopit, P.; Ruktanonchai, U.; Supaphol, P. Electrospun cellulose acetate fiber mats containing curcumin and release characteristic of the herbal substance. *Polymer* **2007**, *48* (26), 7546−7557.
(66) Yang, W.; Sousa, A. M. M.; Fan, X.; Jin, T.; Li, X.; Tomasula, P. M.; Liu, L. Electrospun ultra-fine cellulose acetate fibrous mats containing tannic acid-Fe^{3+} complexes. *Carbohydr. Polym.* **2017**, *157*, 1173−1179.
(67) Huang, X. J.; Chen, P. C.; Huang, F.; Ou, Y.; Chen, M. R.; Xu, Z. K. Immobilization of Candida rugosa lipase on electrospun cellulose nanofiber membrane. *J. Mol. Catal. B: Enzym.* **2011**, *70* (3−4), 95−100.
(68) Chen, P. C.; Huang, X. J.; Huang, F.; Ou, Y.; Chen, M. R.; Xu, Z. K. Immobilization of lipase onto cellulose ultrafine fiber membrane for oil hydrolysis in high performance bioreactor. *Cellulose* **2011**, *18* (6), 1563−1571.
(69) Huang, W.; Xu, H.; Xue, Y.; Huang, R.; Deng, H.; Pan, S. Layer-by-layer immobilization of lysozyme−chitosan−organic rectorite composites on electrospun nanofibrous mats for pork preservation. *Food Res. Int.* **2012**, *48* (2), 784−791.
(70) Huang, W.; Zhan, Y.; Shi, X.; Chen, J.; Deng, H.; Du, Y. Controllable immobilization of naringinase on electrospun cellulose acetate nanofibers and their application to juice debittering. *Int. J. Biol. Macromol.* **2017**, *98*, 630−636.
(71) Vongsetskul, T.; Phurayar, P.; Chutimasakul, T.; Tuchinda, P.; Uamsiri, S.; Kumkate, S.; Pearngam, P.; Jitpibull, J.; Samphaongern, C.; Tangboriboonrat, P. Acanthus ebracteatus Vahl. extract-loaded cellulose acetate ultrafine fibers as a topical carrier for controlled-release applications. *Polym. Bull.* **2016**, *73* (12), 3319−3331.
(72) Taepaiboon, P.; Rungsardthong, U.; Supaphol, P. Vitamin-loaded electrospun cellulose acetate nanofiber mats as transdermal and dermal therapeutic agents of vitamin A acid and vitamin E. *Eur. J. Pharm. Biopharm.* **2007**, *67* (2), 387−397.
(73) Chantarodsakun, T.; Vongsetskul, T.; Jangpatarapongsa, K.; Tuchinda, P.; Uamsiri, S.; Bamrungcharoen, C.; Kumkate, S.; Opaprakasit, P.; Tangboriboonrat, P. [6]-gingerol-loaded cellulose acetate electrospun fibers as a topical carrier for controlled release. *Polym. Bull.* **2014**, *71* (12), 3163−3176.
(74) Yan, J.; White, K.; Yu, D. G.; Zhao, X. Y. Sustained-release multiple-component cellulose acetate nanofibers fabricated using a modified coaxial electrospinning process. *J. Mater. Sci.* **2014**, *49* (2), 538−547.
(75) Sakuldao, S.; Yoovidhya, T.; Wongsasulak, S. Coaxial electrospinning and sustained release properties of gelatin-cellulose acetate core-shell ultrafine fibres. *ScienceAsia* **2011**, *37* (4), 335−343.
(76) Ma, Z. W.; Kotaki, M.; Ramakrishna, S. Electrospun cellulose nanofiber as affinity membrane. *J. Membr. Sci.* **2005**, *265* (1−2), 115−123.
(77) Ma, Z.; Ramakrishna, S. Electrospun regenerated cellulose nanofiber affinity membrane functionalized with protein A/G for IgG purification. *J. Membr. Sci.* **2008**, *319* (1−2), 23−28.
(78) Ma, H.; Burger, C.; Hsiao, B. S.; Chu, B. Fabrication and characterization of cellulose nanofiber based thin-film nanofibrous composite membranes. *J. Membr. Sci.* **2014**, *454*, 272−282.
(79) Wang, X.; Kim, Y. G.; Drew, C.; Ku, B. C.; Kumar, J.; Samuelson, L. A. Electrostatic assembly of conjugated polymer thin layers on electrospun nanofibrous membranes for biosensors. *Nano Lett.* **2004**, *4* (2), 331−334.
(80) Hu, W.; Liu, S.; Chen, S.; Wang, H. Preparation and properties of photochromic bacterial cellulose nanofibrous membranes. *Cellulose* **2011**, *18* (3), 655−661.
(81) Mendes, A. C.; Gorzelanny, C.; Halter, N.; Schneider, S. W.; Chronakis, I. S. Hybrid electrospun chitosan-phospholipids nanofibers for transdermal drug delivery. *Int. J. Pharm.* **2016**, *510* (1), 48−56.
(82) Goto, Y.; Masuda, A.; Aiba, T. In vivo application of chitosan to improve bioavailability of cyanocobalamin, a form of vitamin B12, following intraintestinal administration in rats. *Int. J. Pharm.* **2015**, *483* (1−2), 250−255.
(83) Wongsasulak, S.; Pathumban, S.; Yoovidhya, T. Effect of entrapped α-tocopherol on mucoadhesivity and evaluation of the release, degradation, and swelling characteristics of zein−chitosan composite electrospun fibers. *J. Food Eng.* **2014**, *120*, 110−117.
