Chapter

Active Electrospun Mats: A Promising Material for Active Food Packaging

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Abstract

Nowadays, polymeric materials are widely used in the development of food packages. However, as food products with a greater safety and longer durability are required, packaging research area has been focused on the production of functional materials able to reach such further protection. The incorporation of natural and synthetics active compounds into the polymeric materials by traditional techniques has been the main used strategy, surging thus the research area of active food packaging. Furthermore, the latest science advances provide promising technologies for developing packaging materials, such as the electrospinning. This technique has allowed obtaining ultrathin electrospun mats based on micro- and/or nanofibers that have been proposed as novel active materials able to be applied as wrapper films, sachets and bags during the food packaging. In this chapter, the description of electrospinning, the effect of their principal parameters during the development of active food packaging materials as well as their current applications on different foodstuffs are presented.

Keywords: active compound, food package, food shelf life

1. Introduction

Packaging is one of the most useful tools used by the food industry to protect several foodstuffs against contamination and spoilage. Traditionally, materials such as plastic, glass, metals, paper and board have been used for developing food packages [1, 2]. However, the interest by polymeric materials have enormously increased because they exhibit several advantages, such as low-cost, low-weight and good mechanical, barrier and optical properties [3, 4]. Therefore, processed and non-processed foods are daily packaged into plastic materials in order to avoid their contamination by odors, dust and microorganisms, as well as their deterioration by temperature, humidity, light, shocks, physical damage, among others [5, 6]. Despite of several benefits that packaging industry offers to food, oxidation and microbial spoilage are the principal mechanisms that entail a great loss of fruits, vegetables,

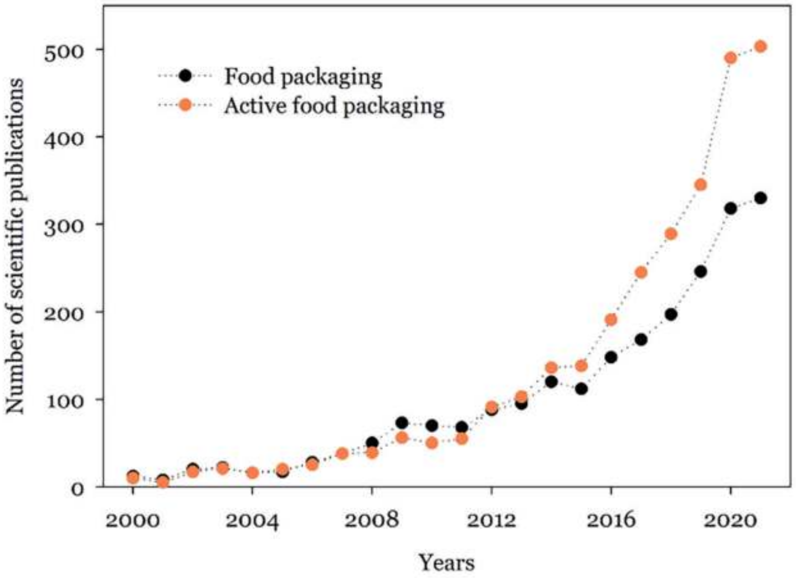

Figure 1.
Articles related to traditional food packaging and active food packaging in the last two decades (data obtained from Web of Science data basis).

meats, dairy and bakery products during their production, transport, processing, storage, and marketing [5]. In this context, during the last decades, the packaging area has centered its aims to the development of materials able to maintain or improve the properties of food, and therefore, extend its shelf-life. Several studies have developed different functional materials which in turn have allowed the surging of active food packaging in the last years. Thus, **Figure 1** shows a comparison between the number of indexed articles about "Food packaging" and "Active food packaging", published in the Web of Science (WOS) data basis. This figure shows the growing interest in food packaging research area during the last two decades, evidencing that active food packaging has been specifically leading during the last 5 years when compared to traditional food packaging published research.

