Electrospinning and electrospun nano fiber food packaging: Application in food system:A review

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Abstract

Food safety is a constraint issue. This research provided an overview of the developments in the electrospinning technology in order to give information regarding cutting-edge and distinctive food packaging methods. There is a lot of interest for the retaining of increasing the quality of food and packing. Food in packaging material is a multi-disciplinary field that includes food science, engineering of food, chemistry of food and microbiology of food. Due to its distinctive features and better processing, electrospinning technology has attracted a lot of attention for this purpose. Research has quickly adopted unexpected electrospinning breakthroughs. The updated studies about packaging of foods and materials used for the packing of food products was included in this review. Additionally, the usage of electrospinning and the substances utilised to create nanofibers are thoroughly covered. However, the use of electrospun nanofibers in the food sector is still in its early stages. In this study, various parameters, nanofiber texture, characteristics, and basic properties are briefly discussed whereas polymers made using electrospinning with improvements in the films of packaging of food are extensively discussed. The application of the polymers for the electrospinning of nanofibers used as packing layers for a range of meals are also a major subject of this in-depth analysis. Researcher exploring different polymers for electrospinning for use for the packaging of food business will find this to be a great source of knowledge.

Introduction

Attaining "food for everyone" and food safety is now a bottleneck issue. The development of food packaging technology is an essential component for ensuring food safety. We must concentrate on obtaining enough food production due to the ever-increasing population and increased international commerce. Immediate postharvest food safety and security are also essential to offer fresh commodity, wholesome, and clean food (Liu, Wu, et al. 2020). The majority food damage and bodily injury happens in transit. In order to increase a product's shelf life without lowering its quality, food packaging is crucial. Minimizing food losses and preventing microorganisms are qualities of a good packing material, in addition to safeguarding and supplying and nourishing nutrition (Ahmed et al. 2020; Bahrami et al. 2020).

The most adaptable and durable methods for creating polymers is electrospinning. It uses the electrical energy to function (Zhao et al. 2020). A collector and a syringe's spinneret are attached to a high-voltage source in this procedure. A plastic syringe containing to be a polymer solution formed into a fibre is utilised, together with a syringe to regulate the fibres' running speed. Under the influence of several forces, including as electrostatic, drag, and gravity forces, release of the conducting solution, Taylor cone is formed, and extra-fine fibrous wires are produced. Finally, collecting devices of various forms are used to gather the fibres (Zhang et al. 2020). This method was invented at the the start of nineteenth era to create fibersnano used in textiles and purification systems (Aman Mohammadi, Hosseini, and Yousefi 2020). After it, this method has undergone enormous development in order to produce tiny nanofibers and profit from their special properties. In addition to advancing food packaging methods, these advancements have made electrospinning technology widely accepted for a variety of other uses, including those in the pharmaceutical and biomedical industries. It is an easy, affordable, and workable technology for manufacture on a wide scale (Coelho, Estevinho, and Rocha 2021; Leidy and Maria Ximena 2019).

Additionally, nanofibers utilising a variety of food waste products and raw food ingredients. Fruit and vegetable seeds and skins, as well as other bioactive substances, are abundant in these waste items. These peels are very good in preventing germs because they shield the food from the hostile environment outside. In recent studies, researchers have used zein, a food-grade polymer, to electrospin packaging sheets (Altan and C. ayr 2020; Aytac et al. 2020). Tea source made from yerba mate was employed as a active substance while packaging food using electrospinning in a different study (Pinheiro Bruni et al. 2020). Another study that was published described the utilisation of juice industry waste to create biocompatible nanofiber films by electrospinning. Researchers created bio papers for food improved conservation with antimicrobial properties using specialised straight after the mitochondria of together kinds of microbes, poly(3-hydroxybutyrate-co-3-hydroxyvalerate, or PHBV) was produced from surplus by fermentation (Gram-positive and Gram-negative) (Figueroa-Lopez et al. 2020). Additionally, a variety of food ingredients may be separated to create biodegradable, edible, and suitable nanofibers that can be used as packaging. Utilizing the highly specialised "gliadin," that is the primary constituent of gluten and is present in wheat and numerous other breakfast cereal, Sharif et al. created a food packaging nanofibrous film (Sharif et al. 2019). Due to these benefits, electrospun nanofibers are often utilised in the pitch of food packing (Topuz and Uyar 2020; Zhang et al. 2020). The key goals of the existing study are: a) evidence gathering and the usage of polymers in electrospinning for nutrition packing; b) demonstrating the value of electrospinning in food conservation; c) evaluating and presenting numerous latest studies created on electrospinning so that writers can access material from single stage; and d) summarising the results of electrospinning to date in order to plan future research and developments and carried out in the forthcoming.