(84) Wen, P.; Wen, Y.; Huang, X.; Zong, M. H.; Wu, H. Preparation and characterization of protein-loaded electrospun fiber mat and its release kinetics. *J. Agric. Food Chem.* **2017**, *65* (23), 4786−4796.
(85) Ge, L.; Zhao, Y. S.; Mo, T.; Li, J. R.; Li, P. Immobilization of glucose oxidase in electrospun nanofibrous membranes for food preservation. *Food Control* **2012**, *26* (1), 188−193.
(86) Huang, X. J.; Ge, D.; Xu, Z. K. Preparation and characterization of stable chitosan nanofibrous membrane for lipase immobilization. *Eur. Polym. J.* **2007**, *43* (9), 3710−3718.
(87) Charernsriwilaiwat, N.; Opanasopit, P.; Rojanarata, T.; Ngawhirunpat, T. Lysozyme-loaded, electrospun chitosan-based nanofiber mats for wound healing. *Int. J. Pharm.* **2012**, *427* (2), 379−384.
(88) Park, J. M.; Kim, M.; Park, H.-S.; Jang, A.; Min, J.; Kim, Y. H. Immobilization of lysozyme-CLEA onto electrospun chitosan nanofiber for effective antibacterial applications. *Int. J. Biol. Macromol.* **2013**, *54*, 37−43.
(89) Siqueira, N. M.; Garcia, K. C.; Bussamara, R.; Both, F. S.; Vainstein, M. H.; Soares, R. M. D. Poly (lactic acid)/chitosan fiber mats: Investigation of effects of the support on lipase immobilization. *Int. J. Biol. Macromol.* **2015**, *72*, 998−1004.
(90) Aceituno-Medina, M.; Mendoza, S.; Lagaron, J. M.; López-Rubio, A. Photoprotection of folic acid upon encapsulation in food-grade amaranth (Amaranthus hypochondriacus L.) protein isolate − Pullulan electrospun fibers. *LWT—Food Sci. Technol.* **2015**, *62* (2), 970−975.
(91) Aceituno-Medina, M.; Mendoza, S.; Rodríguez, B. A.; Lagaron, J. M.; López-Rubio, A. Improved antioxidant capacity of quercetin and ferulic acid during in-vitro digestion through encapsulation within food-grade electrospun fibers. *J. Funct. Foods* **2015**, *12*, 332−341.
(92) Blanco-Padilla, A.; López-Rubio, A.; Loarca-Piña, G.; Gómez-Mascaraque, L. G.; Mendoza, S. Characterization, release and antioxidant activity of curcumin-loaded amaranth-pullulan electrospun fibers. *LWT—Food Sci. Technol.* **2015**, *63* (2), 1137−1144.
(93) Qian, Y.; Qi, M.; Zheng, L.; King, M.; Lv, L.; Ye, F. Incorporation of rutin in electrospun pullulan/PVA nanofibers for novel UV-resistant properties. *Materials* **2016**, *9* (7), 504−512.
(94) Lancuški, A.; Abu Ammar, A.; Avrahami, R.; Vilensky, R.; Vasilyev, G.; Zussman, E. Design of starch-formate compound fibers as encapsulation platform for biotherapeutics. *Carbohydr. Polym.* **2017**, *158*, 68−76.
(95) Bonino, C. A.; Krebs, M. D.; Saquing, C. D.; Jeong, S. I.; Shearer, K. L.; Alsberg, E.; Khan, S. A. Electrospinning alginate-based nanofibers: From blends to crosslinked low molecular weight alginate-only systems. *Carbohydr. Polym.* **2011**, *85* (1), 111−119.
(96) Wen, P.; Feng, K.; Yang, H.; Huang, X.; Zong, M.-H.; Lou, W.-Y.; Li, N.; Wu, H. Electrospun core-shell structured nanofilm as a novel colon-specific delivery system for protein. *Carbohydr. Polym.* **2017**, *169*, 157−166.
(97) İspirli Doğaç, Y.; Deveci, İ.; Mercimek, B.; Teke, M. A comparative study for lipase immobilization onto alginate based composite electrospun nanofibers with effective and enhanced stability. *Int. J. Biol. Macromol.* **2017**, *96*, 302−311.

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

(98) Alborzi, S.; Lim, L. T.; Kakuda, Y. Encapsulation of folic acid and its stability in sodium alginate-pectin-poly(ethylene oxide) electrospun fibres. *J. Microencapsulation* **2013**, *30* (1), 64−71.
(99) Kayaci, F.; Ertas, Y.; Uyar, T. Enhanced thermal stability of eugenol by cyclodextrin inclusion complex encapsulated in electrospun polymeric nanofibers. *J. Agric. Food Chem.* **2013**, *61* (34), 8156−8165.
(100) Sun, X. Z.; Williams, G. R.; Hou, X. X.; Zhu, L. M. Electrospun curcumin-loaded fibers with potential biomedical applications. *Carbohydr. Polym.* **2013**, *94* (1), 147−153.
(101) Uyar, T.; Hacaloglu, J.; Besenbacher, F. Electrospun polystyrene fibers containing high temperature stable volatile fragrance/flavor facilitated by cyclodextrin inclusion complexes. *React. Funct. Polym.* **2009**, *69* (3), 145−150.
(102) Wen, P.; Zhu, D.-H.; Wu, H.; Zong, M. H.; Jing, Y. R.; Han, S. Y. Encapsulation of cinnamon essential oil in electrospun nanofibrous film for active food packaging. *Food Control* **2016**, *59*, 366−376.
(103) Aytac, Z.; Uyar, T. Antioxidant activity and photostability of α-tocopherol/β-cyclodextrin inclusion complex encapsulated electrospun polycaprolactone nanofibers. *Eur. Polym. J.* **2016**, *79*, 140−149.