2. Active food packaging technology

2.1 Definition

Active food packaging is considered a system of positive interaction between the food, the packaging material and the environment with the aim of preserving the properties of food and avoiding its deterioration during transport and storage [7]. In this way, compounds or substances with an active function (active compounds) have been incorporated into polymers in order to obtain active materials [6]. Natural and synthetic active compounds, such as plant extracts, essential oils, peptides, enzymes, organic acids, salts, metals ions, metal oxides, nanoparticles, among others, have afford to the packaging materials different functionalities, such as: (i) releasing/emitting of antioxidants, antimicrobial, sulfur dioxide, preservatives, ethanol and flavors; (ii) absorbing/scavenging of carbon dioxide, oxygen ethylene, flavors, moisture, UV light; and (iii) controlling the microbial, temperature and quality of foods [8, 9].

2.2 Formats and technologies

The design of active packaging systems has been mainly focused on the characteristics of the active compound and packaged food. **Figure 2** shows the five mechanisms for generating an active packaging system through [7, 10]:

Incorporation external devices (labels, pads or sachets loaded with some active compound) into the package able to release or absorb substances.

Coating of active compound onto inner surface of packaging material. This system is useful for heat-sensitive compounds or incompatible and immiscible with polymeric matrix.

Immobilization of active compound in the inner layer of packaging material through ion or covalent linkages. It is important the presence of functional groups on active compound and polymer to get the immobilization.

Direct addition of the active compound into the packaging material matrix [11].

By using polymers with some active function (e.g., chitosan) to develop composites or multilayer materials.

Most polymeric materials that have been part of above-mentioned active packaging systems have been obtained through traditional techniques, such as melting based processes (melt blending, hot pressing, cast extrusion, injection molding), casting, coating [12]. For example, the extrusion technique was recently used by producing active labels based on low-density polyethylene films loaded with different essential oils and vegetable oils [13]. In this work, fresh beef was packaged into commercial trays with modified atmosphere (70% O_2 + 30% CO_2), and the active labels were placed on the top of the tray in order to protect the food. Results

Figure 2.
Routes for obtaining an active packaging system.

demonstrated a great effectivity of active packaging system because the shelf-life of fresh meat was extended by 22%. On the other hand, casting technique has been also a useful tool for producing active food packaging systems. In this context, Sooch and Mann developed an active package from gelatin and copper nanoparticles doped with titanium dioxide. Tomatoes were wrapped with these packaging materials, and the shelf-life of vegetables was extended by 18 days [14]. Likewise, multilayer materials for active packaging of meat products have been also developed through coating technique. Bilayer films composed by poly(lactic) acid (PLA), as substrate, and chitosan or blends of chitosan/caseinate enriched with rosemary essential oil, as coating, were recently used for protecting fresh minced chicken meats. In this case, oxidation process and color changes of food were not shown for 14 days because the food was in direct contact with active materials [15].

On the other hand, non-traditional techniques as carbon dioxide supercritical impregnation and atomic layer deposition (ALD) have been also employed for developing active materials. However, the application of such technologies in food has been not already evaluated. Villegas et al. impregnated cinnamaldehyde through supercritical carbon dioxide into PLA film in order to obtain an antibacterial material. Active film showed a strong and effective antibacterial activity against *Staphylococcus aureus* and *Escherichia coli* [16]. Unlike supercritical impregnation, the combination of electrospinning and ALD process has allowed to produce metallic oxide nanostructures with antimicrobial properties that can be subsequently incorporated into polymers. In this context, nanotubes and spherical particles of titanium dioxide (TiO_2) and zinc oxide (ZnO) have been produced by this combination [17–19]. In all studies, metallic oxide nanostructures showed a high antimicrobial property against Gram-positive and Gram-negative bacteria.

As the technology has been progressed, in the last decade, a novel technique known as electrospinning has been used for developing polymeric materials that posteriorly play a fundamental role in the active packaging system.