Materials used in electrospinning of food packaging films

Inorganic materials

Silicon and oxides

In addition to creating clear films, having great printing adaptability, being microwaveable, and having other highly desirable qualities, silicon oxides offer superb block things. Theoretical evidence indicates that they have zero gas permeability and also act as a flavour and moisture barrier, allowing for nil diffusion. (Li, Chen, et al. 2020; Zhu et al. 2017).

Metal oxides

Different types of metallic oxides are involove in the making packaging of food items in electrospinning (Yu et al. 2020). Here is a quick description of a few commonly used oxides. One of the most often utilised metals, particularly for packaging applications, is silver nanoparticles. They are antibacterial against a variety of microbes, and some research suggests that they may also be antiviral. At both the micro- and macro-scales, silver is often utilized (Wenting Lan et al. 2020). Due to its outstanding germ repelling qualities, its long been utilised in freezers, heats, and further kitchen equipment (Majumder et al. 2020). According to certain research, silver nanoparticles harm mammalian cells in both the cytotoxic and genotoxic ways. They cause oxidative stress and the body to manufacture reactive oxygen species, also known as free radicals, according to some research. Researches have shown that when they go in the body's circulatory structure—whether over ingestion or inhalation—they possibly interact with red blood cells, platelets, and clotting features to cause hemolysis and cause thromboembolic issues in cell sheaths as well as propagation. When utilising this metal for food packaging, these restrictions should be taken into account since the packing straight or circuitously cooperates with the food and, when such components are present, impacts the food chemistry. (Morais et al. 2019; St€ormer et al. 2017).

ZnO is often regarded as a harmless substance. It not only has strong antibacterial action but also has great stability and photocatalytic activity. Since ZnO NPs have all of the aforementioned qualities and are simple to enclose with other polymers for electrospinning, they are commonly utilised in the creation of various films. ZnO nanoparticles have been proven to be highly efficient against decay bacteria and other foodborne microbes by the US Food and Drug Administration (FDA). The FDA has established that ZnO nanoparticles are extremely active against foodborne illnesses and rotting germs (FDA). (Khan et al. 2019; Li, Chen, et al. 2020).

Due to its distinct antibacterial properties, titanium dioxide (TiO2) has also been extensively employed in the packaging sector and has been the subject of several research. It engages in photocatalysis when exposed to light, which is a very unusual characteristic and produces reactive oxygen species. These classes have a considerable capacity to harm the bacterial cell membranes. Polylactic acid (PLA)/TiO2 nanofibers were produced by Toniatto and colleagues. They proved that they do not harm or be poisonous to mammalian cells and had good photocatalytic, thermal, and mechanical characteristics. Most significantly, they showed bactericidal action as TiO2 concentration rose (Ghadimi, Esfahani, and Mazaheri 2021; Toniatto et al. 2017). Table 1 lists the many nanoparticles that were looked at in earlier investigations.

Carbon nanotubes (CNTs)

The extraordinary elasticity and tensile strength of CNTs is one of their key properties. Additionally, because to their great degradability, different walled carbon nanotubes (MWCANTs) have been employed by experts to make great-performance films. In one experiment, MWCNTs and PLA composites were blended in a melt, according to Kuan et al. The elasticity of the PLA polymer was improved by their high strength moduli. They employed crystallinities that were low and high. PLA They found that adding 0.5 weight percent MWCNTs significantly raised the high-crystallinity PLA's tensile strength ranged from 60 to 63.5 MPa, and the low-crystallinity PLA's ranged from 59.9 to 68.5 MPa. (Kuan et al. 2008). Liu et al. investigated the morphologies and mechanical characteristics of PLA/MWCNT fibres as food packing films by adding CS, and they used the films to package strawberrie. (Yaowen Liu et al. 2019; Zou et al. 2020).

