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REVIEW

Electrospun nanofibers food packaging: trends and applications in food systems

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ABSTRACT

Food safety is a bottleneck problem. In order to provide information about advanced and unique food packaging technique, this study summarized the advancements of electrospinning technique. Food packaging is a multidisciplinary area involving food science, food engineering, food chemistry, and food microbiology, and the interest in maintaining the freshness and quality of foods has grown considerably. For this purpose, electrospinning technology has gained much attention due to its unique functions and superior processing. Sudden advancements of electrospinning have been rapidly incorporated into research. This review summarized some latest information about food packaging and different materials used for the packaging of various foods such as fruits, vegetables, meat, and processed items. Also, the use of electrospinning and materials used for the formation of nanofibers are discussed in detail. However, in food industry, the application of electrospun nanofibers is still in its infancy. In this study, different parameters, structures of nanofibers, features and fundamental properties are described briefly, while polymers fabricated through electrospinning with advances in food packaging films are described in detail. Moreover, this comprehensive review focuses on the polymers used for the electrospinning of nanofibers as packaging films and their applications for variety of foods. This will be a valuable source of information for researchers studying various polymers for electrospinning for application in the food packaging industry.

KEYWORDS
Electrospinning; food packaging; antibacterial packaging; food preservation

Introduction

Achieving food safety and "food for all" is currently a bottleneck problem. To ensure food safety, a crucial element is the advancement and development of food packaging technology. Due to the ever-growing population increasing international trade, we must focus on achieving sufficient food production, food safety and security immediately after post-harvesting are also necessary to provide everyone with fresh, healthy, and uncontaminated food (Liu, Wu, et al. 2020). Most of the food contamination and physical harm occurs during transportation. Thus, food packaging plays an integral role in extending the shelf-life of a product without compromising its quality. In addition to protecting and providing safe and nutritious food, minimizing food losses and prevention of microbes are the characteristics of a good packaging material (Ahmed et al. 2020; Bahrami et al. 2020).

Electrospinning is one of the most versatile and robust techniques used for the fabrication of polymers. It operates using the electrical potential (Zhao et al. 2020). This process basically comprises a high-voltage supply connected to the spinneret of a syringe and a collector. A plastic syringe that is filled with a polymer solution to be fabricated into a fiber is used, and a syringe pump that can maintain the flow rate of the fibers is also used. The conducting solution is released, making a Taylor cone, and extra fine fibers threads are achieved under the action of various forces, e.g., electrostatic, drag, and gravitational forces. Finally, the fibers are collected by collection devices with different shapes (Zhang et al. 2020). This process originated in the beginning of the 19th century to produce nanofibers for textile and filtration applications (Aman Mohammadi, Hosseini, and Yousefi 2020). Since then, tremendous advancements to this technique have been made to achieve fine nanofibers and obtain benefits of their unique characteristics. These developments have not only helped advance food packaging techniques but also led to the universal acceptance of electrospinning technology for many other applications, such as those in the pharmaceutical and biomedical fields. It is a simple, cost effective, and practicable technique for large-scale fabrication. (Coelho, Estevinho, and Rocha 2021; Leidy and Maria Ximena 2019).

In addition, nanofibers have been developed using many food waste materials and food-grade raw materials. Furthermore, these waste materials are rich in bioactive compounds, such as the peels and seeds of fruits and vegetables. These peels are highly effective against bacteria, as they protect the food from the outside harsh environment. In recent research, authors use food grade material such as

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zein for electrospinning to make packaging films (Altan and Çayır 2020; Aytac et al. 2020). In another research, yerba mate tea extract was used as a bioactive compound in electrospinning for food packaging (Pinheiro Bruni et al. 2020). One more research published that described the use of waste material from a juice factory for the formation of biocompatible nanofiber films through electrospinning. Researchers utilized specialized poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV), which was derived from waste (through fermentation), indirectly from the mitochondria of both types of bacteria (Gram-positive and Gram-negative), and formed bio-papers for the preservation of food with enhanced antimicrobial characteristics (Figueroa-Lopez et al. 2020). Furthermore, there are many components in food items that can be isolated for the formation of biodegradable, edible, and compatible nanofibers as a packaging material. Sharif et al. made a food packaging nanofibrous film using the very specialized protein "gliadin," which is the main component of gluten and is found in wheat and various other cereals (Sharif et al. 2019). These advantages of electrospun nanofibers have allowed them to be widely used in the field of food packaging (Topuz and Uyar 2020; Zhang et al. 2020). Main objectives of current research are: a) To gather information and use of polymers in electrospinning for food packaging; b) To illustrate the importance of electrospinning in food preservation; c) To evaluate and present various recent researches based on electrospinning so that authors will get information from one platform; d) To summarize the findings of electrospinning till date so that new research and advancements are planned and performed in future.

Materials used in electrospinning of food packaging films

Inorganic materials

Silicon and oxides

Silicon and its oxides show outstanding barrier properties along with some other characteristics, such as forming transparent films, exhibiting excellent printing adaptability, being microwavable, and possessing other high-value properties. They show zero permeability of gases according to theoretical data and also provide a barrier for flavor and moisture, that is, they allow zero diffusion (Li, Chen, et al. 2020; Zhu et al. 2017).