3. Electrospinning

Electrospinning is an efficient and novel technique that consists in the application of an electric field to a polymeric solution in order to produce thinner structures known as “fibers” [11]. As **Figure 3** shows, the electrospinning is composed by three main components: (i) a high voltage source composed by two electrodes that are connected to the output of a metal needle and to collector, (ii) an injection pump that impulses the polymeric solution through plastic tube to metal needle, and (iii) a collector. To obtain the fibers, it is necessary that the surface tension of the drop formed in the tip of the needle be overcome by the force of the electric field. On this way, the polymeric solution is continuously stretched to produce a jet with a conical structure named “Taylor’s cone”, where the solvent is evaporated to obtain the fibers [12].

Characteristics of the fibers depend on the control of the electrospinning parameters. In this context, a change of the properties of the polymeric solution (polymer concentration, viscosity, electrical conductivity, type of solvent) or the operational parameters (flow rate, voltage and the height also known as the distance between the tip of the needle and the collector) can affect the size and morphology of the fibers [20]. This fact will be detailed in the following section.

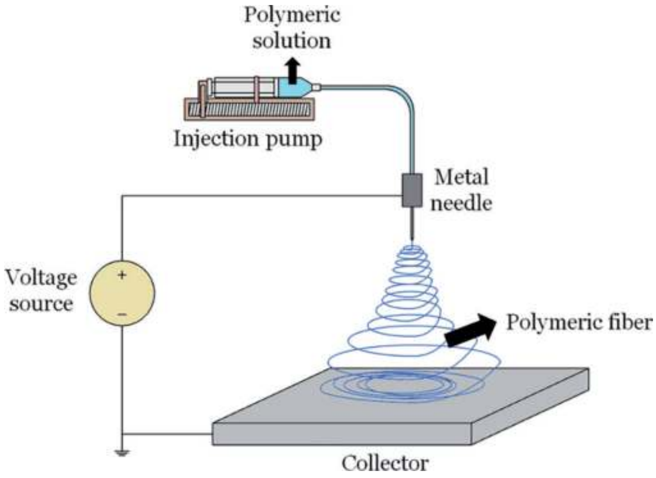

Figure 3.
Electrospinning system.

3.1 Influence of the properties of the polymeric solution

3.1.1 Polymer concentration

The concentration of the polymer is one of the main parameters that affects the size and the morphology of the fibers, and it is closely related to the viscosity of the solution. If the solution concentration is very low, the jet cannot be continuously stretched, and thus, uniform fibers cannot be obtained. This fact in turn can produce a decrease in the diameter of the fibers and the presence of beads in their surface. On the contrary, an increase of the concentration can result in thicker structures, and in some cases, the non-formation of the fibers due to high viscosity of the solution. A recent study evidenced the decrease of the diameter and the presence of beads in polycaprolactone (PCL) nanofibers when the polymeric concentration decreased from 13 to 8 wt% [21]. A similar result was also obtained in the processing of cellulose acetate (CA) and poly(vinyl chloride) (PVC) nanofibers. In both cases, the use of CA and PVC concentrations at 12 wt% resulted in thinner and beaded fibers, while an increase to 16 wt% produced structures with smooth surfaces and large diameters [22].

3.1.2 Electrical conductivity

The increase of electrical conductivity in the polymeric solution has been mainly related with the increase of the concentration of the polymer, favoring the electrospinning process and the formation of the fibers. For example, gelatin nanofibers were only obtained with acid solutions at high gelatin concentrations. The low electrical conductivity obtained with the lowest gelatin solution (7 wt%) did not allow to produce fibers. On the contrary, the increase of polymeric solution concentration to 20 wt% produced an increase of electrical conductivity and the formation of nanofibers [23].