(104) Mascheroni, E.; Fuenmayor, C. A.; Cosio, M. S.; Di Silvestro, G.; Piergiovanni, L.; Mannino, S.; Schiraldi, A. Encapsulation of volatiles in nanofibrous polysaccharide membranes for humidity-triggered release. *Carbohydr. Polym.* **2013**, *98* (1), 17−25.
(105) Fuenmayor, C. A.; Mascheroni, E.; Cosio, M. S.; Piergiovanni, L.; Benedetti, S.; Ortenzi, M.; Schiraldi, A.; Mannino, S. Encapsulation of R-(+)-Limonene in Edible Electrospun Nanofibers. *ICheaP-11: 11th Int. Conf. Chem. Process Eng.* **2013**, *32*, 1771−1776.
(106) Lemma, S. M.; Scampicchio, M.; Mahon, P. J.; Sbarski, I.; Wang, J.; Kingshott, P. Controlled release of retinyl acetate from β-cyclodextrin functionalized poly(vinyl alcohol) electrospun nanofibers. *J. Agric. Food Chem.* **2015**, *63* (13), 3481−3488.
(107) Wen, P.; Zhu, D. H.; Feng, K.; Liu, F. J.; Lou, W. Y.; Li, N.; Zong, M. H.; Wu, H. Fabrication of electrospun polylactic acid nanofilm incorporating cinnamon essential oil/β-cyclodextrin inclusion complex for antimicrobial packaging. *Food Chem.* **2016**, *196*, 996−1004.
(108) Aytac, Z.; Dogan, S. Y.; Tekinay, T.; Uyar, T. Release and antibacterial activity of allyl isothiocyanate/β-cyclodextrin complex encapsulated in electrospun nanofibers. *Colloids Surf., B* **2014**, *120*, 125−131.
(109) Celebioglu, A.; Uyar, T. Cyclodextrin nanofibers by electrospinning. *Chem. Commun.* **2010**, *46* (37), 6903−6905.
(110) Aytac, Z.; Yildiz, Z. I.; Kayaci-Senirmak, F.; San Keskin, N. O.; Kusku, S. I.; Durgun, E.; Tekinay, T.; Uyar, T. Fast-dissolving, prolonged release, and antibacterial cyclodextrin/limonene-inclusion complex nanofibrous webs via polymer-free electrospinning. *J. Agric. Food Chem.* **2016**, *64* (39), 7325−7334.
(111) Celebioglu, A.; Uyar, T. Antioxidant vitamin E/cyclodextrin inclusion complex electrospun nanofibers: enhanced water solubility, prolonged shelf life, and photostability of vitamin E. *J. Agric. Food Chem.* **2017**, *65* (26), 5404−5412.
(112) Aytac, Z.; Kusku, S. I.; Durgun, E.; Uyar, T. Encapsulation of gallic acid/cyclodextrin inclusion complex in electrospun polylactic acid nanofibers: Release behavior and antioxidant activity of gallic acid. *Mater. Sci. Eng., C* **2016**, *63*, 231−239.
(113) Pitkowski, A.; Durand, D.; Nicolai, T. Structure and dynamical mechanical properties of suspensions of sodium caseinate. *J. Colloid Interface Sci.* **2008**, *326* (1), 96−102.
(114) Qi, P.; Zhou, Y.; Wang, D.; He, Z.; Li, Z. A new collagen solution with high concentration and collagen native structure perfectly preserved. *RSC Adv.* **2015**, *5* (106), 87180−87186.
(115) Dror, Y.; Ziv, T.; Makarov, V.; Wolf, H.; Admon, A.; Zussman, E. Nanofibers made of globular proteins. *Biomacromolecules* **2008**, *9* (10), 2749−2754.
(116) He, J. X.; Guo, N. W.; Cui, S. Z. Structure and mechanical properties of electrospun tussah silk fibroin nanofibres: variations in processing parameters. *Iran. Polym. J.* **2011**, *20* (9), 713−724.
(117) Songchotikunpan, P.; Tattiyakul, J.; Supaphol, P. Extraction and electrospinning of gelatin from fish skin. *Int. J. Biol. Macromol.* **2008**, *42* (3), 247−255.
(118) Zhang, S.; Huang, Y. Q.; Yang, X. P.; Mei, F.; Ma, Q.; Chen, G. Q.; Ryu, S.; Deng, X. L. Gelatin nanofibrous membrane fabricated by electrospinning of aqueous gelatin solution for guided tissue regeneration. *J. Biomed. Mater. Res., Part A* **2009**, *90A* (3), 671−679.
(119) Suganya, S.; Venugopal, J.; Agnes Mary, S.; Ramakrishna, S.; Lakshmi, B. S.; Giri Dev, V. R. Aloe vera incorporated biomimetic nanofibrous scaffold: a regenerative approach for skin tissue engineering. *Iran. Polym. J.* **2014**, *23* (3), 237−248.
(120) Wongsasulak, S.; Patapeejumruswong, M.; Weiss, J.; Supaphol, P.; Yoovidhya, T. Electrospinning of food-grade nanofibers from cellulose acetate and egg albumen blends. *J. Food Eng.* **2010**, *98* (3), 370−376.
(121) Nieuwland, M.; Geerdink, P.; Brier, P.; van den Eijnden, P.; Henket, J. T. M. M.; Langelaan, M. L. P.; Stroeks, N.; van Deventer, H. C.; Martin, A. H. Food-grade electrospinning of proteins. *Innovative Food Sci. Emerging Technol.* **2013**, *20*, 269−275.