Metal oxides

There are various metal oxides used in electrospinning for the formation of food packaging (Yu et al. 2020). A few oxides that are used frequently are briefly described here. Silver nanoparticles are one of the most frequently used metals, especially for packaging purposes. They possess antimicrobial properties against a wide range of microorganisms, and some studies have suggested that they also act against viruses. Silver is widely used at the micro- and macro-scales (Wenting Lan et al. 2020). It has been used in refrigerators, microwaves, and other kitchen appliances for many years because of its excellent microbial repelling properties (Majumder et al. 2020). Some studies provide evidence that silver nanoparticles induce genotoxicity and cytotoxicity in mammalian cells (especially those from the liver, lungs, skin, vascular system, and brain). Some studies have revealed that they induce oxidative stress and produce reactive oxygen species or free radicals in the body. Studies have also revealed that once they enter the circulation system of the body, whether through inhalation or ingestion, they cause hemolysis by potentially interacting with plasma cells, red blood cells, platelets, and coagulation factors, and they produce thromboembolic problems in cell membranes along with proliferation. These limitations should be considered when using this metal in food packaging, as the packaging directly or indirectly interacts with the food and ultimately affects the food chemistry with such elements present (Morais et al. 2019; Störmer et al. 2017).

ZnO is generally considered to be a nontoxic material. It not only exhibits good antibiotic activity but also provides photocatalytic activity and high stability. ZnO NPs are frequently used in the formation of different films, as they also possess all of the above characteristics and are easily encapsulated with other polymers for electrospinning. The US Food and Drug Administration (FDA) confirmed that the nanoparticles of ZnO are very effective against spoilage bacteria and other foodborne pathogens. Thus, they are effectively used in packaging. Khan et al. prepared polyvinyl alcohol (PVA) and ZnO NP nanofibers, and they were very effective against Gram-positive and Gram-negative bacteria (Khan et al. 2019; Li, Chen, et al. 2020).

Titanium dioxide (TiO_2) has also been widely used in the packaging industry, and it has been investigated in different studies due to its unique antibacterial characteristics. It undergoes photocatalysis under light, which is a quite unique behavior, generating enough energy to produce reactive oxygen species (ROS). These species have great potential to damage the cell membranes of the bacteria. Toniatto and coworkers developed nanofibers of polylactic acid (PLA)/TiO_2. They possessed good photocatalytic, thermal, and mechanical properties and demonstrated that they do not cause any cell damage or toxicity to mammalian cells. Most importantly, they exhibited bactericidal activity when the amount of TiO_2 increased (Ghadimi, Esfahani, and Mazaheri 2021; Toniatto et al. 2017). A variety of nanoparticles examined in previous studies are summarized in Table 1.

Carbon nanotubes (CNTs)

One of the chief characteristics of CNTs is their extreme elasticity and tensile strength. In addition, they are highly degradable, and scientists have used multi-walled carbon nanotubes (MWCANTs) to attain high-performance films due to their degradable behaviors. Kuan et al. performed an experiment in which he employed melt blending of MWCNTs and PLA composites. Due to their high strength moduli, they enhanced the elasticity of the polymer PLA. They used low- and high-crystallinity PLA in their study, and by adding 0.5 wt% MWCNTs, the tensile strength of the low-crystallinity PLA increased significantly from 59.9 to

Table 1. Nanocomposites and their advancements in food packaging technology with supporting active features.

Nanoparticles	Polymers	Active property in packaging film	References
Phycocyanin/PVA nanoparticles	Polycaprolactone, Poly (L-lactic acid)	Antioxidant	(Schmatz, Costa, and de Morais 2019)
Silica having N-halamine	Polyhydroxybutyrate/ Polycaprolactone	Antibacterial	(Lin, Gu, et al. 2018)
Hollow nanotubes (HNTs) loaded with lysozyme (50 wt% of lysozyme)	Polyamide *11*	Antimicrobial	(Bugatti et al. 2018)
ZnO and SiO2/ZnO NPs	Poly (L-lactic acid)	Antibacterial	(Rokbani, Daigle, and Ajji 2018)
Montmorillonite	Nylon-6	Antifungal	(Agarwal et al. 2014)
Chitosan/CEO NPs	Poly (L-lactic acid)	Antibacterial	(Liu, Wang, Zhang, et al. 2017)
Mesoporous silica nanoparticles (MSN) with loaded eugenol	Poly (3-hydroxybutyrate-co-3-hydroxyvalerate (PHBV)	Antimicrobial	(Melendez-Rodriguez et al. 2019)
Palladium nanoparticles (Pd-NPs), cetyltrimethylammonium bromide (CTAB)	Polyhydroxybutyrate	Oxygen scavenger	(Cherpinski et al. 2019)
Chitosan NPs	Gelatin	Antibacterial	(Lin, Gu, et al. 2019)
Graphene nanoplatelets (GNPs)	Poly (ethylene-co-vinyl alcohol)	Conductive	(Torres-Giner et al. 2018)
Pd-NPs	Polycaprolactone, Polyhydroxybutyrate	Oxygen scavenging	(Cherpinski et al. 2019)
Clove oil-loaded chitosan nanoparticles (CO@CNPs)	Gelatin	Antibacterial	(Cui et al. 2018)

68.5 MPa, and that of the high-crystallinity PLA increased from 60 to 63.5 MPa (Kuan et al. 2008). Liu et al. added CS to PLA/MWCNT fibers as food packaging films to investigate the morphologies and mechanical properties, and they applied the films as packaging for strawberries (Yaowen Liu et al. 2019; Zou et al. 2020).