3.1.3 Type of solvent

The type of solvent has an important role during the electrospinning process. It is stretched related with the surface tension of the solution, and several investigations have shown changes of this parameter by the use of different solvents or the mix of them. This fact in turn has derived in different morphologies and sizes of fibers. Thus, the combination of formic acid (FA) and dichloromethane (DCM) at different ratios as solvent system for producing PCL nanofibers produced changes on the diameter of the structures. A higher amount of FA produced an increase of electrical conductivity solution, while an increase of the amount of DCM increased its surface tension. These effects in turn produced fibers with diameters between 1.5 μm and 220 nm [21]. Likewise, the use of the following solvent systems: acetone/N,N-dimethylacetamide, acetone/N,N-dimethylformamide and tetrahydrofuran/dimethylformamide at different ratios changed the morphology of PCL nanofibers. Beaded, beaded-free, thin, thick and smooth nanofibers were obtained with these different combinations, and this fact could be associated to the changes on the surface tension of polymeric solutions [22].

3.2 Influence of operational parameters

3.2.1 Flow rate

The flow rate is considered a key parameter because controls the diameter of the fibers, the trajectory of jet, initial droplet shape, maintenance of Taylor's cone and the collection area. A high flow rate produces larger droplets in the tip of the needle and favors the formation of thicker and beaded fibers due to minimum solvent evaporation. On the contrary, a low flow rate facilitates the evaporation of solvent, obtaining uniform and smooth structures [24]. This effect has been observed when a poly(vinylidenefluoridene-hexafluoropropylene) solution was electrospun at different flow rates. An increase of flow rate from 0.1 to 0.7 mL/h produced an increase of fiber diameter [25]. The same result was also obtained when the flow rate of a poly(vinyl alcohol) (PVOH) solution increased from 0.75 to 1.5 mL/h [19].

3.2.2 Collection distance

The distance between the needle and the collector has a great effect on the diameter and the shape of the fibers. A small distance avoids the total evaporation of the solvent, and thus, the collection of wet and thicker fibers can occur. In this way, the presence of beads or the formation of ribbon-flat fibers have been the most common results. On the contrary, a high distance can improve the stretching of the jet and favor the formation of uniform and thinner structures. Furthermore, the increase of distance can also increase the needed voltage to produce the fibers [19, 26]. A recent study obtained thinner polyacrylonitrile nanofibers when increased the collection distance from 15 to 45 cm [27]. Similarly, the increase of collection distance from 8.5 to 10 cm produced smaller diameter in PVOH nanofibers [19].

3.2.3 Voltage

Despite of several studies have demonstrated that voltage has a minimum impact on the diameter and morphology of fibers, it is an important parameter to be considered during processing of electrospun materials. This fact is due to its increase can produce change the diameter of fibers and produce the presence or absence of beads in the structures [26]. Some studies have evidenced the effect of this parameter on such characteristics [23, 27].

3.3 Active electrospun materials

As it was earlier mentioned, electrospinning is able to produce smaller and thinner mats composed by fibers with high aspect ratio. In order to functionalize these mats, active compounds can be incorporated into them. These materials in turn could be converted to active packaging materials or be part of an active packaging system, exhibiting the following advantages [11]:

- Lower amount of required active compound due to small sizes of fibers,
- Good distribution of the active compound,
- High surface-to-volume ratio with tailored thicknesses due to the high versatility of this technique.

Despite of active electrospun materials are an excellent alternative to develop active packaging materials in comparison with other traditional techniques (melting processes, coating, casting), their processing remain one of the main challenges. This fact is mainly because the addition of the active compound can produce changes in the properties of the polymeric solution, and therefore, the electrospinning process can be affected. In order to deepen in the topic, the following section will discuss the effect of adding active compounds in the development electrospun materials.

3.4 Influence of active compounds during electrospinning process

The incorporation of an active compound to the polymeric solution to be electrospun can mainly change their physicochemical properties and affect the development of electrospun packaging material as follows.