(122) Fernandez, A.; Torres-Giner, S.; Lagaron, J. M. Novel route to stabilization of bioactive antioxidants by encapsulation in electrospun fibers of zein prolamine. *Food Hydrocolloids* **2009**, *23* (5), 1427−1432.
(123) Neo, Y. P.; Ray, S.; Jin, J.; Gizdavic-Nikolaidis, M.; Nieuwoudt, M. K.; Liu, D.; Quek, S. Y. Encapsulation of food grade antioxidant in natural biopolymer by electrospinning technique: A physicochemical study based on zein−gallic acid system. *Food Chem.* **2013**, *136* (2), 1013−1021.
(124) Neo, Y. P.; Swift, S.; Ray, S.; Gizdavic-Nikolaidis, M.; Jin, J.; Perera, C. O. Evaluation of gallic acid loaded zein sub-micron electrospun fibre mats as novel active packaging materials. *Food Chem.* **2013**, *141* (3), 3192−3200.
(125) Neo, Y. P.; Perera, C. O.; Nieuwoudt, M. K.; Zujovic, Z.; Jin, J.; Ray, S.; Gizdavic-Nikolaidis, M. Influence of heat curing on structure and physicochemical properties of phenolic acid loaded proteinaceous electrospun fibers. *J. Agric. Food Chem.* **2014**, *62* (22), 5163−5172.
(126) Brahatheeswaran, D.; Mathew, A.; Aswathy, R. G.; Nagaoka, Y.; Venugopal, K.; Yoshida, Y.; Maekawa, T.; Sakthikumar, D. Hybrid fluorescent curcumin loaded zein electrospun nanofibrous scaffold for biomedical applications. *Biomed. Mater.* **2012**, *7* (4), 045001.
(127) Bui, H. T.; Chung, O. L.; Park, J. S. Fabrication of electrospun antibacterial curcumin-loaded zein nanofibers. *Polymer* **2014**, *38* (6), 744−751.
(128) Saithongdee, A.; Praphairaksit, N.; Imyim, A. Electrospun curcumin-loaded zein membrane for iron(III) ions sensing. *Sens. Actuators, B* **2014**, *202*, 935−940.
(129) Wang, H.; Hao, L.; Wang, P.; Chen, M.; Jiang, S.; Jiang, S. Release kinetics and antibacterial activity of curcumin loaded zein fibers. *Food Hydrocolloids* **2017**, *63*, 437−446.
(130) Moomand, K.; Lim, L. T. Oxidative stability of encapsulated fish oil in electrospun zein fibres. *Food Res. Int.* **2014**, *62*, 523−532.
(131) Moomand, K.; Lim, L. T. Properties of encapsulated fish oil in electrospun zein fibres under simulated in vitro conditions. *Food Bioprocess Technol.* **2015**, *8* (2), 431−444.
(132) Yang, H.; Wen, P.; Feng, K.; Zong, M. H.; Lou, W. Y.; Wu, H. Encapsulation of fish oil in a coaxial electrospun nanofibrous mat and its properties. *RSC Adv.* **2017**, *7* (24), 14939−14946.
(133) Pérez-Masiá, R.; López-Rubio, A.; Fabra, M. J.; Lagaron, J. M. Use of electrohydrodynamic processing to develop nanostructured materials for the preservation of the cold chain. *Innovative Food Sci. Emerging Technol.* **2014**, *26*, 415−423.
(134) Li, Y.; Lim, L. T.; Kakuda, Y. Electrospun zein fibers as carriers to stabilize (−)-epigallocatechin gallate. *J. Food Sci.* **2009**, *74* (3), C233−C240.
(135) Wang, H.; Hao, L.; Niu, B.; Jiang, S.; Cheng, J.; Jiang, S. Kinetics and antioxidant capacity of proanthocyanidins encapsulated in zein electrospun fibers by cyclic voltammetry. *J. Agric. Food Chem.* **2016**, *64* (15), 3083−3090.
(136) de Oliveira Mori, C. L. S.; dos Passos, N. A.; Oliveira, J. E.; Mattoso, L. H. C.; Mori, F. A.; Carvalho, A. G.; de Souza Fonseca, A.;

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

Tonoli, G. H. D. Electrospinning of zein/tannin bio-nanofibers. *Ind. Crops Prod.* **2014**, *52*, 298−304.
(137) Zhang, M.; Li, X.; Li, S.; Liu, Y.; Hao, L. Electrospun poly(l-lactide)/zein nanofiber mats loaded with Rana chensinensis skin peptides for wound dressing. *J. Mater. Sci.: Mater. Med.* **2016**, *27* (9), 136.
(138) Yao, Z. C.; Chang, M. W.; Ahmad, Z.; Li, J. S. Encapsulation of rose hip seed oil into fibrous zein films for ambient and on demand food preservation via coaxial electrospinning. *J. Food Eng.* **2016**, *191*, 115−123.
(139) Wang, S.; Marcone, M. F.; Barbut, S.; Lim, L. T. Electrospun soy protein isolate-based fiber fortified with anthocyanin-rich red raspberry (Rubus strigosus) extracts. *Food Res. Int.* **2013**, *52* (2), 467−472.
(140) Pérez-Masiá, R.; Lagaron, J. M.; Lopez-Rubio, A. Morphology and stability of edible lycopene-containing micro- and nanocapsules produced through electrospraying and spray drying. *Food Bioprocess Technol.* **2015**, *8* (2), 459−470.
(141) Sajkiewicz, P.; Kolbuk, D. Electrospinning of gelatin for tissue engineering - molecular conformation as one of the overlooked problems. *J. Biomater. Sci., Polym. Ed.* **2014**, *25* (18), 2009−2022.