Graphene oxides

Graphene oxides (GOs) have many oxygen-containing functional groups, such as carbonyl, carboxyl, hydroxyl, and epoxy groups. These functional groups interact strongly with polar solvents and polymer matrices, facilitating the spread of graphene oxides into polymer matrices. GOs are widely used in the packaging industry because of their specialized antibacterial properties (Dong et al. 2021). The act as effective barriers against both Gram-positive and Gram-negative bacteria. In addition, it was confirmed that the GOs are excellent for enhancing the mechanical properties of composite fibers. Lin et al. prepared PVA/GO nanocomposites and compared them with pure PVA. The incorporation of GO suddenly increased the Young's modulus by 40.8% and the yield stress by 83.6% (Ji, Tiwari, and Kim 2020; Lin, Gu, and Cui 2018).

Organic material

Synthetic polymers

Polylactic acid (PLA). PLA is one of the most important synthetic biodegradable polymers, which is generally recognized as being safe according to the Food and Drug Administration (FDA). Furthermore, it is one of the most widely used polymers in electrospinning technology. This polymer is widely used because it is biocompatible, bioavailable, and biodegradable (Zhang et al. 2021). For food packaging technology, it is usually used in combination with some food additives to increase the surface area and biological properties. Most of the fibers made through the electrospinning of PLA are porous fibers. They are mostly formed when volatile solvents are used in the processing (Dong et al. 2021). The porous nanofibers have many advantages as they trap the bioactive compounds, resulting in the slow release of these compounds. Furthermore, they help in the preservation of food by providing good mechanical properties to the film (Huang and Thomas 2018; Valente et al. 2016)

Polyvinyl alcohol. Polyvinyl alcohol (PVA) has been gaining popularity since the invention of electrospinning. It is attractive owing to its unique characteristics, which are its biocompatibility, nontoxicity, water solubility, and biodegradability (Safari et al. 2020). It is generally recognized as safe (GRAS) according to FDA, it has a hydrophilic nature, and it contains a high density of reactive functional groups. Furthermore, PLA is considered to be eco-friendly and has excellent film-forming abilities. It is an atactic semi-crystalline polymer with adhesive and emulsifying properties. Furthermore, it possesses a high elasticity, tensile strength, and flexibility along with high smell and oxygen barrier properties. PLA fibers formed by electrospinning are smooth and fine threads that can be used in high-quality food packaging (Estevez-Areco et al. 2020; Jiang et al. 2020; Weijie Lan et al. 2019).

Poly (ethylene terephthalate). Poly (ethylene terephthalate) (PET) is a lab-made polymer with specialized amorphous and crystalline properties that solely depend on the thermal history and processing (Ling Lin, Yao, & Li, Chen, et al. 2020). It is extensively used in the packaging industry because it is known for its excellent ductility, strength, hardness, nontoxic nature, and negligible permeability for carbon dioxide. Furthermore, it does not influence the flavors of foods. It possesses many other advantageous properties, such as a good processability and recyclability, and it can successfully participate in depolymerization reactions to obtain the initial monomers (Devlaminck et al. 2018; Mu, Zheng, and Xin 2021).

Natural polymer

Cellulose and cellulose derivatives. Cellulose is one of the most abundant natural polymers, and it is mostly obtained from plant sources, such as trees and cotton (Niu et al. 2020). Furthermore, some microorganisms produce cellulose, such as fungi and bacteria. Because cellulose possesses good properties that are useful for food packaging technology, these characteristics may be due to the strong intra- and inter-molecular hydrogen bonding, which makes it insoluble in most of the solvents. It has a high melting point of about 400 °C, and thus, it is found to be a thermally stable polymer that retains its mechanical properties. If it remains in the solid state up to 200 °C, its thermal decomposition starts above this temperature. Some recent studies have shown that ionic solvents are most commonly used for cellulose electrospinning, as they promote the dissolution of cellulose, which is of great importance for technological and industrial applications (Al-Moghazy, Mahmoud, and Nada 2020; Hashmi et al. 2021; Rezaei, Nasirpour, and Fathi 2015).

Chitosan. Chitosan is one of the most important natural antimicrobial agents. It is a cationic natural polymer that is obtained by the deacetylation of chitin, which is one the most important components of the cell walls of fungi and the shells of crustaceans (Wang et al. 2020). It is widely used in the food packaging for film formation due its vast antibacterial and antifungal properties (Ahmed et al. 2020). Furthermore, it possesses a variety of advantages, such as nontoxicity, biodegradability, bio-functionality, biocompatibility, and chelating abilities of metals. Chitosan is mostly used as a polymer in electrospinning because it has a large number of primary amine (-NH2) and hydroxyl (-OH) groups present in its chains that can serve as coordination and reaction sites. Furthermore, it possesses a low surface area and poor mechanical properties and dissolves in highly acidic solutions, which has limited its applications in adsorption. Due to this limitation, many studies have been conducted to overcome this flaw and improve the mechanical properties of chitosan (Yaowen Liu, Wang, Zhang, et al. 2017). Scientists showed that PVA/CS bilayer films exhibited good physical properties and antibacterial activities owing to the specific intermolecular interactions. Adjusting the contents of CS in the PVA/CS bilayer films could improve the efficiency of the film, and it was tested for the preservation of strawberries at 20 °C (Ding et al. 2019; Siying Li, Chen, et al. 2020).