Graphene oxides

Graphene oxides may have a variety of functional groups containing oxygen, including as carbonyl and epoxy groups (GOs).These efficient sets have important interactions with polar liquids and polymer matrices that help graphene oxides disperse into the latter. Because of its unique antibacterial qualities, GOs are frequently utilised in the packing division (Dong et al. 2021). Both Gram-positive-negative bacteria are effectively protected by them. The GOs' superiority in increasing the mechanical qualities of composite fibres was also proven. In a study by Lin et al., PVA/GO nanocomposites were made and put up against pure PVA. The addition of GO abruptly raised the yield stress and Young's modulus by 83.6% and 40.8%, respectively (Ji, Tiwari, and Kim 2020; Lin, Gu, and Cui 2018).

Organic material

Synthetic polymers

Polylactic acid (PLA). (FDA) considers PLA to be single greatest significant artificial recyclable polymers and to be widely regarded as safe (FDA). In addition, it is one of the polymers that is most frequently employed in electrospinning. Due to its biocompatibility, availability, and biodegradability, this polymer is frequently utilized Zhang et al. 2021) It is typically used with various food additives in food packaging technologies to boost the exterior area and organic characteristics. The majority of the PLA fibres produced by electrospinning are porous fibres. They primarily develop when processing steps include volatile solvents (Dong et al. 2021). The permeable nanofibers have several benefits because it setup the bioactive chemicals and cause their gradual release. Additionally, they support in nutrition conservation by giving the film superior machine-driven qualities (Huang and Thomas 2018; Valente et al. 2016).

Polyvinyl alcohol

Since the development of electrospinning, polyvinyl alcohol (PVA) has grown in popularity. Its distinctive qualities make it appealing (Safari et al. 2020). Its hydrophilic nature, great mass of reactive functional groups, and generally acknowledged as safe (GRAS) status from the FDA all contribute to its safety. Additionally, PLA is thought environmentally benign and has good film-forming capabilities. It is an emulsifying and adhesive a tactic semi-crystalline polymer. Along with having strong elasticity, tensile strength, and flexibility, it also has excellent scent and oxygen barrier qualities. Electrospun PLA fibres are smooth, tiny filaments that can be utilised in premium food packing (Estevez-Areco et al. 2020; Jiang et al. 2020; Weijie Lan et al. 2019).

Poly (ethylene terephthalate)

PET, a synthetic polymer created in the lab, has unique amorphous and crystalline characteristics that are totally dependent on the temperature past and treating (Ling Lin, Yao, & Li, Chen, et al. 2020). Owing to its outstanding, power, rigidity, non-hazardous makeup, and slight carbon dioxide porousness, it is widely employed in the packaging sector. Additionally, it has no effect on food tastes. It also has a lot of other beneficial qualities, such high process ability and recyclability, and it may take part in DE polymerization processes to get the original monomers (Devlaminck et al. 2018; Mu, Zheng, and Xin 2021).

Synthetic polymer the derivatives of fiber. One of nature's most common polymers, cellulose is mostly derived from plant bases like cotton and trees (Niu et al. 2020). Additionally, several microbes, including bacteria and fungus, create cellulose. It's possible that cellulose's advantageous features, which make it insoluble in most solvents and are excellent for food packaging technology, are caused by the substance's robust intra- and intermolecular hydrogen bonds. It is discovered to be a thermally unchanging polymer that keeps its mechanical characteristics due to its high melting point of roughly 400 C. Up to 200 C, it can be solid, but once this point is reached, thermal degradation begins. According to several recent research, ionic diluters are most frequently employed for cellulose electrospinning since they encourage cellulose dissolution, which is crucial for scientific and commercial submissions (Al-Moghazy, Mahmoud, and Nada 2020; Hashmi et al. 2021; Rezaei, Nasirpour, and Fathi 2015).

Chitosan

The most significant normal antibacterial agents is chitosan. Chitin, one of the most crucial elements of fungi's cell walls and crustaceans' shells, is converted into a cationic natural polymer via the process of deacetylation (Wang et al. 2020). Due to its extensive antibacterial and antifungal qualities, it is frequently used in food packaging to create films (Ahmed et al. 2020). It also has a number of benefits, including nontoxicity, bio-functionality, biocompatibility, and metal chelating properties. Chitosan is mostly used as a polymer in electrospinning due to the number of primary amine (-NH2) and hydroxyl (-OH) groups occurring in its chains, which can act as reaction sites. It also has a small surface area, weak mechanical qualities, and dissolves in extremely acidic conditions, which has restricted its use in adsorption. Numerous experiments have been done to address this drawback and enhance the mechanical characteristics of chitosan as a result of this restriction (Yaowen Liu, Wang, Zhang, et al. 2017). Researchers presented that PVA/CS bilayer films had superior physical possessions and antiseptic activity because of the exact intermolecular connections. The effectiveness of the PVA/CS bilayer films could be increased by modifying the CS content, and they were tested to preserve strawberries at 20 C. (Ding et al. 2019; Siying Li, Chen, et al. 2020).