3.4.1 Viscosity

The viscosity of the polymeric solution is related to the concentration and molecular weight of the polymer. A polymeric solution with an optimum viscosity can be electrospun in order to obtain the active mat. On the contrary, solutions with very high or low viscosities affect the electrospinning process and the obtaining of homogenous fibers [28]. Depending on the type of the active compound, the viscosity of the polymeric solution can be increased or decreased, and the morphology and diameter of the fibers are affected. As is shown in **Table 1**, the use of essential oils has mainly produced an increase of solution viscosity, which has derived in an increase of fiber diameter. This effect has been mainly associated to a less stretching of the jet [30]. For example, the increasing addition of angelica essential oil into gelatin solutions produced high viscosities which resulted in thicker fibers [30]. Altan et al. also evidenced this same effect when active PLA fibers loaded with carvacrol were developed [29]. Likewise, thicker fibers of glycyrrhiza polysaccharide and polyoxide ethylene (PEO) loaded with tea tree essential oil encapsulated into gliadin nanoparticles were obtained by Cai et al. Like above mentioned studies, the active compound increased the solution viscosity and affected the diameter of the fibers [31].

On the other hand, the effect of incorporating plant extracts in the viscosity of the polymeric solutions has produced different behaviors. A clear tendency of increase or decrease of viscosity by the incorporation of plant extracts has been not obtained.

Polymeric solution	Active compound	Amount of active compound incorporated (%wt.)	Polymeric solution properties			Reference
			V	ST	EC	
Zein	Carvacrol	5–20	↑	—	—	[29]
PLA			↑	—	—	
Gelatin	Angelica essential oil	3–9	↑	—	↑	[30]
Glycyrrhiza polysaccharide and PEO	Tea tree oil-gliadin nanoparticles	2–10	↑	—	↑	[31]
PVOH	LEO and REO	10	↑	↓	↑	[32]
PCL	Sage extract	5–20	↓	C	↑	[33]
Zein	Tomato peel extract	5–20	↑	↓	↓	[34]
Zein	Jaboticaba peel extracts	5–11	↓	—	↑	[35]
PVOH	Coptis chinensis extract	5–15	↑	↑	—	[36]
Zein	TiO_2	1–5	↑	—	↓	[37]
PVOH and gum karaya	Ag	0.2–2	↑	—	↑	[38]
Ethylcelullose/gelatin	ZnO	1–2	↓	—	—	[39]
Amaranth protein and pullulan	Nisin	10 and 20	↓	—	↓	[40]
Gelatin	Nisin	0.5–3	M	—	↑	[41]
Chitosan/PVOH	Lysozyme	10–30	↓	M	↑	[42]

V = viscosity, ST = surface tension, EC = electrical conductivity. Trends: ↓ = decreased, ↑ = increased, M = maintained, C = constant.

Table 1.
Influence of the active compound incorporation on properties of polymeric solution.

A work about PCL fibers loaded with sage extract evidenced that the incorporation and increase of extract concentration in the polymeric solution decreased its viscosity and favored the production of thinner fibers [33]. Likewise, an increase of concentration of jaboticaba peel extract in a zein solution decreased its viscosity and the diameter of the fibers [35]. Meanwhile, an increase of concentration of tomato peel extract in a polymeric solution of zein produced an increase of its viscosity and the development of thicker fibers [34]. Yang et al. also obtained a similar result when *Coptis chinensis* extract was incorporated in a zein solution. Similarly, the extract increased the viscosity of the solution, but favored the decrease of diameter of the fibers [36].

The use of nanoparticles has also influenced the diameter and the morphology of the fibers, and this fact has been mainly related to changes in the solution viscosity. For example, although an increase of TiO_2 nanoparticles concentration into zein solutions caused high viscosity values, thinner fibers were obtained [37]. A similar effect was also observed in the development of PVOH/gum karaya nanofibers loaded with silver (Ag) nanoparticles, whose resulting nanofibers showed roughness in their surface, and this fact was attributed to an increase of the viscosity of the polymeric solution. Meanwhile, Liu et al. evidenced a contrary effect because the viscosity of a blend of ethylcellulose and gelatin decreased with the increase of ZnO nanoparticles concentration, but the diameter of fibers increased [39].