Gelatin. Gelatin is another extensively used polymer that is approved by the FDA. It is biodegradable, biocompatible, and readily available. Gelatin films are used in active and intelligent food packaging along with the incorporation of various other polymers, such as aqueous and ethanol aqueous solutions, essential oils, curcumin, and oxygenated seaweed extract. It was also found in numerous studies that gelatin nanofibrous films were cold-water soluble because they had high surface-to-volume ratios and were very suitable for electrospinning. Electrospinning does not reduce the molecular weight of gelatin nor effect the formation of a triple helix. Subsequently, the slow biodegradation and hydrophobic nature of gelatin have restricted its application, especially as a packaging material in the food industry. To overcome its defects and take advantage of its properties, gelatin should be electrospun with various other natural and advantageous polymers (Wang et al. 2020).

Starch. Starch is a powder-based polymer. It is extensively used for film formation in food packaging, and its properties are enhanced when it is used or blended with other materials. It is one of the most abundantly used natural polymers on earth. However, the mechanical properties of pure starch fibers are very good and provide great properties to the film (Fonseca et al. 2020). Starch contains three hydroxyl groups naturally in each repeating unit, which is the reason that it easily forms inter- and intra-molecular hydrogen bonds. In addition, starch in fibrous form is problematic due to its poor strength, water resistance, thermal stability, and processability. It can be enhanced when blended with other biopolymers, and thus, it is extensively used in the formation of composite films (Hemamalini and Dev 2018). Enzymatic modification of starch leads to the formation of a very unique and important compound, Cyclodextrin. Cyclodextrin are slightly hydrophobic in nature and have ring structure due to which, they make inclusion complex with variety of solvents. Molecular chemistry describe that they consist of 6,7 and 8 glucopyranose units and also named as α, β and, γ-CDs. They are getting attention because they can replace synthetic polymers for electrospinning due to good spinnability because of their chemically modified structures and excellent solubility. These days for the spinning of natural polymers, such as chitosan; cyclodextrins are used as a supporting material for smooth fibers. Various studies are reported showing their applications in food packaging industry (Adel et al. 2019; Andrade-Del Olmo et al. 2019; Simionato et al. 2019).

Collagen. Collagen is very important and is the most abundant component of human and animal bodies. It is extensively used in electrospinning for the formation of fibers, with sizes ranging from nanometers to micrometers, which can be further used in food packaging. It is widely used as material in biomedical science and food engineering because it is natural and found in tissue. If collagen is electrospun alone without the incorporation of any other polymer, it shows poor stability and mechanical properties (Irastorza et al. 2021). Furthermore, studies have shown that electrospinning leads to the denaturation of proteins due the required highly volatile organic solvents. Two methods are used to overcome these limitations: First, various other blends are used for the successful electrospinning of collagen, such as chitosan, polylactic acid (PLA), and polycaprolactone (PCL), to improve mechanical properties. Second, there should be crosslinking in electrospun collagen fibers to stabilize the scaffolds of fibers for further use and applications (Luo et al. 2018).

Pullulan. Pullulan is a food-grade polymer that is also used in the electrospinning of nanofibers for the food packaging industry. There are some specialized properties of pullulan that help improve its electrospinability from solution by lowering the conductivity and raising the viscosity. It is also used to blend with various types of proteins, such as whey protein, pea protein isolate, and amaranth protein isolate, and a protein – pullulan composite nanofiber is obtained that is biodegradable and natural. Thus, these materials are considered to be environmentally friendly (Qin et al. 2019). In one study, pullulan was incorporated with carboxymethyl cellulose (CMC) and tea polyphenols (TP) to make fibers for fruit packaging to increase the shelf life of strawberries (Soto et al. 2019). Various polymers have been electrospun in the last decade, and a few of them are described in Table 2.

Applications of electrospun fibers in food packaging technology

Application in food preservation

Food preservation is important for promoting food safety to provide safe food to all. The organoleptic properties should be maintained to make sure that food is fresh and safe to consume (Zhao et al. 2020). For this purpose, different electrospinning techniques are used for the formation of various fibers for the presentation of numerous food items. Electrospun fibers are not only used for the packaging of dried foods like wheat flour, rice, grains, and dried fruits but they are also utilized on a larger scale for the preservation of various fruits, vegetables, meats, and other cooked food items (Liu, Gough, et al. 2020).

Applications for packaging of fruits

There are many metabolic processes occurring inside perishable foods, and fruits are the most perishable foods. To minimize and slow the metabolic processes of fruits, we must focus on effective preservation, including coating with edible films, use of intelligent films, and regulating the atmospheric storage temperature, to improve the quality and prolong the shelf lives of fruits. There have been many studies performed using applications of electrospinning for the formation of films to preserve fruits. Some of them are provided here. In 2018, Shao et al. (2018) made a film for the preservation of strawberries using active catechins from tea polyphenols, pullulan for its film-forming abilities, such as its adhesion, lubrication, and encapsulating agent properties, and carboxymethyl cellulose (CMC) because it enhances the properties of pullulan. CMC was compatible with pullulan, as it formed hydrogen bonds between the COO^- groups of CMCs and – OH groups of pullulans. The results showed that by adjusting the concentration of TPs and maintaining the sizes of the fibers, better encapsulation was achieved through electrospinning, and the film significantly prolonged the shelf life of strawberries. One of the main reasons for the spoilage of fruits is their early ripening. Ethylene is the main ripening agent that promotes early ripening in fruits and vegetables. Some studies have shown that the degradation of ethylene results in the delay of ripening and thus helps to stop food wastage. This degradation is very helpful, especially for long distance transportation, where food can be spoiled due to ripening (Zhu, Zhang, et al. 2019).