Gelatin

The most widely used polymer that has FDA approval is gelatin. It is easily accessible, biocompatible, and degradable. In addition to a variety of additional in active and intelligent food packaging, polymers are used such as aqueous and ethanol aqueous solutions and gelatin films. Gelatin nanofibrous films were also found in several studies were cold-water solvable due to their high exterior-to-volume ratios and excellent electrospinning properties. Both the development of a triple helix and the molecular weight of gelatin are unaffected by electrospinning. Gelatin's applicability has thus been limited as a result of its slow biodegradation and hydrophobic properties, particularly in the food sector where it is used as a packaging material. Gelatin should be electrospun with a variety of different beneficial and natural polymers to overcome its flaws and utilise its benefits (Wang et al. 2020).

Starch

A polymer with a dust basis is starch. Frequently used to create films for food packaging, and when combined with other materials, its qualities are improved. One of the most widely utilised natural polymers on the planet. However, pure starch fibres have excellent mechanical characteristics and provide the film fantastic features (Fonseca et al. 2020). Each repeating unit of starch naturally has three hydroxyl groups, which explains why it forms inter- and intramolecular hydrogen bonds with other molecules with ease. Furthermore, the weakening, water resistance, thermal stability, and processability of fibrous starch make it challenging. It is frequently utilised in the creation of composite films since it may be improved when combined with other biopolymers. (Hemamalini and Dev 2018). Cyclodextrin is created as a result of the enzymatic alteration of starch, which is a very distinctive and significant molecule. Due to its ring shape and mild hydrophobic nature, cyclodextrin forms complicated inclusions with a wide range of solvents. According to molecular chemistry, they are also known as a, b, and c-CDs and are made up of 6, 7, and 8 glucopyranose units. They are drawing interest because, thanks to their great solubility and superior spinnability due to their chemically modified architectures, they can substitute synthetic polymers for electrospinning. Cyclodextrins are now employed as a supporting substance for smooth fibres when spinning natural polymers like chitosan. Numerous studies have been published demonstrating their use in the food packing business (Adel et al. 2019; Andrade-Del Olmo et al. 2019; Simionato et al. 2019).

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

Nanoparticles	Polymers	Active Property in Packaging film	References
Phycocyanin/PVA nanoparticles	Polycaprolactane, Poly (L-lactic acid)	Antioxidant	(Schmatz, Costa and de Morals 2019)
Silica having N-halamine	Polyhydroxybutyrate/ Polycaprolactone	Antibacterial	(Lin, Gu, et al. 2018
Hollow nanotubes (HNTs) loaded with lysozymes (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)
Montmorilonite	Nylone-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	Antimicrobial	(Lin, Gu, et al. 2019)
Graphene nanoplatelets (GNPs)	Poly (ethylene-co-vinyl alcohol)	Conductive	(Torres-Giner et al. 2018)
Pd-NPs	Polycarpolactone, Polyhydroxybutyrate	Oxygen scavenging	(Cherpinski et al. 2019)
Clove oil-Loaded chitosan nanoparticles (CO@CNPs)	Gelatin	Antimicrobial	(Cui et al. 2018)

Collagen

Because it is the most prevalent substance in both human and animal bodies, collagen is extremely significant. It is widely used in electrospinning to create fibres that range in size from nanometers to micrometres and may be utilised for packing food. Because it is organic and present in tissue, it is frequently employed as a material in biomedical research and food engineering. Without the addition of any additional polymer, collagen electrospun alone has poor mechanical and stability qualities (Irastorza et al. 2021). Additionally, research has revealed that the very volatile organic solvents needed for electrospinning cause proteins to denaturate. To get around these restrictions, two techniques are used: First, different additional blends, including as chitosan, and polycaprolactone (PCL), are utilised to successfully electrospin collagen in order to enhance mechanical qualities. Second, crosslinking of electrospun collagen fibres is necessary to strengthen the fibre scaffolds for more uses and submissions (Luo et al. 2018).