The development of fibers loaded with peptides and enzymes has also been an excellent strategy for producing potential active electrospun materials. Most studies have evidenced a decrease of the polymeric solution viscosity after their incorporation, which in turn has affected the size of fibers. A decrease of diameter of amaranth protein/pullulan nanofibers was evidenced by Soto et al. when nisin was incorporated to the polymeric solution. The increase of nisin content decreased the viscosity of the solution due to the molecular entanglement among the components, and this in turn influenced on the diameter of the fibers [40]. Likewise, a work about active nanofibers of chitosan/PVOH loaded with lysozyme showed a result similar. In this case, the incorporation and increase of the lysozyme concentration caused a decrease of viscosity, and therefore, a decrease of the nanofiber's diameter [42].

3.4.2 Surface tension

This parameter is closely related with the nature of the solvent. Surface tension shows the strong cohesiveness of the molecules in the solution, which allows the formation of the drop on the tip of the capillary before to be formed the jet by action of electric field [43]. A decrease of surface tension results on bead-free fibers while its increase produces instability of the jet and avoids the formation of the nanostructures [44]. As can be seen in **Table 1**, the incorporation of active compounds has mainly produced a decrease of surface tension of polymeric solutions due to their behavior as surfactant. Despite of this, the morphological properties of the fibers have been not affected. This effect was recently evidenced when essential oils of *Laurus nobilis* (LEO) and *Rosmarinus officinalis* (REO) were added to an aqueous PVOH solution [32]. The surface tension value was significantly lower than the solvent, and it decreased even more when the essential oils were added [32]. Horuz et al. also obtained a similar result in their study about active fibers of zein loaded with tomato peel extract. In this case, the addition of the extract decreased the surface tension without affecting the morphology of the fibers [34]. Likewise, the incorporation of sage extract into an organic PCL solution did not produce changes on the morphology of the fibers although its surface tension was decreased [33].

3.4.3 Electrical conductivity

Another of the key parameters for the development of electrospun active fibers is the electrical conductivity. The value in this parameter influences on the fiber's morphology. Generally, an increase of electrical conductivity facilities the elongation of the droplet and jet formation, therefore, thinner and bead-free fibers are reached [45]. **Table 1** shows that the incorporation of an active compound into a polymeric solution has generally produced an increase of its electrical conductivity. Despite of this, the morphology and the diameter of the fibers have shown different trends. For example, although the addition and increase of angelica essential oil concentration into gelatin solutions produced higher electrical conductivity values, an increase of diameter of the fibers was mainly influenced by the increase of the viscosity [30]. A similar result was recently obtained in a study about active nanofibers of glycyrrhiza polysaccharide and PEO loaded with tea tree essential oil encapsulated into gliadin nanoparticles. As the above-mentioned study, the active compound significantly increased the electrical conductivity of the polymeric solution. However, the increase of fiber diameter was attributed to the higher solution viscosities [31]. Meanwhile, a contrary effect was obtained in the study of Avila et al. In this case, the incorporation and increase of jaboticaba peel extract concentration into zein solutions increased their electrical conductivity, which favored the formation of thinner fibers [35]. The same effect was also evidenced in the electrospinning process of chitosan nanofibers loaded with lysozyme [42].

On the other hand, few studies have evidenced a decrease of this parameter when the active compound has been added to the polymeric solution, resulting in the formation of thicker structures. The increase of the diameter of the fibers due to the decrease of electrical conductivity has been explained because static charges of the solution are oriented to jet surface during the electrospinning process. In this way, the capacity of polymer solutions to be electrospun is increased [34]. For example, the adding of TiO_2 or tomato peel extract in a zein polymeric solution has evidenced such effect [34, 37].