Fruit packaging has been studied and used for many years. Various types of fruits require various types of packaging. Fruits are classified in many ways. First, they are classified based on their fiber and second category is fresh cut fruits, such as ready to eat fruits and mixed fruits salads which are very common these days. Back to fiber type, there are two types of fiber found in fruits: water soluble fiber and water insoluble fiber. Fiber can also be classified as hard fiber and soft fiber. Fruits, such as peaches, pears, apples, and melon, contain hard fibers, while berries, such as strawberries, blueberries, and raspberries, have soft fibers. The latter are damaged and contaminated very easily, which is the reason that much more care is required during harvesting, storage, transportation, and packaging. For the packaging of hard fiber fruits, we can easily use hard fibrous mats fabricated through electrospinning, while for soft fibers foods, we must use soft fiber mats for packaging that should not be damaged by the water contents of the fruits. Various other types, such as fruits with hard shells, fruits with thick peels (banana, orange, and watermelon), and fruits with spikes on their outer covering (durian fruit, jack fruit, and pineapple), require various kinds of packaging. However, the main issues are the discoloration and unpleasant smell that form after few hours, making them less useful. Thus, these fruits should be maintained through good fruit packaging films (Mei and Wang 2020). Various electrospun materials used in accordance with the fiber type of the fruits are given in Table 3.

Applications for packaging of vegetables

In addition to fruits, food packaging materials are important for various vegetables. Vegetables containing high water contents, such as tomatoes, capsicum, and cucumbers, are

Table 2. Various organic polymers, their supporting solvents, the active agents and their active properties, and the effect on the features of packaging films.

Organic Polymers	Solvents	Active agents	Active properties	Film features	References
Natural					
Chitosan	(CHEO) Chrysanthemum essential oil	CHEO	Antibacterial	L. monocytogenes growth on beef is protected with an inhibition rate of > 99.9% at various temperatures (4, 12, and 25 °C) after 7 d.	(Lin, Mao, et al. 2019)
Chitosan	Microalgae phenol compounds	Microalgae phenolic compounds	Antibacterial	Antibacterial activity against both types of bacteria	(Kuntzler, Costa, and de Morais 2018)
Pullulan/ carboxymethyl cellulose (CMC)	Tea polyphenols	TPs		Reduces the weight loss and controls the firmness of strawberries, enhancing the food quality during storage	(Shao et al. 2018)
Regenerated cellulose	Carbon nanotubes/ graphene oxide/ lysozymes	Lysozymes	Antibacterial	Cellulose and lysozymes conjugates were found to Provide excellent bioactivity with no cytotoxicity	(Liu, Edwards, et al. 2018)
Bacterial cellulose	Poly-indole by post treatment		Antibacterial	Fibers show good antibacterial properties and provide enhanced biodegradability	(Zhijiang et al. 2018)
Cellulose	Epigallocatechin gallate (EGCG)	EGCG	Antibacterial	Enhanced antimicrobial activity	(Tian et al. 2016)
Zein	Soy protein isolate (SPI), poly (ethylene oxide) (PEO)	Ginger essential oil	Antibacterial	Fibers reduced L. monocytogenes in fresh Minas cheese.	(Silva et al. 2018)
Gliadin	Ferulic acid (FA)/ HP-CD inclusion complex (ICs)	FA	Antioxidant	With the utilization of IC of FE and HP-CD, the photostability of FA was enhanced quickly.	(Sharif et al. 2018)
Zein	Thymol/CD IC	Thymol	Antibacterial	Highest efficiency for the inhibition of microbial growth on meat samples. Good activity was observed against bacteria inside the mats of electrospun fibers	(Aytac et al. 2017)
Whey protein isolate/ pullulan/zein	Polyhydroxy butyrate-*co*-valerate film			Not very effective at reducing the WVP and oxygen of a multilayer system of PHBV3.	(Fabra, Lopez-Rubio, and Lagaron 2014)
Zein	Chamomile essential oil and peppermint essential oil	Chamomile essential oil and peppermint essential oil	Antibacterial	Better antibacterial activity against both types of bacteria and showed no toxicity in cells	(Tang et al. 2019)
Synthetic					
Poly (L-lactic acid) PLA	Carvacrol	Carvacrol	Antioxidant antimicrobial	Maintained freshness of bread samples	(Altan, Aytac, and Uyar 2018)
PLA/ Polyhydroxy butyrate	Poly (3 hydroxybutyrates-3-hydroxyvalerate) (PHBV) film, catechin	Catechin	Antioxidant	High disintegration in compost conditions in ∼3 months	(Arrieta et al. 2019)
PEO	Cinnamon essential oil (CEO)/-CD	CEO	Antimicrobial	Elevated antibacterial activity against B. cereus on beef was detected without any effect on the sensory quality of beef	(Lin, Dai, and Cui 2017)
(PCL) Polycaprolactone	Gelatin film	Black pepper oleoresin (OR)	Antimicrobial	Improved the properties of the gelatin films.	(Figueroa-Lopez et al. 2018)
PVA	Durvillaea Antarctica algae extract	Extract of D. Antarctica algae	Antimicrobial, antioxidant	Increased mechanical. resistance and oxygen barrier properties, combined. with high antioxidant activity.	(Arrieta et al. 2018)
PLA	Tea polyphenols (TP)	TP	Antioxidant, antimicrobial	Antimicrobial activities against E. coli and S. aureus were found.	(Liu, Liang, et al. 2018)

(*continued*)

Table 2. Continued.