(142) Sikareepaisan, P.; Suksamrarn, A.; Supaphol, P. Electrospun gelatin fiber mats containing a herbal— centella asiatica —extract and release characteristic of asiaticoside. *Nanotechnology* **2008**, *19* (1), 015102.
(143) Li, H.; Wang, M.; Williams, G. R.; Wu, J.; Sun, X.; Lv, Y.; Zhu, L. M. Electrospun gelatin nanofibers loaded with vitamins A and E as antibacterial wound dressing materials. *RSC Adv.* **2016**, *6* (55), 50267−50277.
(144) Padrão, J.; Machado, R.; Casal, M.; Lanceros-Méndez, S.; Rodrigues, L. R.; Dourado, F.; Sencadas, V. Antibacterial performance of bovine lactoferrin-fish gelatine electrospun membranes. *Int. J. Biol. Macromol.* **2015**, *81*, 608−614.
(145) Hani, N. M.; Torkamani, A. E.; Azarian, M. H.; Mahmood, K. W. A.; Ngalim, S. H. Characterisation of electrospun gelatine nanofibres encapsulated with Moringa oleifera bioactive extract. *J. Sci. Food Agric.* **2017**, *97*, 3348−3358.
(146) Laha, A.; Yadav, S.; Majumdar, S.; Sharma, C. S. In-vitro release study of hydrophobic drug using electrospun cross-linked gelatin nanofibers. *Biochem. Eng. J.* **2016**, *105* (Part B), 481−488.
(147) Deng, L.; Kang, X.; Liu, Y.; Feng, F.; Zhang, H. Effects of surfactants on the formation of gelatin nanofibres for controlled release of curcumin. *Food Chem.* **2017**, *231*, 70−77.
(148) Aceituno-Medina, M.; Lopez-Rubio, A.; Mendoza, S.; Lagaron, J. M. Development of novel ultrathin structures based in amaranth (Amaranthus hypochondriacus) protein isolate through electrospinning. *Food Hydrocolloids* **2013**, *31* (2), 289−298.
(149) Stephansen, K.; Chronakis, I. S.; Jessen, F. Bioactive electrospun fish sarcoplasmic proteins as a drug delivery system. *Colloids Surf., B* **2014**, *122*, 158−165.
(150) Stephansen, K.; García-Díaz, M.; Jessen, F.; Chronakis, I. S.; Nielsen, H. M. Bioactive protein-based nanofibers interact with intestinal biological components resulting in transepithelial permeation of a therapeutic protein. *Int. J. Pharm.* **2015**, *495* (1), 58−66.
(151) Stephansen, K.; García-Díaz, M.; Jessen, F.; Chronakis, I. S.; Nielsen, H. M. Interactions between surfactants in solution and electrospun protein fibers: effects on release behavior and fiber properties. *Mol. Pharmaceutics* **2016**, *13* (3), 748−755.
(152) Xiao, J.; Shi, C.; Zheng, H.; Shi, Z.; Jiang, D.; Li, Y.; Huang, Q. Kafirin protein based electrospun fibers with tunable mechanical property, wettability, and release profile. *J. Agric. Food Chem.* **2016**, *64* (16), 3226−3233.
(153) Xie, J.; Hsieh, Y. L. Ultra-high surface fibrous membranes from electrospinning of natural proteins: casein and lipase enzyme. *J. Mater. Sci.* **2003**, *38* (10), 2125−2133.
(154) Elakkiya, T.; Malarvizhi, G.; Rajiv, S.; Natarajan, T. S. Curcumin loaded electrospun bombyx mori silk nanofibers for drug delivery. *Polym. Int.* **2014**, *63* (1), 100−105.
(155) Yu, D. G.; Li, X. Y.; Wang, X.; Yang, J. H.; Bligh, S. W. A.; Williams, G. R. Nanofibers fabricated using triaxial electrospinning as zero order drug delivery systems. *ACS Appl. Mater. Interfaces* **2015**, *7* (33), 18891−18897.
(156) Han, D.; Steckl, A. J. Triaxial electrospun nanofiber membranes for controlled dual release of functional molecules. *ACS Appl. Mater. Interfaces* **2013**, *5* (16), 8241−8245.
(157) Kiatyongchai, T.; Wongsasulak, S.; Yoovidhya, T. Coaxial electrospinning and release characteristics of cellulose acetate−gelatin blend encapsulating a model drug. *J. Appl. Polym. Sci.* **2014**, *131* (8), 40167−40176.
(158) Ahmed, F.; Saleemi, S.; Khatri, Z.; Abro, M. I.; Kim, I. S. Co-electrospun poly(ε-caprolactone)/cellulose nanofibers-fabrication and characterization. *Carbohydr. Polym.* **2015**, *115*, 388−393.
(159) Castillo-Ortega, M. M.; Montaño-Figueroa, A. G.; Rodríguez-Félix, D. E.; Prado-Villegas, G.; Pino-Ocaño, K. P.; Valencia-Córdova, M. J.; Quiroz-Castillo, J. M.; Herrera-Franco, P. J. Preparation by coaxial electrospinning and characterization of membranes releasing (−) epicatechin as scaffold for tissue engineering. *Mater. Sci. Eng., C* **2015**, *46*, 184−189.
(160) Ali, S.; Khatri, Z.; Oh, K. W.; Kim, I. S.; Kim, S. H. Zein/cellulose acetate hybrid nanofibers: Electrospinning and characterization. *Macromol. Res.* **2014**, *22* (9), 971−977.