Pullulan

A food-ranking polymer called pullulan is also utilised to electrospin nanofibers for the food packaging sector. Pullulan has a few unique characteristics that aid increase its electrospinability from solution by reducing conduction and increasing thickness. Additionally, it is mixed with a variety of proteins.

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

Organic polymers	solvent	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 temperature (4,12, and 25º) after7 d.	(Lin, Mao, et al, 2019)
Chitosan	Microalgae phenol compound	Microalgae phenol compound	Antibacterial	Antibacterial activity against both types of bacteria	(Kuntzler, Costa,and de Morais 2018
Pullulan/ carboxymethyl cellulose (CMC)	Tea polyphenols	TPs		Reduce the weight loss and control 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	Fiber show good antibacterial properties and provide enhanced biodegradability	(Zhijang et al. 2018)
cellulose	Epigallocatechin gallate (EGCG)	(ECG)	Antibacterial	Enhanced antimicrobial activity	(Tian et al. 2018)
Zein	Soy protein isolate (SPI, poly	Ginger essential oil	Antibacterial	Fiber reduced L. monocytogenes in fresh Minas cheese	(Silva et al. 2018)
Gliadin	Ferulic acid (FA)/ HP-CD indusion 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 sample, Good activity was observed against bacteria inside the mats of electrospun fiber	(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 Lagoran 2014)

Zein	Chamomile essential oil and peppermint essential oil	Chamomile essential oil and peppermint essential oil	Antibacterial	Better bacterial activity against both types of bacteria and showed no toxicity in cells	(Tang et al. 2019)
Synthetic Poly (L-lactic acid) PLA	Carvacrol	Carvacrol	Antibacterial 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 effected on the sensory quality of beef	9lin, dai, and Cui 2017)
(PCL) Polycaprolactone	Gelatin film	Black pepper oleoresin (oR)	Antimicrobial	Improve the properties of galetin films.	(Figueroa-Lopez et al. 2018)
PVA	Durvillaea Antarctica alae 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 to be 92.26 ± 5.93% and 94.58 ± 6.53%.	(Liu, Liang, et al. 2018)
PVA	Cinnamon essential oil nanophytosome (N/CEO)	N/CEO	Antibacterial	Antibacterial activity on a raw shrimp for 7 d of storage.	(Nazal et al 2019)

It is possible to create natural and biodegradable pullulan composite nanofiber. Consequently, these substances are regarded as being ecologically beneficial (Qin et al. 2019). In one study, pollutant was combined with tea polyphenols (TP) and carboxymethyl cellulose (CMC) to create fibres for fruit packing that would prolong the shelf life of strawberries (Soto et al. 2019). In the past ten years, several different polymers have been electrospun; listed in Table 2.v

Applications of electrospun fibers in food packaging technology

Application in food preservation

Food preservation is crucial for helping meals protection and providing everyone with wholesome food. To ensure that food is healthy and safe to eat, the organoleptic qualities should be preserved (Zhao et al. 2020). In order to create diverse fibres for the presentation of multiple food products, several electrospinning procedures are applied. In addition to being used on a wider scale to preserve various food products, electrospun fibres are also employed for the packing of dry goods (Liu, Gough, et al. 2020). Submissions for fruit packing Perishable foods undergo a variety of metabolic processes, and fruits are among the perishablest of them all. In order to increase the quality and lengthen the shelf life of fruits, we must concentrate on efficient preservation techniques, such as covering with eatable films, using smart films, and controlling the ambient storing temperature. Numerous experiments have been conducted utilising electrospinning techniques to create films that preserve fruits. Here, a few of them are offered. In 2018, Shao et al. created a film for strawberry conservation by energetic catechins from tea polyphenols, pullulan for its film-forming properties, because it improves the pullulan's properties. Pullulan and CMC could coexist because CMC created hydrogen connections between the COO groups of CMCs and OH groups of pullulans.