Organic Polymers	Solvents	Active agents	Active properties	Film features	References
				to be 92.26 ± 5.93% and 94.58 ± 6.53%.	
PVA	Cinnamon essential oil nanophytosome (N/CEO)	N/CEO	Antibacterial	Antibacterial activity on a raw shrimp for 7 d of storage.	(Nazari et al. 2019)

more perishable. Nanofibers that are electrospun possess many properties, such as extremely small diameters, which allow them to contain and utilize bioactive compounds while releasing them during storage. There are many food-borne illnesses caused by spoiled vegetables, especially perishable vegetables, such as cucumber and tomatoes. Minimally processed vegetables, which are abbreviated as (MPVs), are also important commodities because of a combination of factors, such as their desirable sensory characteristics and convenience. As these vegetables are processed, such as by dicing, slicing, and peeling, they became more susceptible to the invasion of microbes, which affects their sensory shelf lives. There are limited publications on the preservation of these vegetables, especially using electrospun materials (Böhmer-Maas et al. 2020; Hashmi et al. 2021). A few results are described in Table 3.

Applications for packaging of fish

Fish is a protein source that is very important and highly perishable, and it cannot last even 24 h at room temperature. There are many parameters that are used for the detection of fish spoilage, which can be altered using various packaging techniques. The effects of various processing steps and storage of fish are reviewed in this section. One of the main factors that can be used as an effective indicator for fish spoilage is the instability of vitamins, especially the vitamin B complex. There are many factors that affect the stability of the vitamin B complex, including moisture, heat, light, oxygen, and pH. The vitamin B complex, that is, vitamins B1 (thiamine), B3 (niacin), B2 (riboflavin), B12 (cyanocobalamin), B5 (pantothenic acid), and B6 (pyridoxine, pyridoxal and pyridoxamine), is a group of water-soluble vitamins. The shelf life of fish is determined by the shelf life or instability of the vitamin B complex. To prolong the shelf life, packaging must be made to keep the vitamin B complex stable. Ceylan et al. conducted a study in which nanofibers were prepared through the electrospinning of thymol loaded chitosan to study its effect on the stability of the vitamin B complex during the cold storage period. The results revealed that loading of fish fillets with electrospun nanofibers containing thymol and chitosan helped significantly in maintaining the stability of the vitamin B complex in fish during cold storage (Ceylan et al. 2020; Ceylan, Yaman, et al. 2018). A few studies on the electrospun materials for various fish are mentioned in Table 3.

Applications for packaging of meat

Meat is also another highly perishable food consumed extensively because it is a high source of healthy proteins. Poultry is an extensively used meat due to the abundant poultry farms and the low cost. It is a prevalent food in daily life not only because of its cost effectiveness but also because it has a pleasant flavor. However, it is deteriorated by variety of food borne pathogenic bacteria, such as *Salmonella*, *Campylobacter jejuni*, and *Listeria monocytogenes*. Denaturation of amino acids results in the degradation of meat, called meat spoilage (Surendhiran et al. 2020). Its transport is also very difficult, and it should be properly stored immediately after slaughter. There have been many studies reported on the packaging of meat. Researchers prepared nanofiber films for the preservation of meat from *C. jejuni* in 2018. They prepared a film with thyme essential oil/β-cyclodextrin ε-polylysine nanoparticles, which showed excellent antibacterial properties against *C. jejuni* in chicken (Lin, Zhu, and Cui 2018). Table 3 described some meat sources and electrospun materials used to preserve them.

Applications for packaging of other food products

Many food products also require packaging, regardless of whether they are cooked, such as cheese, milk, bakery items, baked breads, ice creams, cakes, and pizza. Previous researches are shown in Table 3.

Application in antimicrobial food packaging

The formation of antibiotic packaging films is crucial. Most of the food spoilage is caused by bacterial invasion (Ahmed et al. 2020). Some examples of studies performed on antibacterial films are also described in this section. Liu et al. prepared film using curcumin, which was loaded with zein, and performed electrospinning to form fibers. They also showed good antimicrobial activities and antioxidant capacities. The results showed that the predominant release mechanism of curcumin was Fickian diffusion, which is promising for materials with antimicrobial properties. Along with inorganic materials, such as zein, there are many organic polymers used for antibacterial film formation. The most important ones are natural antimicrobial agents, such as essential oils. Essential oils are volatile aromatic specialized compounds for antibacterial properties. They are mostly extracted from plant sources and exhibit many antiviral, antifungal, and antibacterial properties. Numerous studies have been performed to overcome these problems of essential oils, because aside from these limitations, they possess outstanding antibacterial properties (Yaowen Liu, Wang, Lan, et al. 2017). Table 4. Below describe some important previous studies explaining the effect of various polymers against some microorganisms.

Table 3. Applications of various electrospun polymers for the packaging of fruits, vegetables, fish, meat, and other processed items.