(161) Zhou, W.; He, J.; Cui, S.; Gao, W. Preparation of electrospun silk fibroin/Cellulose Acetate blend nanofibers and their applications to heavy metal ions adsorption. *Fibers Polym.* **2011**, *12* (4), 431−437.
(162) Cui, S.; Yao, B.; Sun, X.; Hu, J.; Zhou, Y.; Liu, Y. Reducing the content of carrier polymer in pectin nanofibers by electrospinning at low loading followed with selective washing. *Mater. Sci. Eng., C* **2016**, *59*, 885−893.
(163) Lin, H. Y.; Chen, H. H.; Chang, S. H.; Ni, T. S. Pectin-chitosan-PVA nanofibrous scaffold made by electrospinning and its potential use as a skin tissue scaffold. *J. Biomater. Sci., Polym. Ed.* **2013**, *24* (4), 470−484.
(164) Alborzi, S.; Lim, L. T.; Kakuda, Y. Release of folic acid from sodium alginate-pectin-poly(ethylene oxide) electrospun fibers under in vitro conditions. *LWT—Food Sci. Technol.* **2014**, *59* (1), 383−388.
(165) Tang, S.; Zhao, Z.; Chen, G.; Su, Y.; Lu, L.; Li, B.; Liang, D.; Jin, R. Fabrication of ampicillin/starch/polymer composite nanofibers with controlled drug release properties by electrospinning. *J. Sol-Gel Sci. Technol.* **2016**, *77* (3), 594−603.
(166) Taghavian, H.; Ranaei-Siadat, S. O.; Kalaee, M. R.; Mazinani, S.; Ranaei-Siadat, S. E.; Harati, J. Optimizing the activity of immobilized phytase on starch blended polyacrylamide nanofibers-nanomembranes by response surface methodology. *Fibers Polym.* **2015**, *16* (5), 1048−1056.
(167) Hadisi, Z.; Nourmohammadi, J.; Mohammadi, J. Composite of porous starch-silk fibroin nanofiber-calcium phosphate for bone regeneration. *Ceram. Int.* **2015**, *41* (9, Part A), 10745−10754.
(168) Oktay, B.; Baştürk, E.; Kayaman-Apohan, N.; Kahraman, M. V. Highly porous starch/poly(ethylene-alt-maleic anhydride) composite nanofiber mesh. *Polym. Compos.* **2013**, *34* (8), 1321−1324.
(169) Kim, Y. K.; Cha, S. I.; Hong, S. H.; Jeong, Y. J. A new hybrid architecture consisting of highly mesoporous CNT/carbon nanofibers from starch. *J. Mater. Chem.* **2012**, *22* (38), 20554−20560.
(170) Lubambo, A. F.; Ono, L.; Drago, V.; Mattoso, N.; Varalda, J.; Sierakowski, M. R.; Sakakibara, C. N.; Freitas, R. A.; Saul, C. K. Tuning Fe_3O_4 nanoparticle dispersion through pH in PVA/guar gum/electrospun membranes. *Carbohydr. Polym.* **2015**, *134*, 775−783.
(171) Koosha, M.; Mirzadeh, H. Electrospinning, mechanical properties, and cell behavior study of chitosan/PVA nanofibers. *J. Biomed. Mater. Res., Part A* **2015**, *103* (9), 3081−3093.
(172) Cheng, F.; Gao, J.; Wang, L.; Hu, X. Composite chitosan/poly(ethylene oxide) electrospun nanofibrous mats as novel wound dressing matrixes for the controlled release of drugs. *J. Appl. Polym. Sci.* **2015**, *132* (24), 42060−42067.
(173) Gökmeşe, F.; Uslu, İ.; Aytimur, A. Preparation and characterization of PVA/PVP nanofibers as promising materials for wound dressing. *Polym.-Plast. Technol. Eng.* **2013**, *52* (12), 1259−1265.

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

(174) Jiang, S.; Lv, J.; Ding, M.; Li, Y.; Wang, H.; Jiang, S. Release behavior of tetracycline hydrochloride loaded chitosan/poly(lactic acid) antimicrobial nanofibrous membranes. *Mater. Sci. Eng., C* **2016**, *59*, 86−91.
(175) Zarghami, A.; Irani, M.; Mostafazadeh, A.; Golpour, M.; Heidarinasab, A.; Haririan, I. Fabrication of PEO/chitosan/PCL/olive oil nanofibrous scaffolds for wound dressing applications. *Fibers Polym.* **2015**, *16* (6), 1201−1212.
(176) Zhou, Y.; Yang, H.; Liu, X.; Mao, J.; Gu, S.; Xu, W. Electrospinning of carboxyethyl chitosan/poly(vinyl alcohol)/silk fibroin nanoparticles for wound dressings. *Int. J. Biol. Macromol.* **2013**, *53*, 88−92.
(177) Hu, W. W.; Yu, H. N. Coelectrospinning of chitosan/alginate fibers by dual-jet system for modulating material surfaces. *Carbohydr. Polym.* **2013**, *95* (2), 716−727.
(178) Fathollahipour, S.; Abouei Mehrizi, A.; Ghaee, A.; Koosha, M. Electrospinning of PVA/chitosan nanocomposite nanofibers containing gelatin nanoparticles as a dual drug delivery system. *J. Biomed. Mater. Res., Part A* **2015**, *103* (12), 3852−3862.
(179) Pezeshki-Modaress, M.; Zandi, M.; Mirzadeh, H. Fabrication of gelatin/chitosan nanofibrous scaffold: process optimization and empirical modeling. *Polym. Int.* **2015**, *64* (4), 571−580.