The findings demonstrated greater encapsulation was accomplished using electrospinning, and the film considerably increased the shelf lifetime of strawberries by modifying the concentration of TPs and preserving the diameters of the fibres. Early ripening of fruits is one of the primary causes of fruit deterioration. The primary ripening factor that encourages fruits and vegetables to mature early is ethylene. According to certain research, the breakdown of ethylene causes the ripening process to be delayed, which reduces food waste. As food might perish due to ripening during long-distance travel, this deterioration is particularly beneficial (Zhu, Zhang, et al. 2019). For many years, researchers have investigated and employed fruit packing. Fruits need to be packaged in a variety of ways. There are many different categories for fruits. First, they are categorised according to their fibre content. The second group is new cut fruits, which include ready to-eat fruits and diverse fruit salads, both of which are popular in today's society. Returning to the topic of fibre, fruits contain two different forms of fibre: water soluble fibre and water insoluble fibre. Additionally, there are two types of fibre: hard fibre and soft fibre. Fruits like strawberries, blueberries, and raspberries have soft fibres, whereas fruits like pears, peaches, apples, and melon have hard fibres. The latter are more susceptible to damage and contamination, necessitating greater caution in their collection, storage, transportation, and packing. While we may readily utilise hard fibrous mats made by electrospinning for the packing of hard fibre fruits, we must use soft fibre mats for the packaging of soft fibre meals in order to prevent harm from the water content of the fruits. Fruits with solid shells, those with dense skins, and those with spikes on their skin among others, need for different forms of packaging. The biggest problems, however, are the discoloration and foul smell that develop after a short while and reduce their usefulness. Therefore, these fruits should be preserved using high-quality fruit packing sheets (Mei and Wang 2020). Table 3 lists several electrospun materials utilised in line with the fruit fibre type.

Applications for packaging of vegetables

Food packaging materials are vital for diverse veggies in addition to fruits. High-water-content vegetables like tomatoes, peppers, and cucumbers are more perishable. Electrospun nanofibers have a variety of characteristics, such as very tiny diameters, that enable them to store and use bioactive substances while releasing them over time. Vegetables that have gone bad, especially perishable vegetables like cucumber and tomatoes, are a common source of foodborne infections. Minimally processed veggies, often known as MPVs, are significant commodities for a variety of reasons, including their convenient nature and appealing sensory qualities. These veggies become more vulnerable to the invasion of germs as a result of processing, such as chopping, slicing, and peeling, which reduces their fleshly shelf life time. There are few publications on how to preserve these crops, particularly when electrospun materials are used. (Bohmer-Maas et al. € 2020; Hashmi et al. 2021). Table 3 provides descriptions of a few outcomes.

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

Food	Fiber type	Electrospun material	Nanofiber characteristics	Preservation	References
Fruits			increase in diameter with hexanal loading -		
Fresh cut apple	-	Horde in quercetin - chitosan	Antioxidant Hydrophobic	Antioxidant/Hydrophobic	(LL, 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 , Pallyath , 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, Cul, et al. 2019)
Vegetables					
Mushrooms	Perishable elastic fungi	Poly vinyl alcohol / cinnamon essential oil / B - 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 oll		Improves sensory qualities up to 4 d / restricts E. coll growth	(Cul et al. 2018)
Fish					
Sparus aurata (gilt head sea bream fillets)		Thymol / Chitosan		Vitamin stability for prolonged shelf	(Ceylan, Yaman et al 2018
Dicentrarchus labrax (sea bass fillets)		Liquid smoke / thymol / chitosan		Strong antibacterial properties against mesophilic bacteria	(Ceylan, Sengor 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 / έ-Poly-lysine	Enhanced tensile strength due to glycerin	Strong antibacterial against Listeria monocytogenes	(Lin ,Gu, et al. , 2018)
Chicken		Thyme essential oil cydodextrin poly lysine		Campylobacter jejuni	(Lin, Zhu, et al, 2018)

	nanoparticles (TCPNs)		
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)

Applications for packaging of fish

Fish is a very important and extremely perishable source of protein; it cannot survive even 24 hours at room temperature. Fish rotting is detected using a variety of criteria that can be changed by different packing methods. This section examines the results of various fish processing procedures and storage. The variability of vitamins, mostly the vitamin B complex, is one and only of the key elements that may be utilised as a reliable predictor for fish spoilage. The vitamin B complex is unstable under a variety of conditions, including humidity, heat, light, oxygen, and pH. A collection of water-soluble vitamins known as the vitamin The stability or shelf life of the vitamin B complex determines how long fish will stay fresh. Packing must be planned to keep the vitamin B complex's stability to outspread shelf lifetime. In a research by Ceylan et al., thymol-loaded chitosan was electrospun into nanofibers to see how this affected the firmness of the vitamin B complex throughout cold storing. The findings showed that electrospun nanofibers containing thymol and chitosan loaded onto fish fillets considerably assisted in preserving the fish vitamin B complex stability during cold storage (Ceylan et al. 2020; Ceylan, Yaman, et al. 2018). Table 3 lists a rare research on the electrospun resources for different species.