Food	Fiber type	Electrospun material	Nanofiber characteristics	Preservation	Reference
Fruits					
Fresh cut apples	–	Hordein-quercetin-chitosan	Antioxidant / Hydrophobic	Antioxidant / Hydrophobic	(Li, Yan, et al. 2020)
Fresh cut apple slices	–	Resveratrol/ zein	Sustained release of resveratrol	Retain the color and control moisture loss.	(Maria Leena et al. 2020)
Strawberries	Highly delicate/soft fibrous/high water content/susceptible to fungal attack	Carboxymethyl chitosan/ polyoxymethylene oxide	Soft fibrous mat	Maintains freshness/ reduces weight loss/ antibacterial/ prevents physical damage	(Yue et al. 2018)
Peach	Tender fruit/ high moisture level	Zein/ Hexanal/ Polyethylene oxide	Hydrophilic fibers	Preserves cell membrane from degradation/ increases shelf life	(Ranjan et al. 2020)
Any fruit	Mild citrus/ fresh fruits	Benzaldehyde/ hexanal/ PLA	Bead fibers with smooth surfaces/ thinner fibers	Delivery of bioactive aldehydes for the extension of shelf lives of fresh fruits	(Jash, Paliyath, and Lim 2018)
Mangoes	Thin outer skin/ easily deteriorates and gets bruises	Hexanal/ PVA/ nanocellulose (banana pseudo stem)	Thick fibers due to increase in diameter with hexanal loading	Prevents ripening/ extends shelf life	(Biswal and Subramanian 2019)
Strawberries	Delicate, soft fruit/ susceptible to physical injury and fungal attack	Eugenol (EG)/ polyvinyl pyrrolidone (PVP)/ shellac	Core-sheath fibrous film with strong mechanical tensile strength	Prevents fungal attacks/ prevents physical bruises/ prolongs shelf life of strawberries	(Bounie et al. 2020)
Fresh dates (*Rutab*)		PVA/ Red cabbage extract	Delicate fibers	Antibacterial/ pH sensors for freshness	(Maftoonazad and Ramaswamy 2019)
Banana		Polyacrylonitrile/ TiO_2/DMF		Delays ripening of banana by degradation of ethylene	(Zhu, Cui, et al. 2019)
Vegetables					
Mushrooms	Perishable elastic fungi	Poly vinyl alcohol/ cinnamon essential oil/β-cyclodextrin	–	Maintains freshness/ delays decay	(Pan et al. 2019)
Tomatoes	Highly perishable due to high moisture content	Poly vinyl alcohol/ thymol	Active fibers with moisture triggered release of thymol	Prolongs shelf life for 5 d	(Liu 2016)
Cucumber	High water content soft fibers/ easily ruptured	Gelatin/ chitosan/ clove essential oil	–	Improves sensory qualities up to 4 d/ restricts E. coli growth	(Cui et al. 2018)
Fish					
Sparus aurata (gilt head sea bream fillets)		Thymol/Chitosan		Vitamin stability for prolonged shelf life	(Ceylan, Yaman, et al. 2018)
Dicentrarchus labrax (sea bass fillets)		Liquid smoke/ thymol/ chitosan		Strong antibacterial properties against mesophilic bacteria	(Ceylan, Sengor, et al. 2018)
Meat					
Pork		PEO/ Dendrobium officinale/ Adipic acid	Good mechanical strength was obtained in the fibers due to adipic acid	Strong antibacterial effect due to adipic acid	(Zhu, Cui et al. 2019)
Beef		Gelatin/ Glycerin/ ε-Poly-lysine	Enhanced tensile strength due to glycerin	Strong antibacterial activity against Listeria monocytogenes	(Lin, Gu, et al., 2018)
Chicken		Thyme essential oil/ β-cyclodextrin ε-polylysine nanoparticles (TCPNs)	–	Campylobacter jejuni	(Lin, Zhu, et al., 2018)
Other foods					
Bakery		Cassava starch/ cinnamon essential oil		Antimicrobial activity	(Souza et al. 2013)
Pizza		Oregano essential oil		Antimicrobial activity	(Botre et al. 2010)
Fresh cheese/ apple juice		Nisin/ amaranth protein isolate/ pullulan		antimicrobial activity against S. Typhimurium, L. monocytogens, L. mesenteroids	(Soto et al. 2019)
Whole wheat bread		Carvacrol (CRV)/ PLA		Increased antioxidant activity/ slow release of bioactive agents/ prevented mold, yeast, and aerobic bacterial growth	(Altan, Aytac, and Uyar 2018)

Table 4. Some electrospun materials and their activity against microorganisms.

Electrospun Material	Antibacterial agent	Microorganisms	References
Polyacrylonitrile	Ag NP	*Staphylococcus aureus, Escherichia coli, Monilia albicans*	(Shi et al. 2015)
Polycaprolactone	Ag NP	*Staphylococcus aureus, Escherichia coli, Candida albicans*	(Liao, Li, and Tjong 2019)
Polyacrylonitrile (PAN)/ b-cyclodextrin (b-CD	Cu nanorods	*Escherichia coli*	(Li et al. 2014)
Polyvinyl acetate	CuO/TiO2	*Staphylococcus aureus*	(Hassan et al. 2013)
Nylon 6,6	Polyacrylic acid grafted rose bengal, phloxine B, azure A, and toluidine blue	*Aspergillus fumigatus, Aspergillus niger, Trichoderma viride, Penicillium funiculosum, Chaetomium globosum*	(Kim and Michielsen 2015)
Chitosan (CS)/polyvinyl alcohol (PVA)	Clotrimazole	*Candida albicans*	(Tonglairoum et al. 2015)
Polyacrylonitrile	Amidoxime	*Saccharomyces cerevisiae*	(Sirelkhatim et al. 2015)
Gelatin	Amphotericin B, natamycin, terbinafine, fluconazole, and itraconazole	*Candida albicans, Fusarium solaria, Aspergillus Brasiliense, Aspergillus fumigatus*	(Lakshminarayanan et al. 2014)
Poly (ethylene oxide) (PEO) and poly (vinyl alcohol) (PVA)	Lawsonia inermis (henna)	*Escherichia coli, Staphylococcus aureus*	(Avci, Monticello, and Kotek 2013)
Modified polyurethane (quaternary ammonium salts)	Quaternized polymer backbone	*Staphylococcus aureus*	(Coneski et al. 2014)
Chitosan/ poly (ethylene oxide) (PEO)/ poly (hexamethylene biguanide) hydrochloride (PHMB	PHMB	*Staphylococcus aureus, Escherichia coli*	(Dilamian, Montazer, and Masoumi 2013)