(180) Torres-Giner, S.; Ocio, M. J.; Lagaron, J. M. Novel antimicrobial ultrathin structures of zein/chitosan blends obtained by electrospinning. *Carbohydr. Polym.* **2009**, *77* (2), 261−266.
(181) Luong-Van, E.; Grøndahl, L.; Chua, K. N.; Leong, K. W.; Nurcombe, V.; Cool, S. M. Controlled release of heparin from poly(ε-caprolactone) electrospun fibers. *Biomaterials* **2006**, *27* (9), 2042−2050.
(182) Spadaccio, C.; Rainer, A.; Centola, M.; Trombetta, M.; Chello, M.; Lusini, M.; Covino, E.; Toyoda, Y.; Genovese, J. A. Heparin-releasing scaffold for stem cells: a differentiating device for vascular aims. *Regener. Med.* **2010**, *5* (4), 645−657.
(183) Chen, G.; Guo, J.; Nie, J.; Ma, G. Preparation, characterization, and application of PEO/HA core shell nanofibers based on electric field induced phase separation during electrospinning. *Polymer* **2016**, *83*, 12−19.
(184) Wang, Z. B.; Qian, Y. N.; Li, L. H.; Pan, L. H.; Njunge, L. W.; Dong, L. L.; Yang, L. Evaluation of emulsion electrospun polycaprolactone/hyaluronan/epidermal growth factor nanofibrous scaffolds for wound healing. *J. Biomater. Appl.* **2016**, *30* (6), 686−698.
(185) Li, Z.; Kang, H.; Li, Q.; Che, N.; Liu, Z.; Li, P.; Zhang, C.; Liu, R.; Huang, Y. Ultrathin core−sheath fibers for liposome stabilization. *Colloids Surf., B* **2014**, *122*, 630−637.
(186) Lai, H. J.; Kuan, C. H.; Wu, H. C.; Tsai, J. C.; Chen, T. M.; Hsieh, D. J.; Wang, T. W. Tailored design of electrospun composite nanofibers with staged release of multiple angiogenic growth factors for chronic wound healing. *Acta Biomater.* **2014**, *10* (10), 4156−4166.
(187) Doğan, G.; Başal, G.; Bayraktar, O.; Özyildiz, F.; Uzel, A.; Erdoğan, İ. Bioactive Sheath/Core nanofibers containing olive leaf extract. *Microsc. Res. Tech.* **2016**, *79* (1), 38−49.
(188) Guo, J.; Zhou, H.; Akram, M. Y.; Mu, X.; Nie, J.; Ma, G. Characterization and application of chondroitin sulfate/polyvinyl alcohol nanofibres prepared by electrospinning. *Carbohydr. Polym.* **2016**, *143*, 239−245.
(189) Zhong, S. P.; Teo, W. E.; Zhu, X.; Beuerman, R.; Ramakrishna, S.; Yung, L. Y. L. Formation of collagen-glycosaminoglycan blended nanofibrous scaffolds and their biological properties. *Biomacromolecules* **2005**, *6* (6), 2998−3004.
(190) Liao, N.; Unnithan, A. R.; Joshi, M. K.; Tiwari, A. P.; Hong, S. T.; Park, C. H.; Kim, C. S. Electrospun bioactive poly (ε-caprolactone)−cellulose acetate−dextran antibacterial composite mats for wound dressing applications. *Colloids Surf., A* **2015**, *469*, 194−201.
(191) Islam, M. S.; Rabbani, M. M.; Yang, S. B.; Choi, W. S.; Choi, J. H.; Oh, W.; Shin, J. C.; Lee, J. T.; Yeum, J. H. Poly(vinyl alcohol)/pullulan blend nanofibres prepared from aqueous solutions using electrospinning method. *Polym. Polym. Compos.* **2014**, *22* (9), 779−786.
(192) Atila, D.; Keskin, D.; Tezcaner, A. Cellulose acetate based 3-dimensional electrospun scaffolds for skin tissue engineering applications. *Carbohydr. Polym.* **2015**, *133*, 251−261.
(193) Fu, R. Q.; Li, C. W.; Yu, C. P.; Xie, H.; Shi, S. J.; Li, Z. H.; Wang, Q.; Lu, L. C. A novel electrospun membrane based on moxifloxacin hydrochloride/poly(vinyl alcohol)/sodium alginate for antibacterial wound dressings in practical application. *Drug Delivery* **2016**, *23* (3), 828−839.
(194) Chang, J. J.; Lee, Y. H.; Wu, M. H.; Yang, M. C.; Chien, C. T. Electrospun anti-adhesion barrier made of chitosan alginate for reducing peritoneal adhesions. *Carbohydr. Polym.* **2012**, *88* (4), 1304−1312.
(195) Zhang, M.; Liu, Y. J.; Yi, H. L.; Luan, J. S.; Zhang, Y.; Cai, H. L.; Sun, D. H. Electrospun zein/PVA fibrous mats as three-dimensional surface for embryonic stem cell culture. *J. Text. Inst.* **2014**, *105* (3), 246−255.
(196) Alhusein, N.; Blagbrough, I. S.; Beeton, M. L.; Bolhuis, A.; De Bank, P. A. Electrospun zein/PCL fibrous matrices release tetracycline in a controlled manner, killing *staphylococcus aureus* both in biofilms and ex vivo on pig skin, and are compatible with human skin cells. *Pharm. Res.* **2016**, *33* (1), 237−246.
(197) Unnithan, A. R.; Gnanasekaran, G.; Sathishkumar, Y.; Lee, Y. S.; Kim, C. S. Electrospun antibacterial polyurethane-cellulose acetate-zein composite mats for wound dressing. *Carbohydr. Polym.* **2014**, *102*, 884−892.