Applications for packaging of meat because it is a significant source of nutritious proteins, meat is yet another extremely perishable item that is frequently consumed. Due to the numerous poultry farms and inexpensive price, chicken is a widely utilised meat. It is a common food in everyday life since it is not only inexpensive but also has a delicious flavour. However, a number of food-borne pathogenic bacteria, cause it to degenerate. Meat deterioration, often known as meat rot, is caused by the denaturation of amino acids (Surendhiran et al. 2020). In addition to being extremely difficult to transport, it needs to be carefully kept right away after being killed. On the packing of meat, various research have been published. In 2018, scientists created nanofiber coatings for the preservation of C. jejuni meat. They created a film using b-cyclodextrin e-polylysine nanoparticles and thyme essential oil, and it demonstrated outstanding antibacterial activities beside C. jejuni in chicken (Lin, Zhu, and Cui 2018). The types of meat supplies and the electrospun materials utilised to preserve them are listed in Table 3.

Applications for packaging of other food products Regardless of whether they are cooked or not, a lot of food products, such cheese, milk, bakery goods and pizza, need to be packaged. Table 3 displays previous studies.

Application in antimicrobial food packaging It is essential for antibiotic packaging sheets to form. Bacterial invasion is the main factor in food rotting (Ahmed et al. 2020). This section also provides some instances of studies done on antibacterial films. Curcumin that had been loaded with zein was used by Liu et al. to make a film, and electrospinning was used to create fibres. Additionally, they demonstrated strong antibacterial and antioxidant abilities. The findings demonstrated that Fickian diffusion was the main mode of curcumin release, which is encouraging for substances with antibacterial effects. Numerous organic polymers are also employed for the creation of antibacterial films in addition to inorganic components like zein. The most crucial ones are organic antibacterial substances, such essential oils. Essential oils are specialised antimicrobial volatile aromatic molecules. They have several antiviral, antifungal, and antibacterial activities and are often derived from plant sources. Numerous research have been conducted to address these issues with essential oils since, despite these drawbacks, they offer exceptional antimicrobial effects. (Yaowen Liu, Wang, Lan, et al. 2017). Table 4. The studies that follow provide significant historical context for the impact of different polymers on certain bacteria.

Application in sustained release One of the key benefits of electrospun nanofibers is that they capture bioactive materials in their carpets and permit their late discharge, enhancing the effectiveness and quality of the corresponding films (Karami et al. 2021). Because of its slow-release qualities, curcumin is well known for its potent antibacterial action. Gelatin nanofibers had been used with several surfactants, \ to accomplish the delayed discharge of curcumin (SDS). SDS exhibited an increase in diameter, but CTAB and Tween 80 had no discernible impact. Additionally, the gelatin and SDS interaction did not demonstrate the efficient discharge of curcumin. In difference, the sluggish discharge of curcumin into polar solvents was significantly enhanced by the other two surfactants. Developed radical searching action and more potent antibacterial activity were the results of this. This work produced gelatin nanofibers for the gradual release of curcumin using food-grade surfactants, yielding good results that may hold promise for the food packaging and pharmaceutical sectors (Deng et al. 2017). Numerous further research are also carried out (Hoseyni et al. 2021; Min et al. 2021).