3.5 Application of active electrospun materials on food packaging

Although electrospinning has been a novel tool for developing active food packaging materials, their application to industrial scale has been not still largely exploited. This fact has been mainly associated to its low technological readiness level (TRL) in the food area due to low-yield in the production of packaging materials [11]. However, the numerous researches about the application of this technology in real matrixes reveal their promissing and potential application in the food packaging area in the future. In this sense, the most recent developments that involve the application of active electrospun materials on different foodstuffs, the type of formats used for packaging and the principal assay experimental are shown in **Table 2**.

3.5.1 Meat products

In the food industry, chicken, meat and pork are considered the most appreciated and chosen meat products by the consumers due to a 15% preference of world population [68]. These food have been usually packaged into trays and bags through different systems in order to ensure their quality and safety [69]. Despite of this, microbial contamination, oxidation processes and loss of the sensory properties are still some of main issues that produce their spoilage. In order to avoid such complications, several developments based on the direct application of active electrospun materials as wraps or films has allowed their protection, as **Table 2** shows. In this way, the quality, safety and shelf-life of these products have been guaranteed during long-time in a cold storage condition. A wrapper active film based on PVOH electrospun nanofibers loaded with LEO and REO was used to protect chicken breast fillets against oxidation and microbial contamination during cold storage. The active mat inhibited their lipid oxidation up to 68% and decreased their microbial growth [32]. Likewise, an active electrospun wrap composed by PLA nanofibers loaded with inclusion complexes of γ-cyclodextrin/α-tocopherol was able to reduce the lipidic oxidation of beef up to 50% during its storage at 4°C for 21 days [48]. Li et al. also prepared active gelatin/zein fibers with resveratrol in order to wrap small pieces

Food category	Food Type	Applied format	Principal experimental assays	Reference
Meat products	Chicken	Wrapper film	Antimicrobial, antioxidant and sensory properties	[32, 46, 47]
	Meat	Film and wrapper film		[48–50]
	Pork	Wrapper film		[51–53]
Sea products	Fish	Wrapper film	Antimicrobial, antioxidant and sensory properties	[54–56]
	Seafood	Cover film		[57]
Fruits and vegetables	Fruits	Bag, wrapper film and sachet	Weight loss, firmness, antioxidant, antimicrobial, sensory properties, ripening rate and ethylene production	[58–61]
	Vegetables	Film and wrapper film		[37, 62, 63]
Bakery products	Bread	Sachet	Antimicrobial	[29, 64]
Dairy products	Cheese	Wrapper film	Antimicrobial and sensory properties	[65–67]

Table 2.
Application of active electrospun materials on different food matrices.

of pork. Samples were stored at 4°C and the active mat was able to extend their shelf-life by 3 days [51].

3.5.2 Freshwater and sea products

Fish and seafood are the main products obtained from salt and fresh water. They constitute a great source of animal protein and essential micronutrients, such as minerals, vitamins and essential fatty acids [70]. However, their high fatty content is one of the main reasons of decay, principally evidenced through changes of their sensory properties due to oxidation processes. Furthermore, their deterioration is also related to the presence and growth of pathogens and microorganisms. Therefore, and as **Table 2** shows, the latest developments about electrospun active materials have been mainly focused on the protection of freshwater and sea products against such deterioration processes. In order to achieve this, these products have been wrapped with developed active electrospun mats containing different polymers and active compounds. A work about the development of sodium caseinate/gelatin nanofibers loaded with essential oil of *Mentha spicata* L. and magnesium oxide nanoparticles evaluated their effectivity as fresh trout fillets packaging during cold storage for 13 days. This active material was able to reduce the oxidation in the fillets up to 93% and the presence of microbial population up to 5 log CFU/g [54]. In the same way, *Mentha longifolia* L. essential oil was encapsulated into carboxymethyl cellulose/gelatin nanofibers in order to produce a nanofibrous film able to improve the shelf-life of peeled freshwater prawns during 14 days in refrigeration. A low microbial growth and oxidation of the samples during the storage was reflected with the high sensory scores in terms of odor, color, texture, taste, and total acceptance [57]. Likewise, active electrospun mats composed by PVOH fibers loaded with poly(hexamethylene biguanide) hydrochloride or nisin have also protected these food against microbial growth [55, 56].