(198) Ali, S.; Khatri, Z.; Oh, K. W.; Kim, I. S.; Kim, S. H. Zein/cellulose acetate hybrid nanofibers: Electrospinning and characterization. *Macromol. Res.* **2014**, *22* (9), 971−977.
(199) Fabra, M. J.; Lopez-Rubio, A.; Lagaron, J. M. Use of the electrohydrodynamic process to develop active/bioactive bilayer films for food packaging applications. *Food Hydrocolloids* **2016**, *55*, 11−18.
(200) Fabra, M. J.; Lopez-Rubio, A.; Lagaron, J. M. On the use of different hydrocolloids as electrospun adhesive interlayers to enhance the barrier properties of polyhydroxyalkanoates of interest in fully renewable food packaging concepts. *Food Hydrocolloids* **2014**, *39*, 77−84.
(201) Wan, Z. L.; Wang, L. Y.; Yang, X. Q.; Guo, J.; Yin, S. W. Enhanced water resistance properties of bacterial cellulose multilayer films by incorporating interlayers of electrospun zein fibers. *Food Hydrocolloids* **2016**, *61*, 269−276.
(202) Fang, Q.; Zhu, M.; Yu, S. R.; Sui, G.; Yang, X. P. Studies on soy protein isolate/polyvinyl alcohol hybrid nanofiber membranes as multi-functional eco-friendly filtration materials. *Mater. Sci. Eng., B* **2016**, *214*, 1−10.
(203) Cho, D.; Netravali, A. N.; Joo, Y. L. Mechanical properties and biodegradability of electrospun soy protein Isolate/PVA hybrid nanofibers. *Polym. Degrad. Stab.* **2012**, *97* (5), 747−754.
(204) Ramji, K.; Shah, R. N. Electrospun soy protein nanofiber scaffolds for tissue regeneration. *J. Biomater. Appl.* **2014**, *29* (3), 411−422.
(205) Xu, X. Z.; Jiang, L.; Zhou, Z. P.; Wu, X. F.; Wang, Y. C. Preparation and properties of electrospun soy protein isolate/polyethylene oxide nanofiber membranes. *ACS Appl. Mater. Interfaces* **2012**, *4* (8), 4331−4337.
(206) Garcia-Moreno, P. J.; Stephansen, K.; van der Kruijs, J.; Guadix, A.; Guadix, E. M.; Chronakis, I. S.; Jacobsen, C. Encapsulation of fish oil in nanofibers by emulsion electrospinning: physical characterization and oxidative stability. *J. Food Eng.* **2016**, *183*, 39−49.
(207) Ahmed, S. M.; Ahmed, H.; Tian, C.; Tu, Q.; Guo, Y. D.; Wang, J. Y. Whey protein concentrate doped electrospun poly(epsilon-caprolactone) fibers for antibiotic release improvement. *Colloids Surf., B* **2016**, *143*, 371−381.
(208) Zahedi, P.; Fallah-Darrehchi, M. Electrospun egg albumin-PVA nanofibers containing tetracycline hydrochloride: morphological, drug release, antibacterial, thermal and mechanical properties. *Fibers Polym.* **2015**, *16* (10), 2184−2192.
(209) Cao, Z.; Wang, D.; Lyu, L.; Gong, Y.; Li, Y. Fabrication and characterization of PCL/$CaCO_3$ electrospun composite membrane for bone repair. *RSC Adv.* **2016**, *6* (13), 10641−10649.

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179

(210) Zhang, X. L.; Tang, K. Y.; Zheng, X. J. Electrospinning and crosslinking of COL/PVA nanofiber-microsphere containing salicylic acid for drug delivery. *J. Bionic Eng.* **2016**, *13* (1), 143−149.
(211) Yang, C.; Wu, X. M.; Zhao, Y. H.; Xu, L.; Wei, S. C. Nanofibrous Scaffold Prepared by Electrospinning of Poly(vinyl alcohol)/Gelatin Aqueous Solutions. *J. Appl. Polym. Sci.* **2011**, *121* (5), 3047−3055.
(212) Zhang, Q.; Lv, S.; Lu, J.; Jiang, S.; Lin, L. Characterization of polycaprolactone/collagen fibrous scaffolds by electrospinning and their bioactivity. *Int. J. Biol. Macromol.* **2015**, *76*, 94−101.
(213) Hsu, F. Y.; Hung, Y. S.; Liou, H. M.; Shen, C. H. Electrospun hyaluronate-collagen nanofibrous matrix and the effects of varying the concentration of hyaluronate on the characteristics of foreskin fibroblast cells. *Acta Biomater.* **2010**, *6* (6), 2140−2147.
(214) Lee, J. M.; Chae, T.; Sheikh, F. A.; Ju, H. W.; Moon, B. M.; Park, H. J.; Park, Y. R.; Park, C. H. Three dimensional poly(epsilon-caprolactone) and silk fibroin nanocomposite fibrous matrix for artificial dermis. *Mater. Sci. Eng., C* **2016**, *68*, 758−767.
(215) Singh, B. N.; Panda, N. N.; Mund, R.; Pramanik, K. Carboxymethyl cellulose enables silk fibroin nanofibrous scaffold with enhanced biomimetic potential for bone tissue engineering application. *Carbohydr. Polym.* **2016**, *151*, 335−347.
(216) Zhou, J. A.; Cao, C. B.; Ma, X. L.; Lin, J. Electrospinning of silk fibroin and collagen for vascular tissue engineering. *Int. J. Biol. Macromol.* **2010**, *47* (4), 514−519.

DOI: 10.1021/acs.jafc.7b02956
J. Agric. Food Chem. 2017, 65, 9161−9179