Application in sensors for smart packaging The development of specialised sensors for food degradation is currently greatly facilitated by active and smart packaging. For instance, the cyclodextrin inclusion complex (CD-IC) was previously studied, and it was discovered that CD-IC polymers could incorporate various active compounds and possess later processing characteristics, such as improved solubilities, high thermal stabilities, controlled release capabilities, and long shelf lives, making them appropriate for food packing machinery as well as for nutraceuticals, functional foods, and the pharmaceutical industry. (Aytac et al. 2017; Aytac and Uyar 2017; Aytac et al. 2016; Canbolat, Savas, and Gultekin 2017; Costoya, Concheiro, and Alvarez-Lorenzo 2017). In addition to functional features, smart packaging can also include nanosensors for tracking and monitoring the interior and exterior conditions of food. By doing this, it helps customers determine the precise quality of packed foods at the moment of buying. As an illustration, several pH-sensitive dyes with sensors can alter their hue in reaction to variations in the pH of food. These pH-sensitive devices demonstrate improved thermal and storage stability (Kumar et al. 2019). The amount of ethanol included in alcoholic beverages has been calculated using the amount of fluorescence that terphenyl-ol implanted in nanofibers produces. Researchers have also explored and created gas biosensors that use electrospun nanofibers to identify ammonia and hydrogen sulphide (Mousavi et al. 2016), hydrogen (Drobek et al. 2016), alcohol vapor (Akamatsu et al. 2015), biogenic amines (Geltmeyer et al. 2016), and so on. Electrospun nanofibers are used for microbial detection in addition to chemicals and gases.

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

Electrospun Material	Antibacterial agent	Microorganisms	References
Polyacrylonitrile	Ag NP	Staphylococcus aureus, Escherichia coll, Monilia albicans	(Shi et al. 2015)
Polycaprolactone	Ag NP	Staphylococcus aureus, Escherichia coll, Candida albicans	(Lao, L, and Tjong 2019)
Polyacrylonitrile (PAN)/ b-cyclodextrin (b-CD	Cu nanorods	Escherichia coli	(L et al. 2014)
Polyvinyl acetate	CuO /TiO2	Staphylococcus aureus	(Hassan et al. 2013)
Nylon 6,6	Polyacrylic add grafted rose bengal, phloxine B, azure A, and toluidine blue	Aspergillus fumigatus, Aspe rgillus 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 axide) (PEO) and poly (vinyl alcohol) (PVA)	Lawsonia inermis (henna)	Escherichia coll, Staphylococcus aureus	(Avci, Monticello, and Kotek 2013)
Modified polyurethane (quatemary 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)

Challenges of electrospun nanofibers for food packaging Electrospun nanofibers have several benefits, making electrospinning a reliable and popular technology for film creation in the food packing business. When opposed to traditional film creation techniques, electrospinning is a special process that offers great applications and advancements. However, one major drawback of electrospinning in the food packing sector is that it is only utilized in laboratories, whereas fiber production at the marketable measure is required to advance industrialization and its use in food packaging films on the industrial level in order to reach the market. There is, however, little proof of their commercial use. In the specialised sector of food packing, several expansions are thus needed, with enhancements in the constancy, barrier qualities, worth, and mechanical properties of electrospinning-based fibrous mats (Zhang et al. 2020). It should be highlighted that nanoparticles can affect the environment severely and endanger human health. There is currently a dearth of information on possible risks associated with the usage of nanoparticles in the writings. For instance, silver nanoparticles have significantly harmed liver tissues and eventually result in liver disease. There are several methods of penetration, including ingestion, cutaneous absorption, and inhalation. Packaging using nanoparticles makes all of these approaches possible. According to some research, these particles are absorbed into the body, enter the bloodstream, and then settle in various bodily tissues including the liver and brain, where they cause a variety of disorders and incite immunological reactions. Advances in packaging that won't come into touch with the food are required to solve this bottleneck problem. (Neo, Ray, and Perera 2018; Zhang et al. 2020).

Conclusion

The electrospinning packing method and its use for food conservation were summarised in this paper. Due to its distinctive and innovative uses in the realm of food science, electrospinning has grown in prominence over the past several decades. But most of its applications are still lab-scale and have not yet been sufficiently developed for use in industrial settings. Nanotechnology may be utilised in food manufacturing to improve a variety of foods' colour, flavour, texture, and consistency in addition to its antibacterial properties. Because extremely small nanoparticles can easily enter food and harm various physique parts, particularly liver cells, which are easily entered, and brain tissue, which can activate the immune system, the usage of nanostructures in the creation of food packing films requires additional research and invention. These breakthroughs do, however, have a number of negative side effects. Governmental policies and rules must be created in order to combat environmental dangers and health concerns, and they must be executed by various regulatory agencies in order to provide safe and risk-free food packaging films. In order to provide regulatory authorities with well-established, tried-and-true, and expertly-trained methodologies to build safe nanotechnology-related food packaging, these programmes should provide numerous tools, data, and procedures. Therefore, there are several chances for more study on food security and safety in order to achieve our fundamental goal of "food for all."

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