3.5.3 Fruits and vegetables

Another important group of food used for evaluating the effectivity of packaging systems are fruit and vegetables. Different strategies, such as the use of active sachets or packages with improve physical properties, have been applied for protecting them and extending their shelf-life [71, 72]. Despite of this, their weight loss, textural changes and fungal contamination are still the principal issues causing of their spoilage. In this sense, the most recent developments about wrapper films, bags, films and active sachets obtained through electrospinning have shown their potential application for active food packaging (**Table 2**). These materials have been mainly applied on strawberries, grapes, tomatoes and mushrooms, and promising results have been obtained. For example, an active electrospun sachet composed by PLA and PVOH/poly(ethylene glycol) nanofibers loaded with thyme essential oil was able to maintain the freshness and prolong the softening rate of strawberries stored at 20°C for 5 days [73]. Likewise, active zein fibers with allyl isothiocyanate were applied as a sachet into a package containing strawberries. In this case, the active sachet reduced the weight loss up to 36% and maintained their firmness during 15 days at 4°C [58]. On the other hand, two recent developments based on PVOH nanofibers loaded with inclusion complexes of β-cyclodextrin with cinnamon essential oil (CEO), and zein and ethyl celullose fibers loaded with CEO demonstrated their excellent effectivity during the storage of mushrooms. In both cases, the weight loss of the vegetables decreased, and therefore, their shelf-life was prolonged [62, 63].

3.5.4 Dairy and bakery products

As **Table 2** shows, cheese and bread have been the main food models used for evaluating the antimicrobial effectivity of active electrospun packaging materials. In order to avoid the bacterial and fungal contamination in this food category, wrapper films and sachets obtained from such materials have been developed. Cheese has been mainly wrapped with the active mats to avoid the growth of pathogens microorganisms. For example, a total inhibition of microbial growth of *Salmonella typhimurium*, *Listeria monocytogenes* and *Leuconostoc mesenteroides* was obtained by Soto et al. when cheese cubes stored at 4°C for 7 days were covered with active amaranth protein isolate and pullulan nanofibers loaded with nisin [65]. A study based on PEO nanofibers containing nisin-loaded poly-γ-glutamic acid/chitosan nanoparticles also evidenced a similar behavior. In this case, the strong antibacterial activity of the active mat against *L. monocytogenes* was observed on cheese samples stored at 4 and 20°C for 7 and 15 days, respectively [66].

On the other hand, active electrospun sachets have been the preferred format packaging for protecting bread samples. Contrary to cheese, the sachets have been applied without direct contact, avoiding mainly the fungal contamination. This fact was evidenced in the studies developed by Altan et al. and Fonseca et al. Both researches evidenced that the active sachets obtained from starch, zein and PLA nanofibers loaded with carvacrol were able to inhibit the growth of molds on bread stored at 25°C for 7 days [29, 64].

4. Conclusions

Electrospinning has been one of the most recent and novel technologies used in the packaging research area. This technique has allowed the development of electrospun mats composed by fibers with high aspect ratio. During their development, the modification of electrospinning parameters in turn have generated changes on the morphological characteristics of resulting fibers. Moreover, electrospun mats have been also functionalized through the incorporation of active compounds into polymeric solutions. This fact has eventually modified the viscosity, surface tension and electrical conductivity of the polymeric solutions, and therefore, the morphology and sizes of electrospun structures.

On the other hand, although this technique presents a current low technological readiness level in the food packaging area, the interest and projection of this technology to be applied is growing in an exponential way. This fact has been mainly evidenced by the diverse developments of active electrospun materials able to protect different products, such as meat, chicken, fish, pork, fruits, vegetables, bread, cheese, among others. Therefore, electrospun mats could be proposed as the new generation of materials to be used in the active food packaging.

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Conflict of interest

The authors declare no conflict of interest.

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