Application in sustained release

One of the major advantages of electrospun nanofibers is that they entrap bioactive compounds in their mats and allow the slow release of these compounds, thereby improving the quality and functionality of the respective films (Karami et al. 2021). Curcumin is very effective for antimicrobial activity, and it is known for its slow-release properties. Gelatin nanofibers had been applied to achieve the slow release of curcumin using different surfactants, such as cationic cetyltrimethylammonium ammonium bromide (CTAB), Tween 80, and ionic sodium dodecyl sulfonate (SDS). CTAB and Tween 80 did not significantly affect the diameter, while SDS showed an increase in diameter. Furthermore, the interaction of gelatin and SDS did not show the effective release of curcumin. In contrast, the other two surfactants greatly improved the slow release of curcumin into polar solvents. This resulted in a higher radical scavenging activity and stronger antimicrobial activity. This study provided excellent results by producing gelatin nanofibers with the use of food-grade surfactants for the slow release of curcumin, which may be promising in the food packaging and pharmaceutical industries (Deng et al. 2017). Various other studies are also performed (Hoseyni et al. 2021; Min et al. 2021).

Application in sensors for smart packaging

Smart and active packaging currently provides significant benefits for the formation of specialized sensors for the deterioration of food. For example, the cyclodextrin inclusion complex (CD-IC) was studied previously, and it was found that CD-IC polymers can incorporate various active compounds and possess successive processing characteristics, such as enhanced solubilities, high thermal stabilities, controlled release abilities, and prolonged shelf lives, making them suitable for food packaging technology as well as for nutraceuticals, functional foods, and the pharmaceutical field (Aytac et al. 2017; Aytac and Uyar 2017; Aytac et al. 2016; Canbolat, Savas, and Gultekin 2017; Costoya, Concheiro, and Alvarez-Lorenzo 2017).

Smart packaging not only provides functional properties but also can provide nano sensors for monitoring and tracking the conditions of food internally and externally. In this way, it assists the consumers in finding the exact quality of packaged food at the time of purchase. For example, different pH-sensitive dyes containing sensors can show color changes in response to changes in the pH of food. These pH sensitive sensors show enhanced thermal abilities and storage stabilities (Kumar et al. 2019). In alcoholic beverages, the ethanol content has been estimated from the intensity of the fluorescence elicited from terphenyl-ol implanted in nanofibers. Gas biosensors have also been studied and developed by researchers, using electrospun nanofibers to detect ammonia, hydrogen sulfide (Mousavi et al. 2016), hydrogen (Drobek et al. 2016), alcohol vapor (Akamatsu et al. 2015), biogenic amines (Geltmeyer et al. 2016), and so on. Apart from chemicals and gases, microbial detection is done using electrospun nanofibers.

Challenges of electrospun nanofibers for food packaging

There are many advantages of electrospun nanofibers, which makes electrospinning a robust and widely used technique for film formation in the food packaging industry. Electrospinning is a unique technique that provides tremendous applications and advances compared with conventional film formation methods. However, one main limitation of electrospinning in the food packaging industry is that it is only used at the laboratory scale, while it is necessary to produce fibers at the commercial scale to promote industrialization and application to food packaging films on the industrial level to appear in markets. However, there are limited evidence showing their commercial use. Thus, there are many advances required, including improvements in the stability, barrier properties, functionality, and mechanical properties of electrospinning-based fibrous mats in the specialized field of food packaging (Zhang et al. 2020).

It should be noted that nanoparticles can cause considerable harm to the environment and pose health risks to humans. Information about potential threats due to the use of nanoparticles is still limited and lacking in the literature. For example, silver nanoparticles have shown considerable harm to liver tissues and ultimately cause liver damage. There are various routes of penetration that is, digestion, absorption through the skin, and inhalation. All of these routes are possible with packaging containing nanoparticles. Some studies have shown that these particles enter the blood stream after absorption and settle in different body tissues, such as the liver and brain, thereby causing various problems and triggering immune responses. To overcome this bottleneck issue, advances in packaging that will have no contact with the food are needed (Neo, Ray, and Perera 2018; Zhang et al. 2020).

Conclusion and prospective

This study summarized the electrospinning packaging technique and its application for food preservation. Electrospinning has gained popularity during the last few decades because of its unique and novel applications in the field of food science. However, its applications mostly remain at the lab scale and are not developed well enough for application on an industrial scale. Nanotechnology can be used in food production not only to provide antibacterial effects but also to enhance the color, taste, texture, and consistency of numerous foods. The use of nanostructures in the formation of food packaging films requires further study and innovation because the extremely small-sized nanoparticles may easily absorb in food and cause various types of harm to different body parts, especially liver cells, which are penetrated easily, and brain tissue, triggering the immune system. However, there are many adverse effects related to these advancements. To overcome the environmental hazards and human health risks, there is a need to develop strategies and laws at the government level, which should be implemented by various regulatory authorities for the formation of safe and hazard-free food packaging films. These programs should establish various tools, data, and methods to assist decision making for regulatory authorities, thereby providing well-established, tested, and expertized strategies to create safe nanotechnology-related food packaging. Hence, there are many opportunities for further research on food safety and security to fulfill our main objective of "food for all."

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